Performance evaluation of solar box cooker assisted with latent heat energy storage system for cooking application

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Abstract. Solar cooking is one of the most promising techniques to meet the cooking needs in remote areas where electricity and fuel supplies are meager. Solar box cooker is an efficient device used in solar cooking as it is simple to fabricate, easy to operate and hazard-free**.** In this context, the performance evaluation of a solar box cooker with varied number of reflectors has been undertaken. It was found that the time consumed for cooking in a box type solar cooker with four reflectors is lesser compared to that of a single reflector and its overall utilization efficiency increases with increase in the cooking mass. Further, a latent heat energy storage system was designed and fabricated to cook the food at off-peak hours of solar radiation. This latent heat energy storage system was combined with the solar box cooker. Oxalic acid dihydrate was used as the phase change material due to its high specific enthalpy and its melting point lying close to the cooking temperature. It was found that the solar box cooker with phase change material could be effectively utilized to cook food during off-peak hours of solar radiation.

1.   Introduction

Major energy needs of domestic consumers include cooking, heating and lighting. Of this, cooking predominantly account for 36% of India's primary energy demand; hence it is necessary to meet this particular demand by using clean and efficient fuel like Liquefied petroleum gas (LPG) for cooking applications. In India, even today about 90% of rural people do not have access to modern cooking fuels and it drops to 33% in urban areas [1].

About 90% of the energy consumed by low-income people is used to satisfy their cooking demands. Hence, the need of the hour is to find out a cheap energy source which is locally available and ensure its availability to meet the energy demands of the poor and needy. As of now, biomass cook stoves and solar cookers are the best available alternatives because both biomass and solar energy are locally available renewable fuels. Among the two, solar energy is preferred as most parts of India is blessed with more than 275 sunny days with a mean daily solar radiation ranging from 5–7 kWh/m^2 [2]. According to estimates released on March 25, 2012, globally 4.3 million deaths were attributed to household air pollution (HAP), almost all in low and middle income (LMI) countries [3]. Hence it is necessary to design an improved solar cooker which can satisfy these demands either totally or partly. Though different type solar cookers are available, the solar box cooker (henceforth SBC) is easy to operate, simple and hazard-free [4]. But its slower cooking rate, lower absorber plate temperature and its inability to cook food during cloudy hours have resulted in lower adaptation. Moreover, it cannot be used in many cooking processes that involve deep frying. In spite of all these disadvantages, about 1,00,000 SBC's were disseminated in India with the help of government promotion by providing 50% subsidy [5]. Many researchers continue to toil hard to

overcome the shortcomings of SBC's. The solar irradiation reaching the cooker was enhanced by using booster mirrors and it was found to be more efficient than box cookers without booster mirrors [6-7]. The primary benefit of using SBC's with booster mirrors is that it has the capacity to cook two meals per day. In addition to that, it also keeps the foodstuffs warm in the evening [8].

The temperature of the absorber plate must be as high as possible for effective cooking and this available heat energy must be efficiently transferred to the cooking vessel. The temperature of the absorber plate can be increased by using selective coating instead of normal black coating [9] and the heat transferred to the cooking vessel can be enhanced by 7%, by using fins [10]. Moreover, usage of trapezoidal shaped absorber plate helps in capturing the solar irradiation of larger incident angle [11]. Similarly, absorber plate of thickness 0.5 mm to 1 mm can be used to reduce radiative and convective heat losses [12, 13]. It is estimated that only 55% of the utensil heat is utilized to cook the food and the remaining is lost in the form of heat losses. Therefore, the utensils must be properly insulated for efficient transfer of heat [14]. Sometimes, the utensils are also covered with air tight plastic bags instead of normal metallic lids to enhance the heat transferred to it [15]. Further, use of concave lid instead of flat lid in SBC's decreases the cooking time span by about 10-13% [16]. The efficiency of the SBC increases by 5.9% when vessels with central cavity are placed in the SBC using lugs [17, 18]. As far as glazing is concerned, double glazing is found to be more effective than single glazing but, when transparent insulating material (TIM) of thickness 40 mm was introduced between this double glazing; the temperature of absorber plate increased by 40°C thereby making cooking possible even during off-peak hours [19,20]. This is because the convective loss occurring at the glazing is minimized with the introduction of TIM. Hence, the efficiency of the SBC using TIM increased to 30.5% resulting in energy savings of up to 1485 MJ of fuel equivalent per year [21].

