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# Experimental Analysis of Box Type Solar Cooker for Performance Improvements and Off-Sunshine Cooking

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***Abstract***

*The energy for cooking accounts for 50% of the total primary energy consumption, and it is the most important energy consuming operation in the domestic sector. Among the thermal applications of solar energy, solar cooking is one of the simplest, most viable and attractive options in terms of utilizing solar energy. A solar cooker is a device which uses solar energy to cook food. Box type solar cooker is a simple device to collect the incoming solar radiation and convert it into heat energy, with a low efficiency. Also, the box type solar cookers are not used for off-sunshine cooking. In this paper, an experimental analysis is done in order to estimate the performance of a box type solar cooker and then to compare the same when using a finned absorber plate. Also, an experimental analysis is made by using sand and water as thermal energy storage materials, which helps in off-sunshine time cooking. While using finned absorber plate, the efficiency can be increased and cooking time can be reduced. Also, sand performs well as a TES when compared with water.*

***Keywords-*** *Box type solar cooker, Finned absorber plate, Performance analysis, Solar cooking technology, Thermal energy storage*

## I. INTRODUCTION

Solar box cookers, also known as solar ovens, are the most common and inexpensive type of solar cookers. These box cookers are simple in construction and are made of low cost materials which consist of a black painted metallic tray or cooking tray, usually made of aluminium and is usually covered with a double glass window (Fig 1). It is kept in an outer casing made of metal or fibre-glass and the space between the cooking tray and outer casing is filled with the insulation like glass wool [1].

cooker

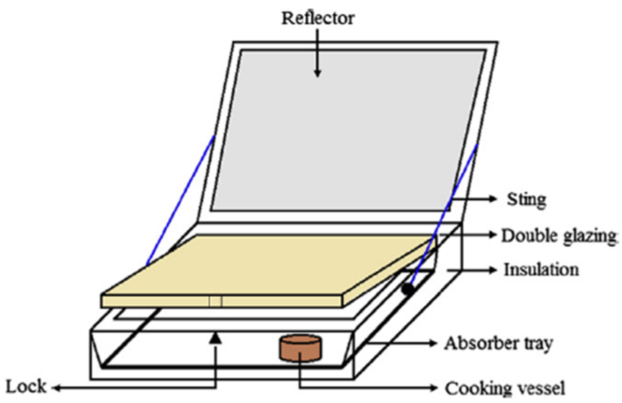


***Figure 1. Box type solar cooker***

The literature review on box type solar cookers revealed that the maximum attainable temperature is very less in box type cooker due to non-concentrated radiation [2]. Also, off-sunshine/evening or night cooking is not possible with them. Solar cookers are helpful only in cooking at day time when sun is shining. This is the main limitation of solar cookers.

The main objective of this project is therefore to overcome these limitations. Experiments have been done in order to find the solutions and found that for attaining higher temperatures, finned absorber plate can be used instead of unfinned one. To overcome the problem of off-sunshine cooking, Thermal Energy Storage (TES) can be employed.

A fin is a surface that extends from an object to increase the heat transfer rate to or from the environment by increasing convection. Fig.2 shows an absorber plate with fins.

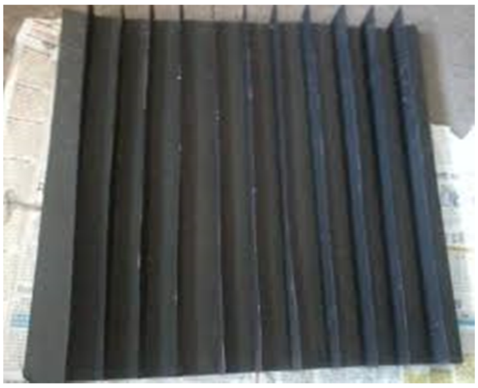

***Figure 2. Finned absorber plate***

The amount of conduction, convection or radiation determines the amount of heat an object can transfer. The heat transfer can be increased either by increasing the temperature difference between the object and the environment, increasing the convection heat transfer coefficient, or by increasing the surface area of the object [3]. Adding a fin to an object increases the surface area and increases the heat transfer. Fins are used to increase the effective area of a surface in an attempt to maximize heat transfer in both cooling and heating applications. Typically, the fin material has a high thermal conductivity. When fins are employed, the overall area for heat transfer increases, which contribute towards the improvement in efficiency of solar cooker. Fins cause multiple reflections, due to which the irradiative absorption increases, resulting in the increase in the temperature difference. Also, fins obstruct the flow of air inside the cooker. Hence, the temperature can rise due to the low air flow rate. But, when the radiation level falls, the temperature also falls down rapidly. Hence alternative methods is to be found for eliminating the adverse effect caused due to sudden fall in radiation. One such method is using TES.

