Performance Evaluation of a Solar Cooker with Low Cost Heat Storage Material

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Abstract: A solar box cooker (SBC) has been developed for the thermal performance evaluation by operating it on a low cost thermal storage. For this, a mixture of sand and granular carbon has been prepared and tested for an optimum ratio under a solar collector. After testing, the ratio of 4:6 (sand: carbon) has been observed to maintain a high temperature range with long term heat storage. This mixture has been used as thermal heat storage inside the SBC. The experimentation procedure has been conducted under climatic conditions of Moradabad, India. Results indicated that the first Figure of merit (F_1) was 0.13 $m^2°C$ /W, second Figure of merit (F_2) was 0.44 $m^2°C$ /W, thermal efficiency was estimated to be 37.1%, cooking power was estimated as 44.81% and overall heat loss coefficient was 3.01 $W/m^2°C$. The system was found feasible for cooking during the off sunshine conditions.

Keywords: Solar Cooker, Thermal Performance, Thermal Storage, Cooking Power

1. Introduction

Cooking is a major activity for different households, all over the world. People use different fuels for this task such as; firewood, charcoal, kerosene, dung cakes, LPG, electricity etc. But now days, people from the different regions/countries are attracting towards the solar energy applications like solar water heater, solar cooker, solar lights etc [1]. Solar energy is a good option for them as an alternative source of energy for cooking and water heating. There are many social and economic benefits by using them. Solar cookers are less in cost, simple in design, easy to fabricate, low maintenance, easy convenience, safe cooking and free from pollution [2]. Generally, solar cookers are for two types; solar dish cooker (SDC) and solar box cooker (SBC). Dish cooker is a concentrating type of solar cooker and required a continuous tracking mode for operation while box cooker is a non-concentrating cooker and don't require any tracking mode for cooking.

A box cooker is mainly a rectangular or square box of a specific size (according to the need) with a transparent glass cover to trap the sunlight into it and can perform as an oven.

However, thermal losses over a larger surface area will moderately offset the extra gain by having a better heat collecting surface. What is commonly done to compensate for this is that a glazed cover and mirror boosters (reflectors) are used to enhance the apparent collector area. The primary function of a reflector is to reflect the sunlight into cooking chamber through glazed surface.

The greenhouse effect takes place inside the cooker and solar heat (irradiance) cooks the food within SBC. An insulator is provided to SBC to reduce heat losses from bottom and surroundings as well as insulation helps to prevent from leakages. A blackened absorber plate and cooking vessel is required for absorbing maximum amount of solar heat and permits for a higher cooking temperature. In that way, solar cooker perform for efficient cooking [3]. Apart this, one can easily enhance the cooking efficiency of SBC by improving the design of cooker [4] or cooking vessel [5], by using a quality heat storage material or by making it 'hybrid'

2. Materials and Methods

Table 1 summarizes the previous work done for enhancing

thermal performance of a box cooker by using additional reflectors to boost up the input or some novel thermal storage materials etc.

In the present work, a solar box cooker (SBC) has been modified to evaluate the thermal performance by operating it on a low cost thermal storage. For a reference, a solar box type cooker is simple designed rectangular or square shaped solar cooker which consists of an insulated blackened box carrying two to four cooking utensils, a double or triple glazing and a mirror booster. Stuff is placed inside the cooking vessel and glazed cover is then easily closed.

