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Low cost solar cooker: Promising solution towards reducing indoor air pollution from solid fuel use

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Abstract

This paper presents the design, development and on-field studies of a low cost solar cooker which can act as a promising solution towards reducing the adverse impacts of indoor air pollution on the health of women and children of developing countries. The developed low cost solar cooker has been fabricated mainly through packaging cardboard, used oil tins, packaging insulation material, light weight polymeric glaze and reflector. The study reveals that the temperature profiles of the developed solar cooker are slightly better than the commercially available fibre body solar cooker. The figures of merit (F_1 & F_2) for the low cost solar cooker are 0.122 and 0.55 which are higher as compared to the commercial solar cooker values of 0.115 and 0.43. The payback periods for the developed solar cooker with respect to various fuels such as firewood, kerosene, LPG, coal and electricity are in the range of three months to less than 2 years.

Keywords: Solar cooker, on-field study, payback periods, figures of merit, indoor air pollution.

Introduction

Currently about 1.5 billion people in developing countries lack access to electricity and about 3 billion people rely on solid fuels for use (UNDP, 2009). The purchasing power of both the rural and urban low income households is less and cannot afford initial investment required in Worldwide around 50% of all households and 90% of rural households utilise solid fuels for cooking or heating (Desai *et al.,* 2004;UNDP 2009). Fifty six percent of people in developing countries depend on solid fuels such as coal and traditional biomass for the cooking requirements. Their access to improved cooking stoves is also very limited. Only 27% of those relying on solid fuels have access to the improved cooking stoves. From the total procurable energy available to the household sector in India, cooking alone consumed more than 80% of the energy (Pandey *et al.,* 2003; Pachauri, 2007). Firewood is the most commonly used fuel in rural India but its use has severe repercussions. The productive time of women and children is spent on collecting firewood which is indirectly affecting the social and economic development of the country. The felling of trees for fuel is an offence against environment resulting in serious ecological imbalance, which shows the after effects as droughts, famines and floods. The use of the bio-fuels with conventional low efficiency (~10%) stoves result in economic burden on the poor households and simultaneously cooking in a poorly ventilated kitchen is a threat to the health due to indoor air pollution. The combustion of biomass fuels in poor ventilation leads to the release of a large amount of respirable particulates, carbon monoxide, nitrogen oxides, benzene, formaldehyde, 1,3 butadiene and polyaromatic compounds. The combustion of coal may also emit sulphur oxides and other toxic elements, including arsenic, lead and fluorine, depending on the quality of coal. The cook (mainly women), children and old age people who are generally exposed to these pollutants are at the risk of serious diseases such as chronic obstructive pulmonary disease, acute respiratory infection among children, cataract, adverse pregnancy outcomes, pulmonary tuberculosis, asthma and cancer. Acute respiratory infections (ARI) are a leading cause of childhood illness and death worldwide, accounting for an estimated 6.5% of the entire global burden of disease. Exposure from biomass smoke is estimated to cause a global death toll of 2.5 million every year equivalent to 4-5% of total global deaths (Parikh *et al.,* 2001; Mishra, 2003; Joshi, 2006; Peter & Vennila, 2007; WHO, 2008). Thus indoor air pollution due to the use of solid fuels for cooking in developing countries is a major factor in increasing the environmental burden of disease.

In order to reduce the indoor air pollution the households should be educated about proper ventilation and improved cooking stoves should be made available to them. Further they should be encouraged to switch to cleaner fuels. In this regard, solar cookers can play an extremely important role. Solar cookers do not involve the risk of the release of pollutants, radiations and global warming. These have clean and benign image. With the use of the solar cookers the health hazards to women, children, and old age people as mentioned above can also be avoided. Ironically, many countries/states having tremendous solar potential are also the victims of energy crises since the available solar energy is not utilized efficiently (Painuly, 2001; Bahaj, 2002; Jefferson, 2006).