The thermal energy storage (TES) can be defined as the temporary storage of thermal energy at high or low temperature. Solar energy or the product of solar process can be stored in different forms as electrical, chemical, mechanical and thermal energy [4]. Energy storage can minimize the rate of mismatch between energy supply and energy demand, and it plays an important role in energy conservation. Therefore, the need for the storage of solar energy can have a significant impact on energy sectors. Otherwise, solar energy has to be used as soon as it is received.

Energy storage materials are mainly of two types depending on the way it stores energy. These are: (a) Sensible/Specific heat storage materials, (b) Latent heat storage materials/phase change materials (PCMs). Specific heat storage materials are those which stores energy in the form of specific heat are called specific heat storage materials. The most probable specific heat storage materials used are sand, used engine oil, mineral oil, water, pebbles etc. The amount of energy stored by these materials is dependent on specific heat, temperature change and mass of the storage material. Large mass of material is required for storing solar energy if material has low specific heat; which makes the system bulkier and requires large time for cooking. Latent heat storage materials/phase change materials (PCMs) have advantage over the specific heat storage materials because they require small mass for storing large amount of energy. So these materials are helpful in making energy storage system compact.

***Table 1. Properties of sand and water***

| Properties | Sand | Water |
|---|---|---|
| Density (kg/m$^3$) | 1450 | 1 |
| Thermal conductivity (W/m K) | 0.23 | 0.6 |
| Specific heat (kJ/kg K) | 0.87 | 4.187 |
| Thermal diffusivity (m$^2$/s) | $0.37\times10^{-6}$ | $0.143\times10^{-6}$ |

The main properties considered for using as TES are its density, thermal conductivity, specific heat, thermal diffusivity, heat capacity, etc. [5]. The storage materials used and their properties are shown in Table 1. Due to the ease of availability, sand and water are used as thermal energy storage in this experiment. The experimental analyses done and their results obtained will be discussed in the further sections.

## II. EXPERIMENTAL ANALYSIS

The box type solar cooker used for experimental analysis is shown in Fig.3. The solar cooker is made up of UV resistant molded fibre glass body. The dimensions of box type solar cooker are 540mm ×540mm×200mm. The cooking capacity is about 2kg at a time or 6-8 kg per day according to the intensity of radiation. The absorber tray is made of 0.5mm thickness aluminium sheet, which is black powder coated. Similarly, the cooking vessels are made of black powder coated stainless steel. The absorber tray material should have high absorptivity and low emissivity, so as to assist the trapping of radiation within the solar cooker. Black coating on absorber plate and cooking vessel enhances the solar radiation absorption by the box type solar cooker. The lid of solar cooker is made of double glazed glass, which is opaque to long radiations, and is transparent to high energy, short wavelength solar radiations. A hinge is provided so that the reflector is properly positioned to allow manual tracking.


***Figure 3. Solar cooker used for experimental analysis***

As per specification, the first figure of merit ($F_1$) is greater than or equal to 0.12, and the second figure of merit ($F_2$) is greater than 0.4. Hence the solar box type cooker purchased was categorized as ‘A’ graded.

For performance analysis of box type solar cooker, the temperature of the absorber plate, the temperature of water in cooking vessel, and the upper and lower glazing temperatures need to be measured. For measuring temperature at these points, thermocouple of suitable range can be incorporated. Here the thermocouple used is J type, which has a temperature range of -40 to 800 °C.

Four numbers of thermocouple are necessary for experiment. One thermocouple is inserted in the cooking vessel through a small opening, to measure the water temperature. Two thermocouples are attached to inner glazing and outer glazing of cooker in order to measure the inner glazing temperature and outer glazing temperature of solar cooker respectively. The remaining one thermocouple can be placed as per the experiment. Thermocouples are connected to digital displays, which show the temperature reading directly. Solar radiation was measured using the solarimeter.

### 2.1. Experiment using unfinned absorber tray

In case of experiment using unfinned absorber tray/plate. The temperatures to be measured are upper glazing temperature, lower glazing temperature, absorber tray temperature as well as the water temperature, and the corresponding solar radiation is to be measured. The experimental setup is shown in Fig.4.