Even after following all the above performance enhancement techniques in SBC, it is still not possible to cook food during cloudy days or off-peak hours unless energy storage is available in the SBC. Therefore, a 160 W heater must be incorporated in the SBC to make it operate throughout the year, in Indian weather conditions [22]. However, SBC's are generally used in rural areas where electricity is either not available or highly unreliable. Hence, SBC's must have an energy storage system to make it operate during cloudy days or late evening period. Though both sensible heat energy storage materials and latent heat energy storage materials can be used as energy storage medium latent heat energy storage material is preferred because of its higher energy density. The use of phase Change Material (PCM) which has its melting point around 100°C to 110°C is recommended because cooking takes place in the SBC between 95°C to 97°C [23]. Recently, a comprehensive performance assessment of a solar domestic cooking unit using high melting phase change material temperature (~167 °C) of D-Mannitol PCM was carried out [24-26]. Further, many studies have been carried out by using PCM's like stearic acid, acetamide and acetanilide but none of them have melting point in the range of 100°C to 110°C [27-28]. This range of temperature is suitable for cooking by boiling which is a common need in food preparation by most Indian homes. Hence, in this paper, the performance evaluation of a SBC that uses Oxalic acid dihydrate as PCM, which has a melting point of 103°C, is carried out to study the feasibility of the designed SBC. should be indented by 5 mm.

2. System description

The cooking experiments were conducted with a double glazed (glass covers) SBC whose area is 0.49 X 0.49 m with 0.07 m depth. Fig. 1, shows the photographic view of the SBC with single reflector, multiple reflectors and fabricated PCM storage container with thermocouples. It consists of absorber plate made of aluminium coated with black paint. The experiments were carried out for both types, with and without additional reflectors; which was supported by frame and wooden blogs. A cooking vessel made of stainless steel was used for cooking inside the SBC. It was also painted with dull black paint in order to absorb the incident solar radiation. A PT100 thermocouple with an accuracy of ±0.15°C was used to measure the temperature of the food item kept in the cooking pot. The absorber plate and the upper glass plate temperatures were also measured by using thermocouples. The solar radiation was measured by

using a pyranometer (Hukseflux LPO2) with an accuracy of $< \pm 1\%$; the ambient temperature and wind speed were measured using a weather station (WatchDog 2000). All the sensors were connected to a data acquisition system (Agilent make, Model no. 34970A) and observed values were recorded at regular time intervals during the experimentation. Oxalic acid dihydrate is used as PCM for storage of solar heat by its change of phase during sunshine hours thereby making cooking possible using a SBC, even during late evening hours. The PCM was selected by considering various aspects like phase change temperature, high latent heat and ready availability in the market.
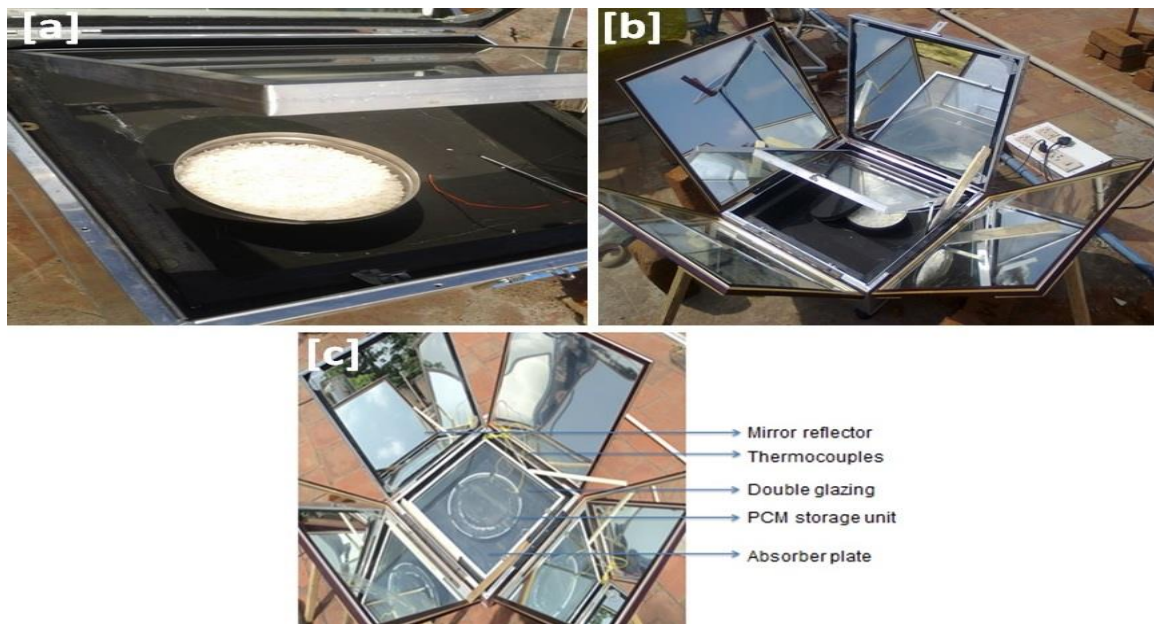

Figure 1. Photographic view of SBC with single reflector /multiple reflectors fabricated with PCM storage container with thermocouples.

