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Development and Testing of a Solar Cooker with Thermal Energy Storage System

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Abstract – *Cooking is the major necessity for people all over the world. It accounts for a major share of energy consumption in developing countries. Therefore there is a critical need for the development of alternative and affordable methods of cooking. Solar cooking is a novel and eco friendly method of harnessing sun's energy. There are many types of solar cookers like solar panel cookers, solar parabolic cookers and solar box cookers which are expensive. Solar cookers can be of a great use in saving fuel and enabling in eco friendly cooking of food. In this work a solar cooker with thermal storage system using phase change material is developed. The size of the cooker is designed by calculating the energy required to cook food for 2-4 persons. Paraffin is chosen as phase change material to store the energy, which will be utilized in the absence of sunlight. A solar cooker with phase change material will be compared with another solar cooker of similar dimensions. The cooker is tested as per the standard procedure to estimate the figures of merit which was estimated to be 0.3102 for the cooker with thermal storage and 0.2946 for a cooker without thermal storage. The payback of the cooker was 7.87 years reducing a carbon foot print of 80.541 kg* CO_2*/year.*

Keywords – carbon footprint, economics, figures of merit, phase change material, solar cooker.

1. INTRODUCTION

Solar energy as it is widely recognized as abundantly available yet intermittence, unpredictability and meteorological dependence are the limiting factors that retard its usage extensively. With its availability in the range of 5-7 kWh/m^2 and 275 days of availability, low cost cooking options and environmentally benign techniques like solar cookers has a good potential in a tropical country like India and has a big market potential [1], [2]. The reliability of solar energy can be increased by storing its portion of the energy during excess availability and using the stored energy as and when it is needed. The mismatches in the demand and supply of thermal energy can be mitigated by incorporating a suitable storage medium in a device like a solar cooker. As solar radiation cannot be stored as such but it can be realized by suitable energy conversion method through thermal, electrical, mechanical and chemical methods. Phase change materials (PCM) in solar cookers uses the latent heat to change their state from solid to liquid and in that process stores the heat upon solidification the heat is released which can prolong the cooking period during intermittent availability of solar energy. Various designs of solar cooker with both sensible and latent heat storage materials were reviewed rectangular and cylindrical containers were used as heat storage devices in solar cookers and a wide range of organic phase change materials were used [3]. The ideal phase change material must possess certain desirable characteristics like high sensitive heat capacity and heat of fusion, stable composition, high density and heat conductivity, chemically inert, non toxic, non inflammable, inexpensive. Of the many options of PCM available, the ones that has a latent heat of fusion in the range of 0-150^{o}C is very apt for solar energy applications. Some examples that falls in this category are salt hydrates, paraffin waxes, fatty acids, *etc.* [4]. Of the many variants of the solar cookers, the box type solar cooker is the one that had undergone many characteristic modifications due to its simplicity and straightforwardness in its design [5]. The box type solar cooker is a stationary device that does not require any tracking and can be fabricated with simple materials available.

2. AN ALTERNATIVE OF A SOLAR COOKER

A solar box type cooker is basically an insulated box with a transparent glass cover. The box has a cavity which has blackened sides and can hold the cooking vessels. Some of these box type cookers have booster mirrors to enhance the sunlight falling on the horizontal glass surface [6],[7]. Selection of readily available materials for fabricating the cooker reduces the manufacturing cost of the same and makes it easily available for common man at affordable price. Hence, circular type solar cookers are developed which can be easily fabricated with the materials available in the market.

2.1 Estimation of Area of the Collector and Estimation of Thermal Losses in the Cooker

Table 1 shows the specifications with reference to cooking rice for 2 people in general for a family. It is assumed that the rice required is 200 grams and the density of the rice is assumed to be 812 kg/m^3, furthermore the water required for the cooking is 2 times than that of the volume of rice. About 10% of the water is lost in evaporation during the cooking process.

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Table 1. Specification with reference to pre and post cooking of rice.

Pre cooking	Number of people	2
	Rice required	200 gm
	Volume of Rice	$2.46 \times 10^{-4} m^3$
	Volume of Water	$4.926 \times 10^{-4} m^3$
	Volume of food to be cooked (Rice + Water)	$7.386 \times 10^{-4} m^3$
	Mass of water required	0.4911 kg
	Total mass of food to be cooked	0.691 kg
Post cooking	Mass of water lost	0.04911 kg
	Mass of cooked food	0.642 kg

Table 2. Energy requirements for cooking.