Table 1. *Some selected designs of solar cookers with TES materials.*

Reference	Design	Results
Sharma et al., [6]	A simple box cooker with commercial grade acetamide as latent heat storage	The SBC was found to satisfy the two Figures of merit (F_1 and F_2) and it was remarked that if quality storage is used than night cooking was possible.
Nahar [7]	A hot box solar cooker with storage	A box cooker was tested with a storage material (material not specified) and found better than a SBC without heat storage. The efficiency of SBC was 27.5%.
Buddhi et al., [8]	A solar box cooker with three reflectors	Commercial grade acetanilide was successfully tested as latent heat storage in a SBC with 03 reflectors to store the Sun energy during sunshine hours as well as cooking the food during evening time.
El-Sebaii et al., [9]	Solar box type oven	Commercial grade magnesium chloride hexahydrate ($MgCl_2 6H_2O$) was investigated as a TES material for solar cookers and found suitable for solar cooking.
Saxena et al., [10]	A simple designed solar box type cooker	Two different sensible heat storing material; sand & carbon were used to estimate F_1 and F_2 by performing on individual storage and a mixture of undefined ratio of both of them
Lecuona et al., [11]	Solar portable solar concentrating parabolic cooker of standard size	Technical grade paraffin and erythritol has chosen as PCM and the results indicate that the food can be cooked the day around concurrently with heat storage along the day.
Mawire et al., [12]	Indoor solar cooking unit	Three different thermal oils; Sunflower oil, shell thermia C and shell thermia B has been evaluated for thermal performance. The exergy factor was proposed to evaluate the ratio of exergy content to energy content. The sunflower oil was found better than other TES
Kumaresan et al., [13]	A double walled cooking unit was developed which was integrated with a TES system and suitable for solar cooking	The $\eta_{overall}$ and $\eta_{tava\ unit}$ were found to be 10.2% and 73.5%, respectively. Thermal losses incurred in piping circuit, TES tank and cooker during the cooking were around 54.3%, 25.3% and 4.1% respectively.
John et al., [17]	All designs of box type cookers in which the PCM can be incorporated	Experimental studies reveals that the galactitol (PCM) is more suitable then other type of PCMs because lowest cycle temperature (200°C) yielded around 90 thermal cycles and appropriate for solar cooking
Yadav et al., [18]	A parabolic dish based solar cooker	Four configurations were developed to test the different combinations of sensible heat storage materials in which the PCM- stone and PCM-sand was found suitable for solar cooking
Kumaresana et al., [19]	A double walled indirect type solar cooking unit	A new indirect type of solar cooking unit has been introduced in which Therminol-55 and D-mannitol were used as heat transfer fluid. The unit efficiency was found around 73.5%

Figure 1. Experimental set up with load.

The sun lights directly fall on the blackened surface (aperture area), on the top surface of vessel and on the mirror booster. In this manner, conduction and convection takes place inside the cooker through the solar radiant energy and the stuff get cooked (see Figure 1 and 2).
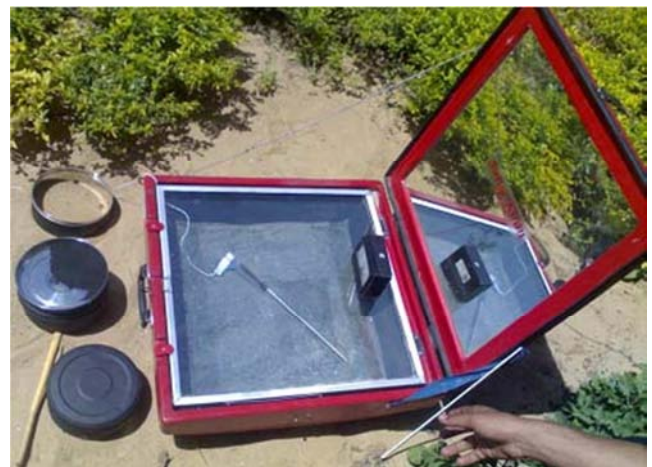

Figure 2. Experimental set up without load.

In the present case, the cooker is tested for stagnation (no

load) and sensible (load) test conditions by operating it on a low cost TES material prepared by sand and carbon (granular). The experiments were carried out to estimate some major parameters like as; two Figures of merit, thermal efficiency, overall heat loss coefficient and cooking power. Following equations were used to estimate some major parameters [3].