The thermo-physical properties of oxalic acid dihydrate PCM are shown in Table 1.

Table 1. Thermo-Physical Properties of Oxalic Acid Dihydrate[a].

Property	Value (Unit)
Density	1.65 (kg/m^3)
Latent heat of fusion	370 kJ/Kg
Phase change temperature	101 ℃
Specific heat capacity	1.62 kJ/Kg ℃

[a] Supplier: Excel Bio-Sciences, Chennai.

The required amount of oxalic acid PCM was evaluated as 2.9 kg by considering the energy requirement to cook half a kg of rice. For effective heat transfer, the energy storage unit must be as close as possible to the utensils. The fabrication of the PCM storage unit consists of two hollow cylinders made from aluminium with a diameter of 25.5 cm and 17.5 cm, placed one inside the other, as shown in Fig. 2. The PCM was heated to its melting point and poured into the outer container in liquid form. The outer surface of the PCM storage unit was painted with dull black paint in order to absorb the maximum solar radiation falling on it. The top cover of the PCM storage unit was also covered with aluminium sheet and was also coated with dull black paint.
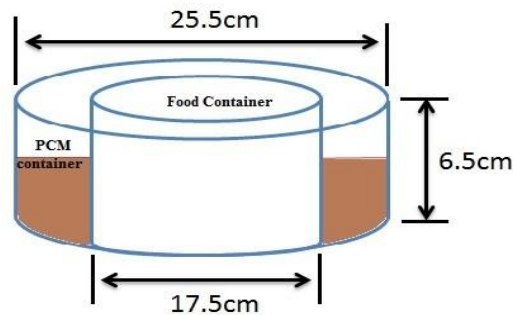

Figure 2. Schematic diagram of PCM storage unit with dimensions.

3.   Experimental procedure

The performance of the SBC was studied in Anna University, Chennai, India. It is located at 13° latitude and 80° longitude. The test was initially conducted with water loaded in the SBC having single reflector and four reflectors. The experimental setup was developed to store the heat energy in the SBC during daytime hours and to utilize the stored energy for late evening time cooking requirements. In order to evaluate the maximum temperature achievable by the SBC, a known quantity of palm oil was loaded in it and tested. The temperature results confirmed the capability of the SBC to melt the selected PCM during daytime hours. The actual cooking trials and the thermal performance of the SBC integrated with energy storage system were conducted. During the experiment, a known quantity of rice kept in the SBC was cooked by using the stored energy in the PCM.

4.   Results and discussion

4.1.   Performance evaluation of the SBC with single and multiple reflectors

Initially, the experiment was carried out for a load of 400g of water in the SBC consisting of a single reflector and the temperature values obtained during the experimentation are shown in Fig. 4. The experiment was repeated in the same way for a higher load of 800g water hold-up in the SBC with four reflectors and the temperature values obtained during the experimentation are given in Fig. 4. Both the experiments were conducted in the afternoon, between 13.25 hrs. and 15.15 hrs. There was only a small ambient temperature variation of 2 ℃ (31 ℃-33 ℃) during entire period of the conducted experiment. During the first half of the experiment, absorber plate temperature (T_p) increased suddenly. Then the variation in temperature was seen at slower rate. The fluctuation in glass cover temperature (T_{gu}) is due to the wind velocity effect. From Fig. 4, it is seen that due to more reflectors in the SBC, water temperature (T_f) was able to reach a higher value than the absorber plate temperature. The solar radiation intensity was highest at the start of the experiments and lowest at the end of the experiments. Fig.3 shows that the mean temperature of water is 77.5 ℃ whereas in Fig. 4 it is 81.6 ℃. The overall utilization efficiency of the SBC was calculated using equation (1) [29].

$$\eta_u = \frac{m_f \; C_f \; \Delta T_f}{I_{av} \; A_c \; \Delta t} \qquad (1)$$

Where η_u is the overall utilization efficiency, m_f is the mass of the fluid , C_f is specific heat capacity of the fluid, I_{av} is average solar radiation, A_c is aperture area , ΔT is temperature difference and Δt is the time taken. The overall utilization efficiency of the SBC with single reflector containing 400g of water was found to be 15.74%, whereas for 800g of water but with four reflectors, it was found to be 25.47%. It is also inferred from Fig. 3 and 4 that the time taken to reach maximum temperature for single reflector SBC is two hours whereas for four reflector SBC it is one and half hours, in spite of increase in load.