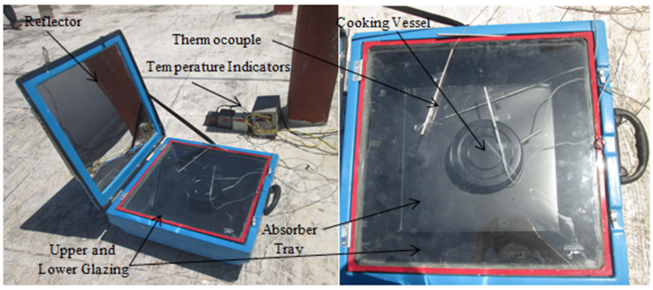


***Figure 4. Experimental setup of box type solar cooker using unfinned absorber plate***

The readings obtained while using unfinned absorber plate on 14/05/2015 is shown in Table 2.

***Table 2. Observation table for temperature at various points of cooker for experiment with unfinned absorber plate dated on 14/05/2015***

| Time (Hrs.) | Solar Radiation ($W/m^2$) | Upper Glazing Temperature (°C) | Lower Glazing Temperature (°C) | Absorber Plate Temperature (°C) | Temperature of water within pots (°C) |
|---|---|---|---|---|---|
| 09.30am | 369.6 | 29 | 23 | 51 | 30 |
| 10.00am | 612.5 | 31 | 40 | 55 | 32 |
| 10.30am | 832.3 | 38 | 54 | 64 | 38 |
| 11.00am | 821.1 | 41 | 58 | 77 | 49 |
| 11.30am | 670.6 | 43 | 67 | 83 | 60 |
| 12.00pm | 599.9 | 43 | 69 | 92 | 62 |
| 12.30pm | 872.9 | 48 | 72 | 97 | 68 |
| 01.00pm | 653.8 | 45 | 76 | 93 | 72 |
| 01.30pm | 766.5 | 51 | 79 | | 73 |
| 02.00pm | 556.5 | 55 | 75 | 99 | 70 |
| 02.30pm | 510.3 | 51 | 72 | 86 | 69 |
| 03.00pm | 428.4 | 48 | 72 | 87 | 64 |

Based on the experimental data obtained, performance curves have been plotted. The average solar radiation for the whole day was only 641.2 $W/m^2$. Fig.5 shows the graph of temperature at various points of solar cooker versus time of day.

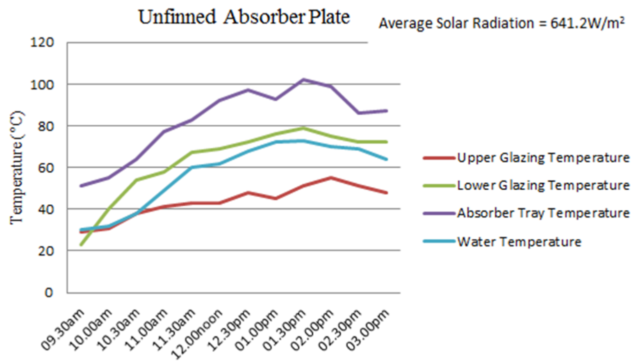


***Figure 5. Temperature at various points v/s time of day for cooker with unfinned absorber plate***

The maximum temperature of water reached is about 73 °C. Due to the weather conditions of the day which the experiment was conducted, the water temperature began to decrease due to low availability of solar radiation. If intense solar radiation is available throughout the day, the water may start boiling. Depending on the availability of solar radiation, the maximum reachable water temperature and plate temperature may vary accordingly. Solar radiation should be high for the favorable cooking. When comparing the temperatures at different points, the absorber tray temperature has reached the maximum temperature, which is above 100 °C. Hence the topmost curve is tray temperature. The curve just below absorber tray shows the lower glazing temperature, which is clearly above the water and upper glazing temperatures. The upper glazing temperature is lower than the lower glazing temperature due to the greenhouse effect, which is the principle behind solar cooking.

### 2.2. Experiment using finned absorber tray

The experiment was repeated by replacing ordinary absorber plate with a finned absorber plate, in which the fins of suitable size is inserted inside the box type solar cooker. The solar cooker before and after inserting the fins is shown in Fig.6 and the results of experimental analysis on 23/06/2015 is given in Table 3.