From the principle of conservation of energy, the input and output energy for SBC can be calculated by equation (1) and (2)

$$\dot{E}_{in} = I_{avg}.A_{ap}.t \tag{1}$$

$$\dot{E}_{out} = m.C_{p}.(T_{final\ of\ water} - T_{intial\ of\ water})$$

$$\dot{E}_{out} = m.C_{p}.\Delta T \tag{2}$$

With the help of equation (1) and (2), thermal efficiency of SBC can be estimated by:

$$\eta_{th} = \frac{m.c_{p}.\Delta T}{t.I_{avg}.A_{ap}} \tag{3}$$

The cooking power can be defined as the rate of useful energy available during the heating period and for a standard cooking test, this can be estimated by [14]:

$$P_{sbc} = m.c_{p}\frac{(T_{wf} - T_{iw})}{600} \tag{4}$$

Equation (4) is divided by 600 to account for the number of seconds in each 10 minutes interval as per recommendation [14]. The Figures of merit (F_1 and F_2) for the box cooker suggested by Mullick et al., [15] and can be described as: the first Figure of merit is the optical ratio efficiency and overall heat loss coefficient for a SBC and experimentally, it can be termed as equation (5), while second Figure of merit can be expressed as equation (6);

$$F_1 = \frac{(T_p - T_{amb})}{I} \tag{5}$$

Where, I (W/m^2) is the insolation on a horizontal surface (taken at time of stagnation testing)

$$F_2 = \frac{m_w c_{p-w}}{A_{sbc}t}F_1 \ln\left[\frac{1 - \frac{1}{F_1}\left(\frac{T_{wi} - T_{amb}}{I}\right)}{1 - \frac{1}{F_1}\left(\frac{T_{wf} - T_{amb}}{I}\right)}\right] \tag{6}$$

Where, T_{wi} is the water temperature at state 1 (at starting), T_{wf} is the water temperature at state 2 (final temperature), C_{p}-is specific heat of water (4200 kJ/kg°C). Overall heat loss coefficient has been obtained by summing the top loss coefficient and bottom loss coefficient [20], while the side losses are assumed negligible.

$$U_L = \left[\frac{2.8}{\frac{1}{\varepsilon_P}\left(\frac{1}{N_c^{0.025} + \varepsilon_c} - 1\right)} + 0.825(x_m)^{0.21} + aV_{win}^b - 0.5(N_C^{0.95} - 1)\right]$$
$$(T_{pm} - T_{amb})^{0.2} + \frac{k_i}{t_i} \tag{7}$$

Where, T_{pm} is the mean plate temperature, N_c is number of glazing, V_{win} is wind velocity, a and b is constant, ε_p and ε_c is emissivity of the plate and glass cover, respectively and k_i is thermal conductivity of insulation while, t_i is the thickness of insulation.

All the specifications of the present solar box type cooker have been shown in table 2.

Table 2. *Specifications of the solar box type cooker.*

Dimensions of outer box	640×640×200 mm^3
Material for outer casing of SBC	Fibre
Aperture area	485×515 mm^2
Glazing	522×548 mm^2
Depth of the tray from glazing	80 mm
Emissivity of absorber plate (Al made and blackened)	0.90
Thickness of absorber plate	0.60 mm
Thickness of glass covers	2 mm
Spacing in between glazing (double glazed)	10 mm
Emissivity of the glass	0.91
Insulation	Glass-wool
Thermal conductivity of insulation	0.05 W/m°C
Thickness of insulation from all sides	50 mm
Cooking vessel height (Al made and blackened) and diameter	65 mm and 160 mm
Mirror booster	522×548 mm^2

Apart this, for preparation of heat storage material, sand and granular carbon were purchased at a low cost from the local market. A simple flat plate solar collector (FPSC) has designed and fabricated purposely to get an optimum ratio of mixture of two different heat storage materials namely; sand and carbon (granular) to prepare a quality TES material for the present SBC (Figure 3). Sand was purchased @ of 0.1 $/kg (₹ 6.50 per kg), while carbon was purchased @ of 0.07 $/kg (₹ 4.00 per kg). Both the tested TES materials are shown in Figure 3, while a few properties of test materials are shown in table 3.