From the above results, it was decided to carry out further experiments with the SBC having four reflectors (booster mirrors).
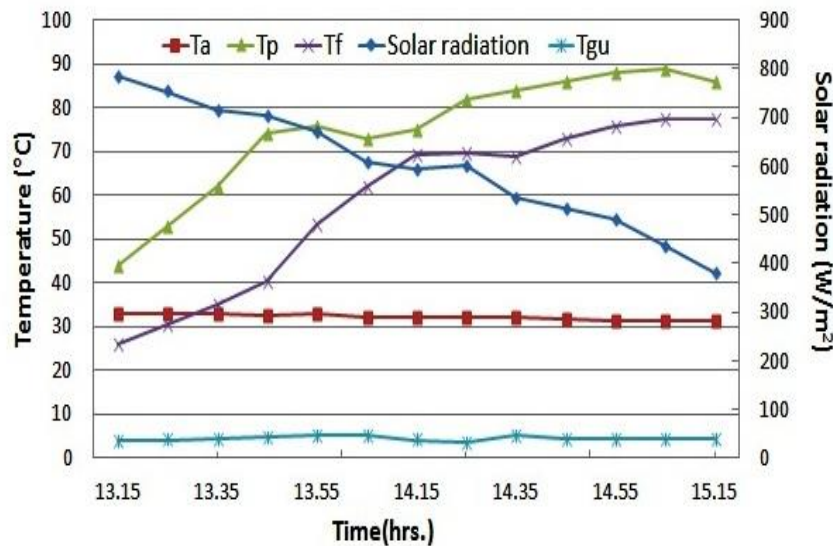

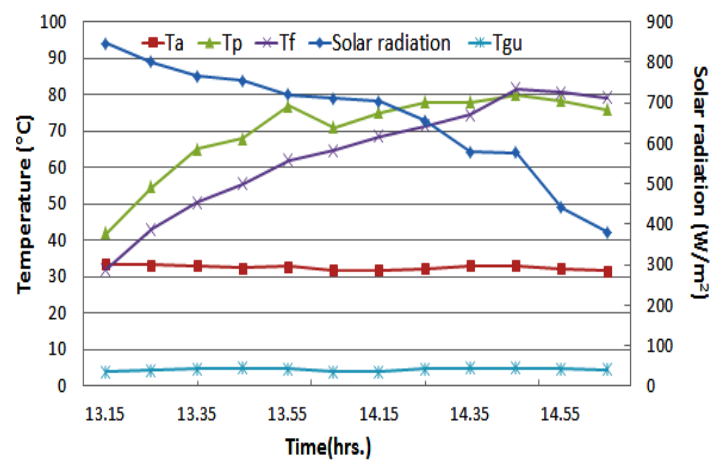**Figure 3.** Various Temperatures during boiling of 400 g of water.

Figure 4. Various Temperatures during boiling of 800 g of water.

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4.2. *Performance testing of loaded sbc with palm oil*

In order to check whether the SBC is capable of heating the PCM beyond its melting point of 103 ℃, tests were carried out by heating 250g of palm oil in the SBC with booster mirrors on four sides. Fig. 5 shows the temperature responses of the cooker with palm oil. The experiments were conducted at 1.00 p.m. and the palm oil attained maximum temperature (T_f) of 136.8 ℃ at 14.45 hrs; thereby ensuring that Oxalic acid dihydrate PCM can be melted using the SBC with four reflectors. Quick decrease in palm oil temperature was observed at the end of the experiment due to less intensity of solar radiation.