Keeping in mind the above mentioned problems the authors have been working on the design, development and study of solar thermal appliances in particular on solar cookers. The main hindrances in the popularization of the solar cooking are high cost, lack of proper repair and maintenance services, and inconvenience due to heavy weight, fragility of glass glaze and mirror, and unacceptability by the user due to the food habits and inertia to change. To cover a wide spectrum of users authors have developed a wide variety of user need based cooking systems ranging from light weight cardboard makes to fixed structure building material ones (Dashora & Sengar, 2002; Dashora *et al.,* 2005).

Fig. 1.The developed light weight solar cooker (LSC)

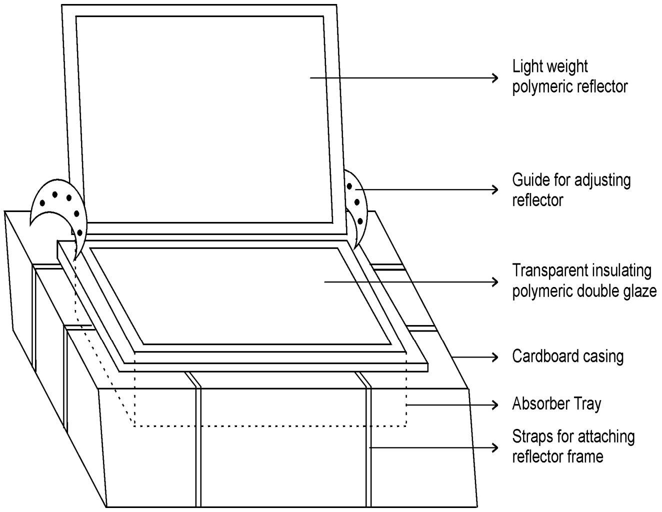
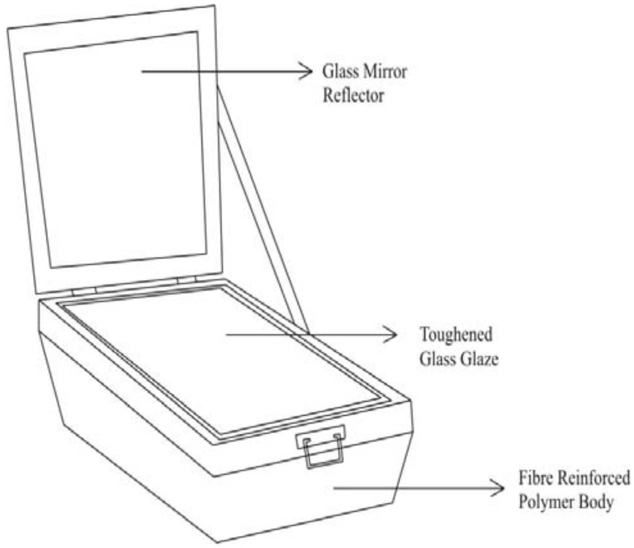


Fig. 2. The commercial fibre body solar cooker (CSC).



This paper presents the design, development and on-field studies of a low cost solar cooker. It is interesting to see that on the one hand such inexpensive structure shows cooking and thermal performance better than the commercially available solar cooker, while on the other hand it also suggests promising solution towards reducing the health problems due to indoor air pollution.

Structural details

Developed low cost solar cooker (LSC): The body of the cooker has been fabricated through cardboard boxes that have sufficient load bearing capacity (about 20 kg) and mechanical strength. The insulation is of thermocole and the metal tray that has been used is prepared through empty oilcans. Two cardboard boxes of dimensions 54.6 cm × 52 cm × 24 cm and 42 cm × 39.3 cm × 10.2 cm were taken. The smaller box has been placed inside the bigger one and complete space between them is filled with insulation. The edges have been sealed with cardboard and binder. The metal tray that acts as absorber surface has been painted with dull matt paint. The glaze has been fabricated through two 3 mm thick transparent polymeric sheets with 1.3 cm air in between with a special frame around it to allow expansion. No screwing has been done in it. This polymeric glaze is three times lighter and has transmissivity 10% higher than the glass glaze. It is not as fragile as glass, and has good weathering resistance and UV stability along with good mechanical strength. The dimensions of the glaze are 42 cm. x 39 cm. A lightweight polymeric mirror on wooden frame is used as reflector for the solar cooker. The dimensions of the mirror are 45 cm × 45 cm. Both, the area of the absorber plate and the aperture area of the cooker is 0.16 sq. m. A view of the structure of the LSC has been shown in the Fig. 1.