Thermal energy required to cook the rice	321.36 kJ
Power required for cooking	35.706 W
Cooking time	150 min
Losses	73.96 W
Total power required	100.706 W
Aperture area of the cooker	$0.359 m^2$
Diameter of the cooker	0.33 m

Table 2 shows the thermal energy requirements for cooking food (rice and water). The thermal energy required is the sum of the sensible and latent heat part. The losses are the sum of the top and side losses along with the losses from the vessel based on standard assumptions like 7% of the incoming solar radiation on the cooker glass surface top and side losses for a glass wool (k = 0.034 W/m-K) insulated cooker.

2.2 Material Selection for the Fabrication of Solar Cooker

Outer casing (GI sheet and wood): Outer casing is necessary so that the box will retain a given shape and form, and remain durable over time. Outer casing materials include cardboard, wood, plywood, metal, cement, bricks, fiberglass, woven reeds, plastic, clay, rammed earth or other material. As it holds the components of the cooker it should have good structural strength [8]. Many materials that perform well structurally are too dense to be good insulators. To provide both structural integrity and good insulation qualities, it is usually necessary to use separate structural and insulating materials. Hence a galvanized sheet of sufficient thickness is used for covering the body of the cooker which weighs less and easy to work.

2. Inner Cooker Box (Aluminium Trays)

Aluminium is remarkable for its low density and for its ability to resist corrosion due to the phenomenon of passivation. Because of its high thermal conductivity (237 W/m-K) *i.e.*, 59% of the conductivity of copper, both thermal and electrical, while having only 30% of copper's density, it finds its use in solar cooking and heat transfer. Aluminum trays are the major components that support cooking vessels since it absorbs the useful energy from sun to be able to succeed cooking process. Three aluminum trays of diameter 680 mm were used out of which two trays were used for cooker with thermal storage system and one for cooker without thermal storage system. As the trays are single components, radiation and convective heat losses through gaps are nullified. Leakage, which is a main problem while using liquid PCM has been overcome by using trays.

2.4 Cooker Insulation (Glass wool)

Glass wool is a thermal insulation that consists of intertwined and flexible glass fibers, which causes it to "package" air, resulting in a low density that can be varied through compression and binder content. Insulation is one of most crucial key points for a box type solar cooker to be able to provide an efficient cooking. All materials with low thermal conductivity may be used as an insulation material in solar cookers. However, the main purpose for material selection should be minimizing heat loss from the solar cooker to the environment with minimal cost. In order for the box to reach interior temperatures high enough for cooking, the sides and bottom of the box must have good insulation. For the solar cooker, it is important that the insulating material surround the interior cooking cavity of the solar box on all the sides except the top side. Lower the heat losses, higher will be the cooking temperatures.

2.5 Glazing Surface (Clear Window Glass)

Glazing material covers the absorber plate and allows sunlight to reach the absorber plate while preventing wind and cold from reaching the plate surface that will cause loss of heat. The glazing traps the solar energy and increases the cooking efficiency. Glass is a good glazing material for solar cookers The ideal glazing material for solar cookers must have good transmittance, longer life, good impact resistance, light weight, opaque to long wave radiation and easily affordable tempered glass can be used for this purpose, since it is more durable and heat resistant and will not break off easily. Tempered glass- though, is more expensive than regular window plane glass. So plane window glass is being used for this purpose.

2.6 Paraffin Wax

Paraffin qualifies as heat of fusion storage materials due to their availability in a large temperature ranges. Due to cost consideration, however, only technical grade paraffins may be used as PCMs in latent heat storage systems. Paraffin is safe, reliable, predictable, less expensive and non-corrosive. They are chemically inert and stable below 500°C, show little volume changes on melting and have low vapor pressure in the melt form. For these properties of the paraffin, system using paraffin usually have very long freeze–melt cycle. Apart from some several favorable characteristic of paraffin, such as congruent melting and good nucleating properties, they show some undesirable properties such as low thermal conductivity, non compatible with the plastic container and moderately flammable. Since the availability of solar energy is intermittent, it must be ensured during off peak hours by some means of storage in a device like solar cookers. Latent heat storage (LHS) is based on the heat absorption or release when a storage material undergoes a phase change from solid to liquid or liquid to gas or vice versa. A total quantity of 2.9 kg of paraffin wax (latent heat of 210 kJ/kg), is used as a thermal storage medium in the proposed solar cooker for storing 50 W of heat which is equivalent to that of what is lost through the top surface of the cooker. The dimensions of the cooker are fixed based on the availability of commonly used materials with a requirement to hold two medium sized vessels inside.