4.3. *Performance evaluation of the SBC assisted with PCM storage unit*

Generally, the noon meal is cooked by using the solar radiation available up to 12.00 noon. Hence, the radiation available in the second half of the day was used for charging the PCM. The experiment was started at 12.30 hrs. Without load, i.e. nothing was placed inside the food chambers of the SBC, and temperatures were measured as shown in Fig. 6. An average ambient temperature (T_a) of 32 ℃ and average solar radiation of 717.5 W/m^2 were recorded during experimentation.
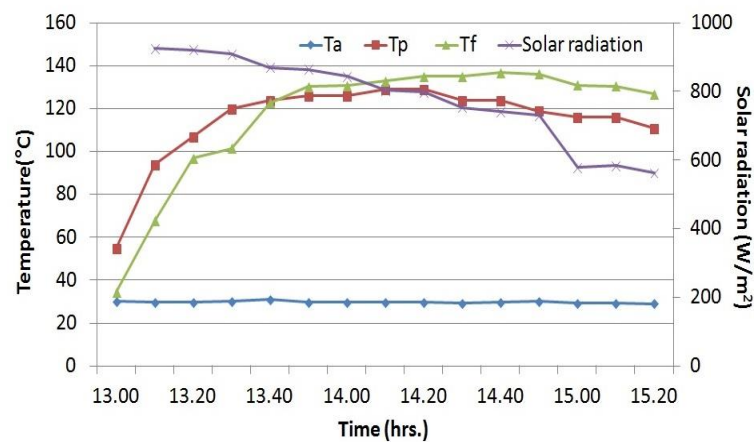

Figure 5. Various Temperatures during boiling of 250g of Palm Oil

The figure shows that the temperature of PCM (T_{pcm}) attained a maximum of 121 ℃, well beyond its melting temperature. It is evident from the figure that during phase change process, the temperature of PCM maintained a constant value of 103 ℃ between the time period of 13.30 hrs. to 14.45 hrs. After charging the PCM up to 16.15 hrs in the evening, the cooker was kept closed to minimize the heat loss. The total energy stored in the PCM at the end of the charging process was calculated as 759.12 kJ at a temperature of 121 ℃ by using equation (2).

Energy stored in the PCM = [(m x c_p x ΔT) $_{solid, PCM}$ + m (ΔH) + (m x c_p x ΔT) $_{liquid,\ PCM}$ (2)

Where ΔH represents the latent heat of fusion. But the cooking process was initiated from 19.00 hrs and the temperature of PCM dropped to a value of 104 ℃ at this time. The energy contained by the PCM at this time was calculated as 720.24 kJ. The difference between these energy quantities are considered as losses in the storage unit and it was 38.88 kJ. The 140g of rice with 360g of water was loaded and cooked in the SBC by using energy stored in the PCM. The amount of energy spent to cook the food item was calculated as 410.63 kJ by using equation (3). Therefore, there was enough energy stored in the PCM to cook the food completely.

Total heat energy required to heat the whole mass to the boiling point = (m x c_p) $_{system}$ x (Water boiling temperature - ambient temperature)   (3)

The time taken for cooking in the SBC and storage unit was 45 minutes. The food was found to be well-cooked using PCM as latent heat storage unit. The discharging efficiency (η_{dis}) of the latent heat energy storage system was calculated, using the above-stated energy quantities as 57% by using equation (4)

$$\eta_{dis} = \frac{\text{Energy required to prepare the food item}}{\text{Energy stored in the PCM}} \qquad (4)$$
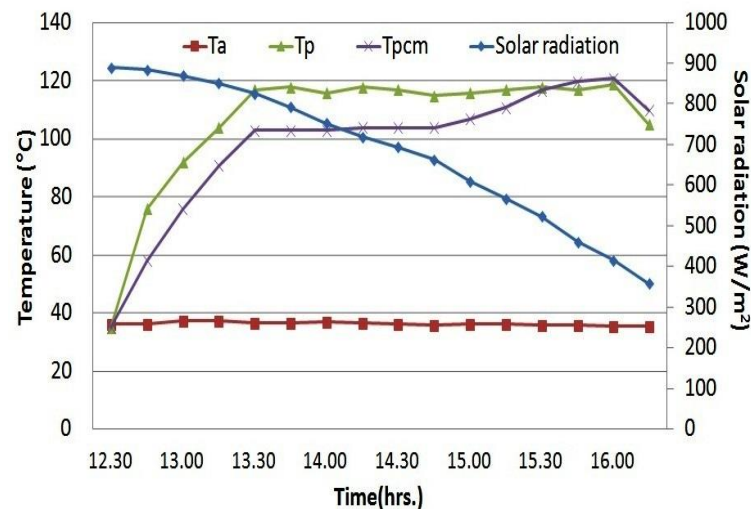

Figure 6. Temperature responses of SBC with PCM

5. Conclusion

In this work, an improved latent heat energy storage system was designed and fabricated to carry out experiments with conventional box type solar cooker for late evening cooking purposes. It was found that the efficiency of the solar cooker increased as the mass of the cooking substance increased when boosters were used. Moreover, the time taken to reach high temperature of fluid in the SBC also reduced when boosters were used. Oxalic acid dihydrate of 2.9 kg was used as phase change material. The results of the cooking experiment conducted at late evening hours showed that the selected PCM was able to supply heat energy effectively, with a discharge efficiency of 57%.

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