Commercial hotbox solar cooker (CSC): The commercial solar cooker that has been used for initial theoretical and experimental studies is a fibre reinforced polymer body hotbox solar cooker. It consists of outer case of fibre and inside it is a blackened metal tray of trapezoidal shape. The bottom of the tray has dimensions 40 cm × 40 cm. The upper dimensions of the 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. There is glass wool insulation between the outer fibre casing and the metal tray. The thickness of the insulation at the bottom is 5 cm and at the sides is 3 cm. The solar cooker consists of a glass glaze and a glass mirror. The glass glaze is made up of two glass sheets 4 mm thick with 1.5 cm of air in between. The dimensions of the glaze are 50 cm × 50 cm. It is placed horizontally over the absorber tray. The dimensions of the glass mirror that acts as the reflector are 46 cm × 46 cm. The area of the absorber plate is 0.16 sq. m and the aperture area of the cooker is 0.21sq. m (Fig.2).

On-field studies

Thermal performance: For studying the thermal performance of the cookers experimentally, instead of the laboratory testing, field testing has been adopted, which is more reliable and informative. The cookers were placed in Sun and observations have been taken for various days throughout the year. During the experiment, the cookers were loaded with water in four containers. The diameter of a container is 16.5 cm and each was filled with 500 ml of water during the experiment. The temperature profiles of the base plate and the water loaded in the containers have been recorded through the K-type thermocouples and CIE 305 digital temperature indicator. The ambient temperatures have also been noted down. Though the observations have been taken for various days over a long period, here some of the representative observations are presented. The temperature profiles for the base plate and water corresponding to the LSC and the CSC have been shown in Fig. 3 and 4.

Cooking performance: The cooking performance of the cooker has been observed on various days for boiling and baking applications. Boiling of rice, pulses, potatoes, beans etc. has been successfully tried along with some local food recipes that require boiling/baking. The cooking results for the LSC for boiling of rice, potatoes, beans, roasting of peanuts and semolina and baking of cake and a local food recipe (bati) have been shown in Table 1.

Figures of merit

For the evaluation of the thermal performance of the solar cookers and to compare and quantify the performance of the different solar cookers, test procedures have been described by the Bureau of Indian Standards (Mullick *et al.*, 1987; BIS, 1992) which have been further revised (Mullick, 2002). The first test is a stagnation test without load and through it the first figure of merit (F_1) is obtained. 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 (F_2) is obtained. The first figure of merit (F_1) for thermal performance of the 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 (F_2) 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 the water in the containers, τ_m is the measured time for the sensible heating of water between the two known temperatures T_{w1} and T_{w2} of water, T_a is the average ambient temperature over the time period τ_m and H is the average insolation over the horizontal surface for the time period τ_m.

As per the BIS standards for the efficient working of the cooker, the value of the first figure of merit F_1 should be equal to or greater than 0.12. The minimum required value of F_2 should be 0.4 for cookers loaded with all the four pots. The standard load of water for the full load test has been specified as 8 kg of water equally distributed in the pots per square metre aperture area. The water to be loaded in the pots should be at the ambient temperature and the values of T_{w1} and T_{w2} have been fixed at 60°C and 90°C respectively. The figures of merit for the CSC and the LSC are found to be 0.115, 0.43 and 0.122, 0.55 respectively.