Table 3. Specifications and standards of the materials.

Material	Specifications	Standard
Aluminium	inner diameter = 680 mm outer diameter = 780 mm height = 98 mm	IS 1660
Glass wool	NA	NA
Clear window glass	diameter = 780 mm thickness = 4 mm	NA
Paraffin wax	2.9 kgs-	IS 4654
Galvanized iron sheet	sheet thickness = 0.2 mm	IS277

Fig. 1. Cooker with PCM storage with top and bottom trays.

The details and standards of the materials that are used for the fabrication of the cooker is shown in Table 3 above. The materials chosen are of Indian standards.

The above Figure 1 shows the sectional view of the double circular tray solar cooker with phase change material between the trays. Space between the two trays has to be filled with paraffin wax granules with fin arrangement so that heat transfers from top absorber plate to bottom wax surface uniformly. Paraffin wax being a solid has different temperature regions throughout its mass. A numerical analysis based on the Stefan's problem is done which is useful to determine the temperature distribution of a homogeneous medium like paraffin wax undergoing phase change using the finite element method, through the software COMSOL Multiphysics. The behaviour of melting front could thus be understood. In this way heat transfer by conduction and phase change are considered to be present in the proposed solar cooker. The PCM medium is semi-infinite, initially solid at its melting temperature Tm, and at t = 0, the wall temperature is raised to Tw ≥ Tm, prompting the PCM to start melting in a linear fashion starting at x = 0 from pure conduction in the liquid phase. An initial height of 10 mm between the two trays are fixed for this study.

Figures 2, 3 and 4 shows the temperature distribution in the paraffin wax contained in the 10 mm space between the trays. The wall temperature is set at 75°C which is much higher than the melting point of the phase change material. The phase change material is expected to melt in a linear fashion. As seen from Figure 2 the paraffin wax medium starts melting when the heated wall temperature was sufficiently higher than the melting point of paraffin at 50 to 55°C, from Figures 3 and 4, the melting front reaches midway at 5 mm to represent the liquid phase at 585 seconds and further penetrates the solid phase at 1800 seconds. From the above study, it was concluded that the space between the trays to be adjusted to about 5 mm to facilitate the complete change of phase of the paraffin wax in the latent heat storage process. The mushy region where the phase change material melts over a temperature range is observed in Figure 2 and later moves down at increasing time steps at 585 and 1800 seconds.

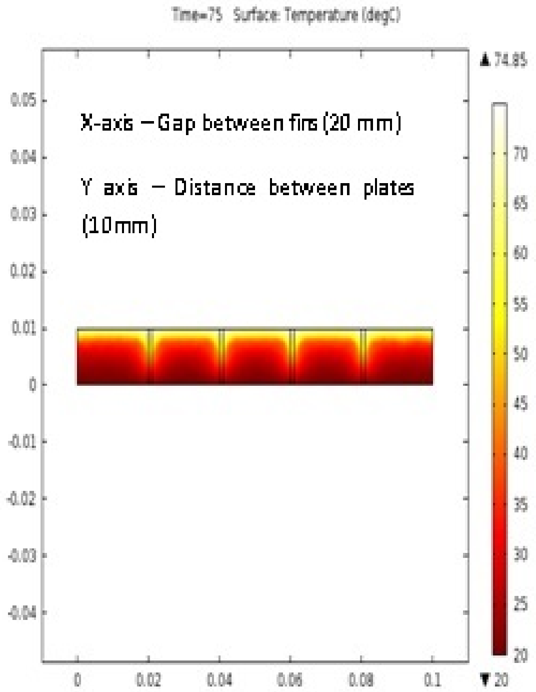

Fig. 2. Temperature distribution at 75 seconds.