***Figure 6. Experimental setup of box type solar cooker using finned absorber plate***

***Table 3. Observation table for temperature at various points of cooker for experiment with finned absorber plate dated on 23/06/2015***

| Time (Hrs.) | Solar Radiation (W/m$^2$) | Upper Glazing Temperature (°C) | Lower Glazing Temperature (°C) | Absorber Tray/Fin Temperature (°C) | Temperature of water within pots (°C) |
|---|---|---|---|---|---|
| 09.45am | 264.6 | 29 | 23 | 51.2 | 30 |
| 10.15am | 812 | 38 | 58 | 64.9 | 40 |
| 11.15am | 840 | 43 | 75 | 83.1 | 60 |
| 12.05pm | 878.5 | 45 | 88 | 97.2 | 79 |
| 01.30pm | 911.4 | 44 | 91 | 102 | 85 |
| 02.00pm | 829.5 | 46 | 84 | 99.5 | 84 |
| 02.45pm | 625.8 | 51 | 98 | 105.9 | 88 |
| 03.15pm | 796.6 | 50 | 85 | 95.2 | 85 |

The temperatures to be measured in this experimental setup includes upper glazing temperature, lower glazing temperature, absorber fins temperature as well as the water temperature. The average solar radiation for the whole day is only 736.4 W/m$^2$. Fig.7 shows the graph of temperature at various points of solar cooker versus time of day.

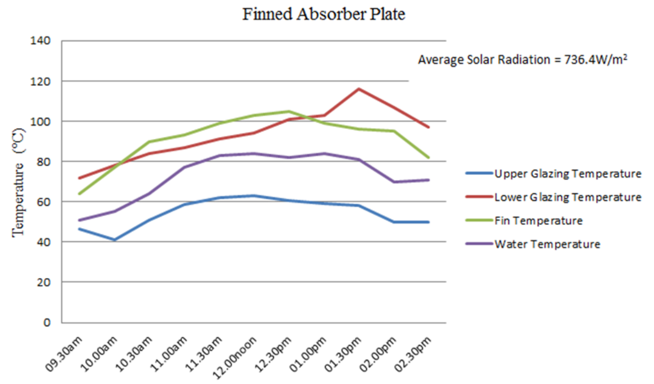


***Figure 7. Temperature at various points v/s time of day for cooker with finned absorber plate***

When fins are employed, the overall area for heat transfer increases, which contribute towards the improvement in efficiency of solar cooker. Fins cause multiple reflections, due to which the irradiative absorption increases, resulting in the increase in the temperature. The maximum temperature reached is 88 °C. Due to the limited height of inside part of solar cooker, the heights of fins were not uniform throughout. In order to place the cooking vessel, the fins were to be modified accordingly.

### 2.3. Experiment using water as thermal energy storage

During this experiment, the space surrounding the cooking vessel is filled with water. In this experiment, 4 litres of water has been used (as per size of solar cooker and cooking vessel). The experimental setup is shown in Fig.8.

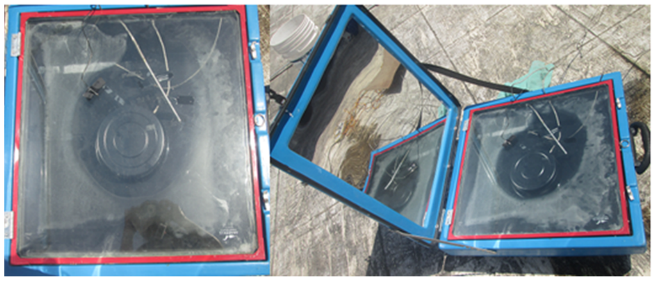

***Figure 8. Solar cooker with water as TES***

The temperatures to be measured are upper glazing, lower glazing and water temperature, as well as the temperature of water in absorber tray. The result of experimental analysis on 30/07/2015 is given in Table 4.

***Table 4. Observation table for temperature at various points of cooker for experiment using water as TES dated on 30/07/2015***

| Time (Hrs.) | Solar Radiation (W/m$^2$) | Upper Glazing Temperature (°C) | Lower Glazing Temperature (°C) | Temperature of water in absorber tray (°C) | Temperature of water within pots (°C) |
|---|---|---|---|---|---|
| 09.30am | 647.5 | 48 | 67 | 50 | 49 |
| 10.45am | 728 | 54 | 74 | 61 | 54 |
| 11.30am | 848.4 | 56.5 | 78 | 71 | 66 |
| 12.00pm | 668.5 | 46.6 | 71 | 67 | 66 |
| 01.15pm | 948.5 | 57.6 | 81 | 78 | 74 |
| 02.00pm | 933.1 | 51.5 | 77 | | 76 |
| 02.45pm | 711.2 | 49 | 74 | 75 | 74 |

The average solar radiation for the whole day was only 783.6 W/m$^2$. Fig.9 shows the graph of temperature at various points of solar cooker versus time of day.