Fig. 3. Temperature profiles for the LSC & CSC with standard time when the cookers are loaded with 2 litres of water & are without reflector (Apr.).

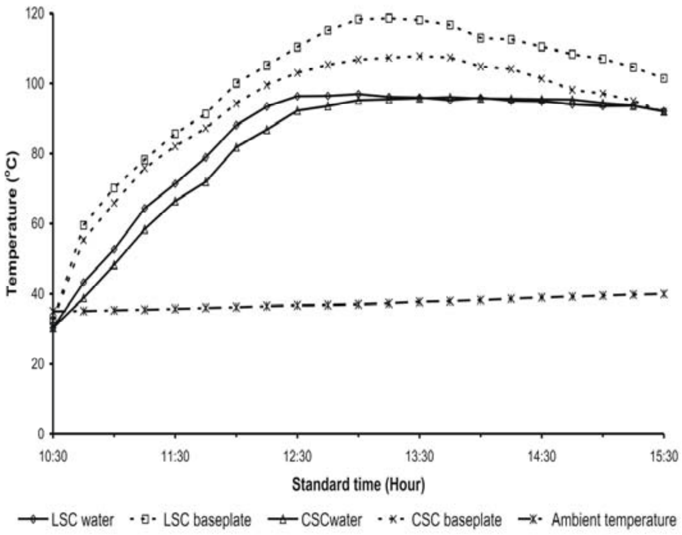
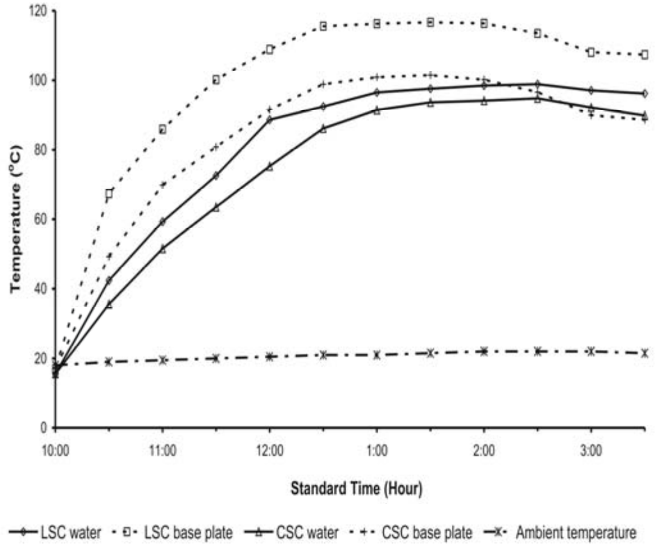


Fig. 4. Temperature profiles for the LSC & CSC with standard time when the cookers are loaded with 2 litres of water & are with reflector (Jan.).



Payback periods

For the calculation of the payback periods the following relation has been used (Nahar, 2001).

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

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

It has been assumed that the solar cookers can be used for the cooking of two meals for four persons for about 300 days in a year at places like Jaipur, and therefore can save around 1080 MJ of energy per annum. The energy savings and the 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 LSC is Rs. 900/- and the cost of the CSC is Rs. 1760. The results for the energy savings and the payback periods have been shown in the Table 2.

Table 1. Cooking tests for the LSC.

Month	Loading Time	Food	Cooking method	Cooking time
February	10:00 a.m.	0.5 kg potatoes + 0.3 kg water (container 1), 0.5 kg kidney beans + 0.4 kg water (container 2)	Boiling	3 hr
March	10:30 a.m.	0.8 kg rice + 1.2 kg. water	Boiling	1 hr 45 min.
May	10:00 a.m.	0.7 kg lentil +1.4 kg. water	Boiling	1hr 45 min.
May	10:30 a.m.	0.8 kg cake	Baking	1 hr 50 min.
June	11:00 a.m.	1.8 kg wheat flour balls (bati)	Baking	2 hr 15 min.
September	10:00 a.m.	1 kg peanuts	Roasting	1hr 45 min.
September	12:30 p.m.	1.8 kg semolina	Roasting	1hr 45 min.