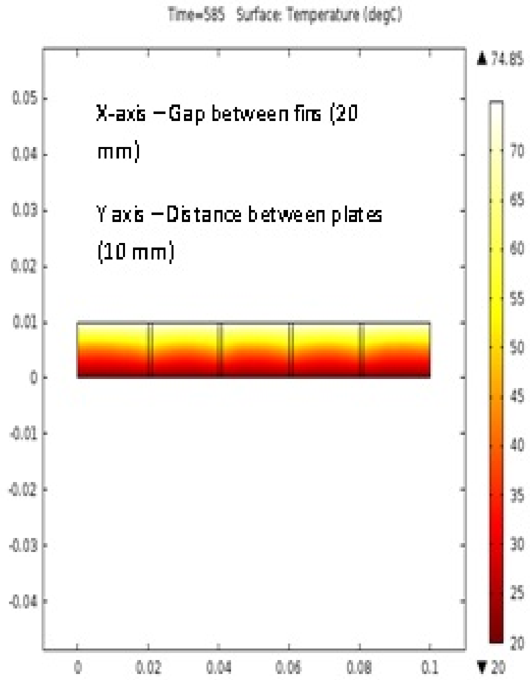

Fig. 3. Temperature distribution at 585 seconds.

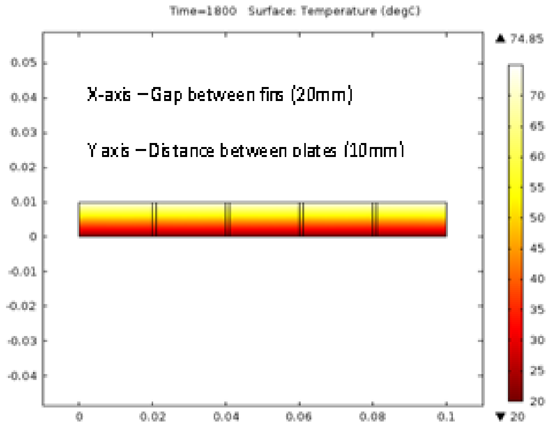

Fig. 4. Temperature distribution at 1800 seconds.

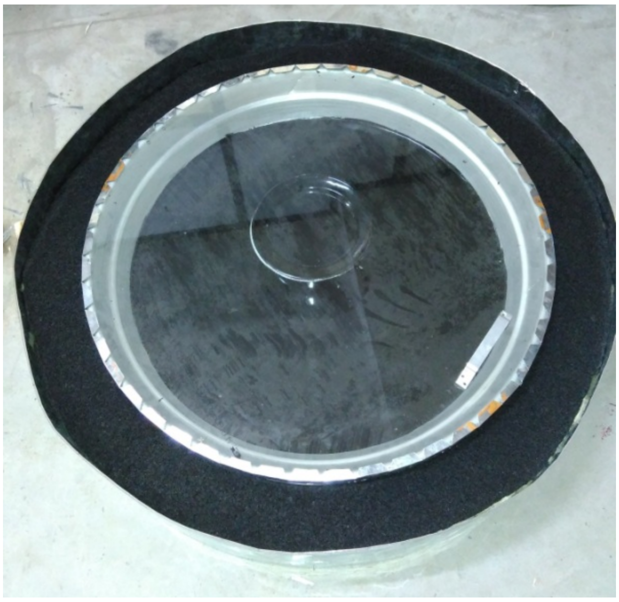

Fig. 5. Solar cooker with phase change storage system.

The above Figure 5 shows the complete assembly of the cooker with a storage medium. The internal surface of the cooker is painted black to ensure maximum absorptivity of solar energy. The advantage of this cooker lies in the fact that it could be fabricated with commonly available materials in the market as indicated in Table 3. An identical cooker without the paraffin wax based thermal storage is fabricated for comparison.

3. TESTING OF THE SOLAR COOKERS

A procedure for testing the solar cookers was developed based on IS 13429-3. Based on the standards the tests that were performed on the cookers are:

i. The stagnation temperature test (the stagnation temperature test was conducted for the evaluation of first figure of merit F1).
ii. Thermal load test, heat up condition test (the thermal load test was conducted to determine the second figure of merit and it was evaluated under full-load condition.

3.1. First Figure of Merit (F_1)

The first figure of merit (F_1) is defined as the ratio of optical efficiency, (η_0), and the overall heat loss coefficient, (U_L). A quasi-steady state (stagnation test condition) is achieved when the stagnation temperature is attained. High optical efficiency and low heat loss are desirable for efficient cooker performance. Thus the ratio ($\frac{\eta_0}{U_L}$) which is a unique cooker parameter can serve as a performance criterion. Higher values of F_1 would indicate better cooker performance:

$$F_1 = \frac{T_p - T_a}{H_s} \qquad (1)$$

Where F_1 is first figure of merit (Km^2w^{-1}), $\eta_0$is optical efficiency (%), U_L is overall heat loss factor ($WK^{-1}\,m^{-2}$), T_P is absorber plate temperature (°C), T_a is ambient temperature (°C), and H_s is insolation on a horizontal surface (Wm^{-2}).