Table 3. *A few properties of sand and granular carbon [10].*

	Desert	**Carbon**
Density (kg/m^3)	1450	460
Thermal conductivity (W/m K)	0.26	0.11
Thermal diffusivity (m^2/s/10^6)	0.35	1.02
Specific heat (kJ/kg K)	0.80	0.93
Emissivity	0.91	0.90
Absorptivity	0.95	0.97

The FPSC was made of 8 mm thick plywood with a cross sectional area of approximately 1.50 x 1.02 m^2 and total height of the FPSC was around 0.3 m. This FPSC was subdivided into eleven sections (11 sub-sections of similar specifications), which were carrying the mixture of desert and carbon in different ratios as shown in Figure 4 (experimental set-up) and Figure 5 (schematic diagram).
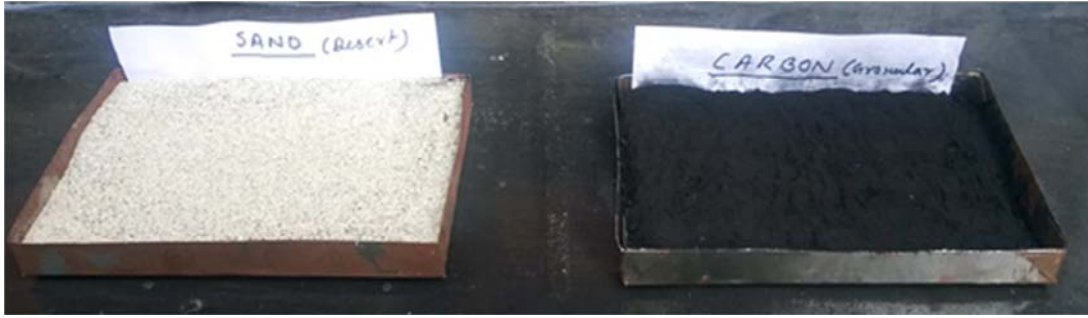
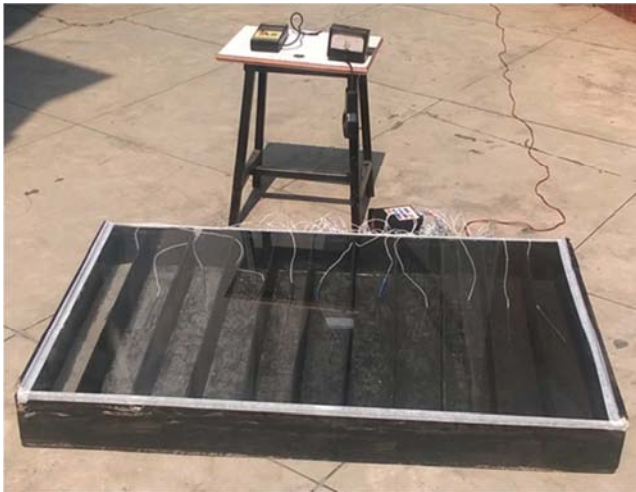*Figure 3. Sample of tested materials [desert and carbon].*

Figure 4. Experimental set-up of a simple FPSC carrying the mixture in different ratio.

In this fashion, total eleven small sections have developed to be performed as a solar collector with different TES materials. These solar collectors were fabricated with the help of a 8 mm thick plywood and then laminated by a thin *Al* sheet of 0.5 mm (thickness) and painted dull black for a maximum gain. The specific area of an individual absorber tray was approximately 0.1 x 1 m^2 and height was around 127 mm of each section. There was a space gap of 73 mm (filled by glasswool) between solar collector and bottom of the system to reduce thermal losses.