Results and discussion

When the cookers are fully loaded with 2 litres of water in four containers each, the temperature profiles of the water and base plate for the LSC and CSC without reflector have been shown in the Fig. 3. As the observations are for 25th April (a summer day), the ambient temperatures are quite high around 40°C and therefore the temperatures for the base plate and water are high for both the LSC and the CSC. The base plate temperatures for the LSC are higher than the CSC, the maximum difference is seen around noon (118.7°C for the LSC & 107.4°C for the CSC) and the water temperature for the LSC reaches 80°C around 15 min. earlier than the CSC. Here it should be mentioned that the maximum stagnation temperature achieved by the LSC in summers is around 146°C without reflector. Fig. 4 presents the temperature profiles for the water and base plate of the LSC and the CSC each loaded with 2 litres of water in four containers with reflector on 30th Jan. From the figure it can be seen that the base plate temperatures of the LSC remain 10-15°C higher and the water temperatures are 5-10°C higher than the corresponding values of the CSC. The water temperature reaches around 80°C in less than 2 h for the LSC whereas the CSC takes additional half an hour to reach this temperature. This shows that the cooking would be slightly faster in the LSC as compared to the CSC. These results are for a winter day (30th Jan.) and hence the cooker would be useful even in winter months.

The experimental observations related to the temperature profiles indicate that the cooker (LSC) can be easily used for the cooking of the soft food material even without reflector in summer months as within one and a half hour the water temperature is above 80°C. During the winter days the cooker takes around two hours in attaining the temperatures above 80°C with reflector and therefore use of reflector is essential for cooking of two meals in winter days.

The cooking performance of the cooker shows that it is ideal for boiling, roasting and baking purposes (Table 1). 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. Soft food materials such as rice and pulses can be easily cooked within two hours in the cooker.

Besides, being better in performance, in cost LSC is lower by a factor of 1.9 as compared to CSC and as shown in Table 2 has lower payback periods. Table 2 clearly shows that the payback period for the LSC with

Table 2. Energy savings & payback periods for the CSC & the LSC.

Fuel	Calorific value	Efficiency (%)	Cost (Rs.)	Energy savings (Rs.)	Payback period CSC (year)	Payback period LSC (year)
Firewood	19.711 MJkg^{-1}	17.3	2.50 kg^{-1}	791.79	2.87	1.33
Charcoal	29.015 MJkg^{-1}	28.0	8.00 kg^{-1}	1063.49	2.03	0.97
Kerosene	38.192 MJL^{-1}	50.0	11.00 L^{-1}	622.12	3.87	1.75
LPG	45.561 MJkg^{-1}	60.0	25.00 kg^{-1}	987.69	2.21	1.05
Electricity	3.6 MJkWh^{-1}	25.0	4.00 kWh^{-1}	4800	0.40	0.20

respect to LPG, which is commonly used fuel, is around one year. Though payback periods for electricity (heater) are very low, but it is not commonly used cooking fuel. 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. The cooker (LSC) though light weight is quite durable and is in use for more than five years. The payback periods are less than 2 years for the LSC and therefore this system is economically viable.

Conclusion

The use of solar cookers offer a promising solution towards the problems related to the health, economy, environment and energy crises to a considerable extent. Therefore, more efforts should be made in the direction of their popularisation and in creating mass awareness for utilisation of solar energy for cooking purposes. The design of the developed cooker LSC is simple and convenient to be made by users and local labourers, which can help in popularising the solar cookers. The thermal performance studies of the LSC and the CSC show that LSC performs better than the CSC. The figures of merit are higher for the LSC. The cost of the LSC is about half the cost of the CSC and therefore the payback periods are less. LSC has other advantages also such as it is light weight and easily portable.

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