3.2. Second Figure of Merit (F_2)

The second figure of merit, of box type solar cooker is evaluated under full-load condition as:

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

Where:

T_p = temperature of the absorber plate (stagnation) in ^oC
T_a = ambient air temperature in ^oC
H_s = insolation on a horizontal surface (taken at time of stagnation) in Wm^{-2}
M = mass of water in kg
C = heat capacity of water in J/kg°C
A = aperture area in m2
t = time in minutes
Tw1 = water temperature at state 1 (initial) in °C
Tw2 = water temperature at state 2 (final) in °C

The results of this research work will be discussed under the following:

i. Stagnation temperature test of solar cooker for first figure of merit ($F1$);
ii. Water heat up test of solar cooker for second figure of merit ($F2$).

The thermal evaluation experiment to determine the stagnation temperature of the box-type solar cooker was carried out on 20th April 2015. The stagnation temperature test that is, no load test was started at 11.00 am local time till the maximum plate temperature (120^{o}C), which occurred at 14:00 pm, was achieved. The following measurements were taken: solar radiation, ambient air temperature, and base plate temperatures at a regular interval. This test was performed in order to determine the first figure of merit of the cooker and compare it with the standard. The solar radiation was measured using a Pyranometer (LP 02 – Hukseflux make).

Without thermal storage (F_1):

T_a = 38^{o}C, T_p = 120 ^{o}C, H_s = 852.77 W/m^2.

With thermal storage (F_1):

T_a = 38^{o}C, T_p = 120 ^{o}C, H_s = 852.77 W/m^2.

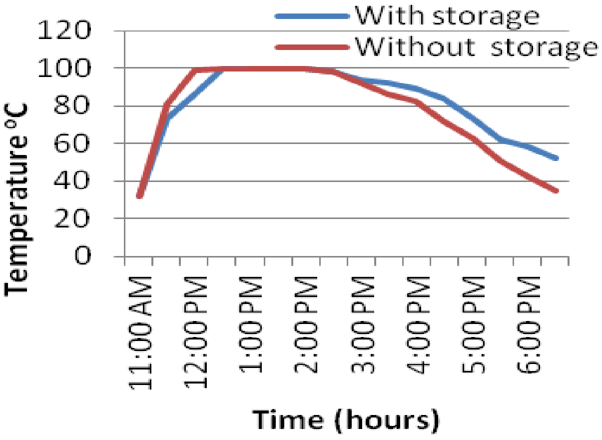

Fig. 6. Experimental values of water temperature at 30 min time interval for with and without thermal storage system, respectively.

Equation 1 was used to compute F_1. However, the obtained value of F_1 is (0.1009 Km^2w^{-1}) is same for both cookers as the maximum temperatures reached are same and at same solar insolation. The allowed standard F_1 test states that if the value of F_1 is greater than 0.12, the cooker is marked as A-Grade and if F_1 is less than 0.12 the cooker is marked as a B-Grade solar cooker [6]. The constructed cookers are to be marked as B-Grade solar cookers. The low value of first figure of merit may be an indication that there were higher convection and radiation losses from the side walls made glass wool and maybe the side insulator is not thick enough.

Water heat up test experiment of the solar cooker was conducted in order to determine the second figure of merit (F_2). The test was carried out on 22nd of April 2015. For the full load test water temperatures for T_{w1} = 65^{o}C and T_{w2} = 95^{o}C were chosen. The following values were recorded at a regular interval during the experiment: ambient temperature, water temperature, insolation, wind speed, and time for the water temperature to increase from T_{w1} to T_{w2} as shown in

Tables 3. For the computation of F_2 the following values are obtained from Table 3.