In FPSC, absorber tray No. 2 to absorber tray No. 10 were carrying the mixture of desert and carbon in ratio (desert: carbon) of 9:1 to 1:9, while section 1 (absorber tray No. 1) was carrying only desert and section 11 (absorber tray No. 11) was carrying only carbon. There was a gap of 10 mm in between all eleven *Al* made absorber trays (0.5 mm thick) inside the FPSC and glass-wool was used to fill this gap. Glass-wool was used as an insulation material. An *Al* sheet (with good reflectivity) of 0.5 mm thickness was positioned vertically for separation of all the sections (Figure 5). There was a gap 10 mm in between each section. All different TES materials were spread out in the form of a thin layer of a 2 mm in eleven sub-divided sections of the system. A high temperature resistant transparent glass of 5 mm thickness was placed over the each tray, to seal the heat absorbing medium (to make a small solar collector unit). In this manner, total eleven solar absorbers were modified inside the system (FPSC). Apart this, another transparent glass of 5 mm thickness was used for glazing of the system.
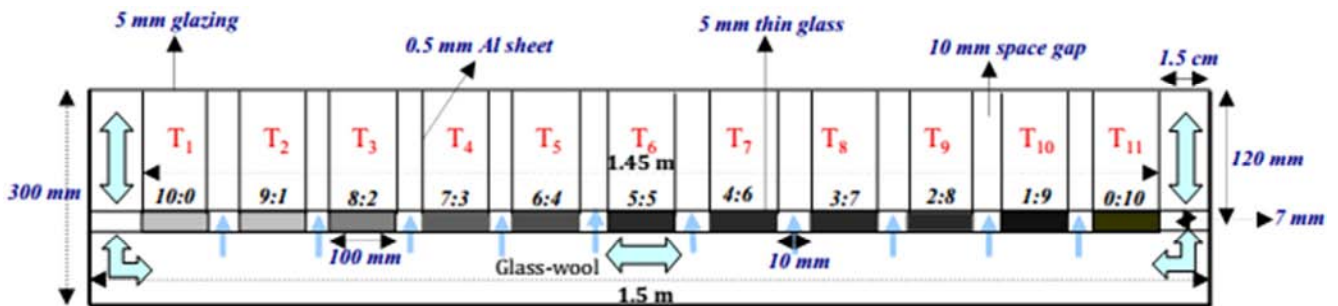

Figure 5. Schematic diagram of experimental set-up of FPSC showing TES mixtures in varying ratio.

The metrological parameters like; solar irradiance (I - W/m^2), ambient temperature (T$_{amb}$ - °C) and wind velocity (V$_w$ - m/s) were measured with the help of a data logger of Solar Radiation and Resources Assessment station, installed on the rooftop of Mechanical Engineering Department at M. I. T., Moradabad (India). The temperature variations (T- °C) in the said system were measured with the help of a 12 wire digital thermocouple meter with + 0.01°C accuracy (range from 0°C - 250°C). Wind velocity was measured with the help of digital anemometer (range from 0.01 m/s – 50 m/s) with accuracy of 1 m/s. All the measuring instruments were well calibrated and checked properly for error before conduction of experiments.

3. Result & Discussion

In the present work, a SBC has been modified and tested for thermal performance evaluation by operating on a low cost TES material. The TES material was prepared by mixing sand and carbon (granular) in an optimum ratio and tested under a simple designed FPSC (Figure 4). For a detail, a FPSC was designed and tested to get an optimum ratio of sand and carbon among various test sections carrying the same materials but in different ratios. The FPSC was placed southward at angle of 43.5° from horizontal surface and tested experimentally in climatic conditions of Moradabad (Longitude- 28.83′ and latitude- 78.78′). Experiments were conducted on four different days (11.05.16, 11.08.16, 11.11.16, and 11.03.17) of four different months to observe the thermal performance of quality TES material in different climatic conditions. The testing was started at 10:00 hrs in the morning (at the time of the full sunshine) and finished at 19:00 hrs (at the time of the complete sunset) on respective days. It is notable that FPSC was completely closed, while conducting experiments. An array of eleven thermocouple wires was used to read out the temperature variations for all the individual storages and placed over the different absorbing trays.

During the experimentation, a significant effect of ambient parameters was noticed over the design parameters. Tested section 1 was found good in comparison of section 11 for short term heating (i.e., for a short duration), while increasing the ratio of carbon in test sections was found a major cause of temperature rise in respite sections (i.e., test section 2 to 11) of the system. It is noteworthy that section 2 to 11, having a carbon rich mixture (in a varying ratio) with sand were noticed for a minor effect of ambient conditions after attaining the maximum values of the T_p. It has been also observed that as decreasing the desert ratio, the test section T_9 to T_{11} took much time to get hot and to attain the T_{max} in comparison of T_1 to T_8. After successful experimentation of FPSC carrying the mixture of desert and granular carbon in different ratio in 11 similar test sections, the test section T_7 was found appropriate to achieve and maintain a higher surface temperature among all sections (referring table 4). On this basis, an optimum ratio of sand and carbon (4:6) has been considered as a quality TES material for solar cooker.

Table 4. Temperature variations of different sections in FPSC.

Temperature variations on				
Section	11.05.16	11.08.16	11.11.16	11.03.17
T_1	41-73	39-64	33-55	41-64
T_2	40-70	38-66	31-51	42-65
T_3	40-74	41-67	31-52	41-67
T_4	43-73	43-69	32-51	41-70
T_5	44-75	44-71	33-52	45-71
T_6	45-78	45-73	34-57	47-72
T_7	46-81	46-75	35-66	43-74
T_8	44-78	44-74	33-65	42-71
T_9	41-76	42-72	32-65	42-70
T_{10}	40-74	39-71	30-64	39-69
T_{11}	38-74	36-72	29-62	36-67

After obtaining the optimum ratio of mixture, the mixture was prepared and spread over the absorbing tray of solar cooker in the form of a thin layer to store solar radiant energy in a good amount for a long period. The test mixture was sieved to 20 x 50 (US Sieve) mesh, yielding a particle size range from 0.25 to 0.90 mm. A high temperature resistant and thin transparent glass was placed over the TES material inside the cooker and sealed to avoid thermal losses. This transparent glass acts like absorber plate for solar cooker.

As mentioned in section 2 (Materials and methodology), the cooker was tested for stagnation and sensible test conditions. It is notable that the cooker was tested with prepared TES material. The experiments were carried out from 11:00 hrs and finished at 12:40 hrs on two continuous days of May 2017. Besides this, to observe the thermal response of SBC with TES, the cooker was kept under testing on load conditions during the off sunshine (discussed below).

3.1. Stagnation Test

The cooker was tested first on no load conditions (stagnation testing) on 10.05.17. The system was placed southward exposing to the sun at 10:00 hrs. The TES material was fully covered with a transparent glass sheet and properly sealed with an adhesive M-Seal™ (Figure 1). Readings were taken from 11:00 hrs after attaining the steady state by the system. At this time, T_{amb} was noticed around 34°C, T_P was around 94°C and irradiance was 630 W/m². A significant effect of the ambient conditions was observed over plate temperature. T_P was observed increasing and decreasing with increasing and decreasing of T_{amb}. Maximum plate temperature was observed 131°C around 12:00 hrs (Figure 6) and the first Figure of merit (F_1) was determined to be 0.13 m²°C /W, which satisfy the standard [15].
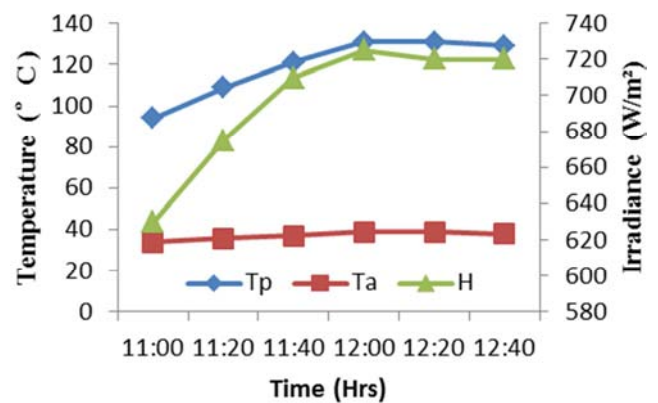

Figure 6. Temperature variations curves of SBC for stagnation test.

3.2. Sensible Test

After the stagnation test, the said system was tested on load conditions (sensible testing) on 11.05.17. In this, 1 kg water was considered as a cooking stuff and placed into two similar cooking vessels for an equal quantity (500 grams in each vessel). Readings were taken in the same fashion as in stagnation test.

Around 11:00 hrs, T_{amb} was notified to be 35°C, T_p was

around 92°C, T_w was around 38.1°C, and irradiance was 620 W/m^2. The wind velocity was observed for a range of 0.20 m/s - 0.29 m/s at the ground level. After 100 minutes of starting of experiments, water inside a cooking vessel was found to attain its maximum temperature i.e., 96.5 while the other one vessel was notified for the same at 12:40 hrs. The plate temperature was found 137°C, maximum at 12:20 hrs. With the help of equations 3 to 7, second Figure of merit (F_2) was calculated to be 0.44 m^2°C /W, maximum thermal efficiency (η_{therm}) was estimated 37.1%, cooking power (P) was estimated 44.81 W and the overall heat loss coefficient was calculated 3.01 W/m^2°C.