3.3. Calculated Values of the Figures of Merit for both Cookers

The measurement of ambient temperature, water temperature, plate temperature for both cases and the global solar radiation were used to calculate the first and second figures of merit as shown below:

Without thermal storage system

F_1 = 0.1009 Km^2w^{-1} (computed)
M = 0.7 kg
c = 4186 J/kg°C
$t_2 - t_1$ = 1980 sec
A = 1.036 m^2
T_{w1} = 65°C
T_{w2} = 95°C
H = 852.77 W/m^2
T_{ave} = 33.2 °C
F_2 = 0.1157

With thermal storage system

F_1 = 0.1009 Km^2w^{-1} (computed)
M = 0.7 kg
c = 4186 J/kg°C
$t_2 - t_1$ = 3300 sec
A = 1.036 m^2
T_{w1} = 65°C
T_{w2} = 95°C
H = 852.77 W/m^2
T_{ave} = 33.2°C
F_2 = 0.0693

Using Equation 2 second figure of merit was computed to be 0.1157 and 0.0693, respectively for cooker without and with thermal storage which is less than recommended standard value of greater than 0.40 [6]. The F_2 of cooker without PCM show higher value of second figure of merit showing gradual temperature changes. The possible reason behind this is due to the heat from the solar radiation is utilized for cooking and simultaneous storage in the heat storage medium. It is observed from Figure 6 that the cooker with heat storage has the ability to sustain higher temperatures than the one without heat storage as high as 17°C towards the end of the day at 6:30 pm. This indicates that the food can be kept warm even during the lean sunshine hours.

3.4. Economics of the Solar Cooker

Table 4 indicates the cost break up of various components that make up the solar cooker with thermal storage, in the case of the cooker without the thermal storage only the cost of the insulation is negated. The total cost of the cooker us around US$ 52.5 inclusive of the labor cost. If a 20 % margin is considered for the selling price the cost of the cooker is around US$ 70.9 which is competitive to any such available model in the market.

Payback and carbon footprints avoided

Payback period is the period of time required to recoup the funds expended in an investment [9].

$$Payback\ period = \frac{Cost\ of\ solar\ cooker}{Cost\ of\ Energy\ saved\ per\ year\ by\ LPG} \tag{3}$$

The payback period has to be calculated based on the replacement of a known technology that is used for cooking the food for a small family in a conventional way. When the total availability of energy from a single cylinder is 612.360 MJ/cylinder (considering the calorific value of the cylinder to be 12.6 kWh/kg which has a mass of 13.5 kg of gas). If 60 % of the cylinder's energy is used for burning then 367.416 MJ/cylinder is the final available energy from the cylinder. If cooking for 2 people, 2 meals a day, 40% by the cooker and 900 kJ for cooking as per the standard estimates indicates about 1440 kJ/day. There will be a saving of roughly 2 cylinders per year if 255 days are required by the solar cooker to produce energy equivalent to that of a cylinder. If a single cylinder would cost US$ 9 (without subsidies) [9]. The payback period for the cooker based on (3) indicates that the money on investment towards a cooker is retrievable in 7.8 years.

Based on GHG protocol the liquefied petroleum gas (LPG) has an emission potential of 2.983 kg CO_2 per kilogram [10]. If 2 cylinders are saved and considering the weight of the gas in the cylinder as 13.5 kg the emissions avoided would be 80.541 kg/year.

Table 4. Cost report for cooker with thermal storage system.

S. No.	Component	Quantity	Cost (US$)
1	Aluminium tray	2	21.4
2	Glass	1	9.2
3	Paraffin wax	3 kg	5.4
4	Glasswool	4 kg	3.8
5	Cooking vessel with lid	1	1.9
6	Sheet metal(GI)	2 kg	3.8
7	Aluminium handle	1	0.3
8	Hinge	1	0.2
9	Black paint	1	0.4
		Total	46.4

4. CONCLUSIONS

Solar cooker with phase change materials as thermal energy storage medium is a good alternative to the conventional cooking methods and also with the solar cookers that does not store thermal energy. The cooker was designed as per cooking requirements of a small family and fabricated with materials that are commonly available in the market. Two cookers similar in dimensions are fabricated, one with thermal storage system. The gap between the trays which houses paraffin wax as the storage medium is optimized based on Stefan’s model with suitable boundary conditions using COMSOL software. The cookers are tested for the figures of merit as per the testing standards which showed that the cooker without thermal storage medium had a higher second figure of merit value when compared to the one with storage medium. However the solar cooker with thermal storage medium was able to retain temperatures as high as 17°C than the cooker without storage medium at 6:30 pm. The cooker was priced nominally at US$ 70.9 and it yielded a payback of 7.8 years. The carbon dioxide emissions avoided are 80.541 kg per year.

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