Apart this, the system was kept under observation to monitor the variations in plate temperature and water temperature in absence of irradiance. For this, after completion of sensible test on 11.05.2017 from 11:00 to 12:40 hrs, the lid of SBC was closed properly and readings were taken for T_p and T_w from 12:40 hrs to 16:00. Readings show that the T_p was slightly down in absence of solar heat because TES material beneath the absorber plate (glass cover) released it stored heat energy with poor rate. This process was observed due to the properties of sand and carbon (granular). The optimum mixture become hot soon because of sand and absorbs the solar heat in a good amount and provides a long term heating because of carbon. The significant effects can be seen on water temperature (placed in vessel). The conduction took place from TES material to the glass absorber plate and from plate to cooking vessel and then to the water. Figure 7 also shows that the water temperature dropped with respect to the plate temperature. The plate temperature was noticed around 130°C and water temperature was around 86.5°C at 16:00 hrs when there was no source of heating and the cooker was performed only on the heat of TES material. It shows that cooking is possible in off sunshine conditions if once TES material is completely charged.
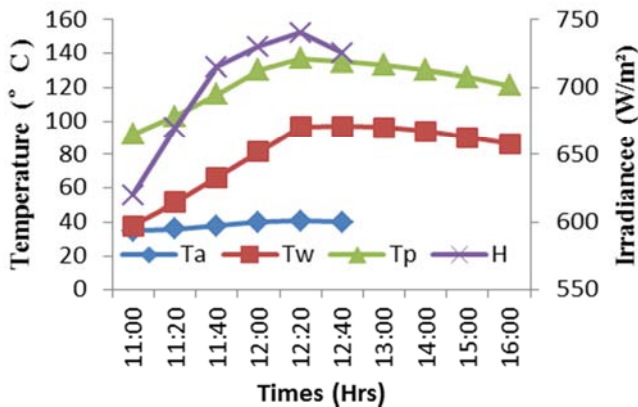

Figure 7. *Temperature variations for sensible test and thermal response of SBC without irradiance.*

The present model has been found better in terms of estimated parameters in comparision of other models [table 1]. Allthough, compound parabolic cookers [16] for phase change material (PCM) based box cookers has better performance over the cookers with sensible heat storage (SHS). But PCM are higher in cost and need a typical design

for incorporating. In the present model, the tested material is low in cost, easily implimentable to the sytem and has a better perfromance over the other avalable designs of cookers with SHS.

4. Conclusion

A low cost heat storage material was prepared with help of sand and carbon and tested under a solar collector. After getting the optimum ratio of both the materials, to prepare a quality mixture, the mixture was used inside a solar cooker as thermal energy storage for long term cooking. The cooker was found feasible for cooking during off sunshine conditions after completely charging of the TES material. The cooker satisfies the standard cooking criterion for Figures of merit and cooking power. After completing the experimentation, first Figure of merit (F_1) was calculated to be 0.13 m^2°C /W, second Figure of merit (F_2) was obtained as 0.44 m^2°C /W, maximum thermal efficiency (η_{therm}) was estimated around 37.1%, cooking power (P) was estimated for 44.81 W and the overall heat loss coefficient was 3.01 W/m^2°C. Apart this, because the TES material was tested in different climatic conditions for possible cooking during off-sunshine hours, it can be considered as a low cost TES material for solar box types cookers for a year round efficient cooking. There is a possibility of using this quality test mixture in parabolic dish cookers by filling this mixture in side outer shell of cooking vessel of the cooker.

Nomenclature

Abbreviations

I- Solar radiation (W/m^2)

SBC- Solar box cooker

TES- Thermal energy storage

F_1- First Figure of merit (m^2°C /W)

F_2- Second Figure of merit (m^2°C/W)

U_L- Overall heat loss coefficient (W/m^2°C)

C_p- Specific heat of water (kJ/kg°C)

η- Efficiency (%)

m- Mass of water (kg)

t- test time (sec)

FPSC- Flat plate solar collector

T- Temperature (^{o}C)

Subscript

p- plate

amb-ambient

ap-aperture

avg- average

w- water

i- initial

f- final

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