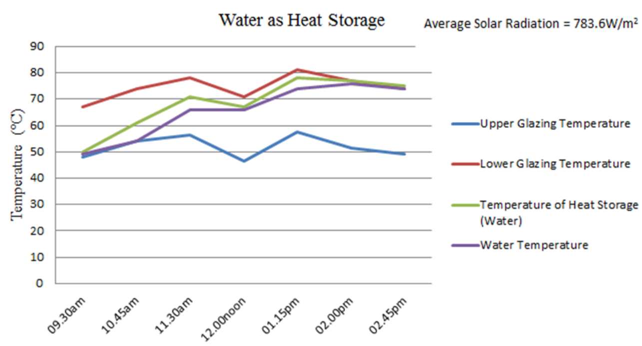


***Figure 9. Temperature at various points v/s time of day for cooker with water as TES***

From the graph, it is observed that, the increase in water temperature is very slowly unlike the previous cases, and the maximum temperature attained is around 76 °C only. This is due to the reason that, initially the solar radiation aids in increasing the temperature of water in absorber tray. Hence the rate of increase in water temperature will be lower. The advantage of using water is that even though there occurs a sudden fall in solar radiation, the water temperature remains the same for a long duration, which is not possible in case of cooker with finned and unfinned absorber plate. The problem encountered in this experiment was the evaporation and leakage of water. As the solar radiation increases, the evaporation of water in absorber tray occurs at a faster rate. Due to imperfections in insulation, water may escape as water vapor, resulting in severe evaporation losses. Also, due to the cooker design imperfections, the water gets escaped through the edges/joints.

### 2.4. Experiment using sand as thermal energy storage

During this experiment, the space surrounding the cooking vessel is filled with sand. In this experiment, 2 kg of sand has been used. When compared to the height of cooking vessel, sand level was around three-fourth the height of cooking vessel. The experimental setup is shown in Fig.10.

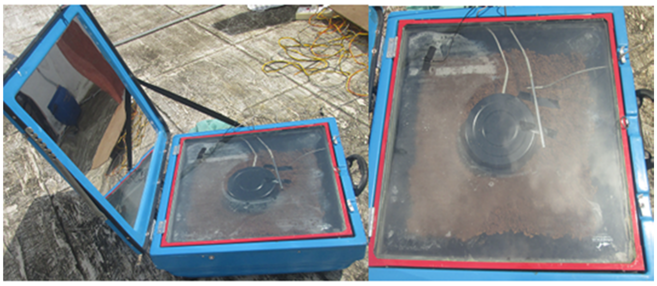

*Figure 10. Solar cooker with water as TES*

The temperatures to be measured are upper glazing, lower glazing and water temperature, as well as the temperature of sand in absorber tray. The results of experimental analysis on 08/08/2015 are given in Table 4.

*Table 5. Observation table for temperature at various points of cooker for experiment using sand as TES dated on 30/07/2015*

| Time (Hrs.) | Solar Radiation ($W/m^2$) | Upper Glazing Temperature (°C) | Lower Glazing Temperature (°C) | Temperature of sand in absorber tray (°C) | Temperature of water within pots (°C) |
|---|---|---|---|---|---|
| 10.00am | 866.6 | 36.8 | 50 | 33 | 33.3 |
| 10.30am | 879.2 | 38.8 | 58 | 38 | 35.3 |
| 11.00am | 803.6 | 37.2 | 52 | 41 | 40.8 |
| 11.30am | 840 | 45.9 | 97 | 56 | 50.5 |
| 12.00pm | 1019.2 | 41.4 | 92 | 60 | 59.1 |
| 01.20pm | 941.5 | 44.1 | 88 | 64 | 66.1 |
| 01.50pm | 931 | 44.4 | 87 | 66 | 68.4 |
| 02.00pm | 806.4 | 45.6 | 95 | 68 | 69.5 |
| 02.30pm | 252 | 40.4 | 68 | 64 | 68.8 |

The average solar radiation for the whole day is only 815.5 $W/m^2$. Fig.11 shows the graph of temperature at various points of solar cooker versus time of day.

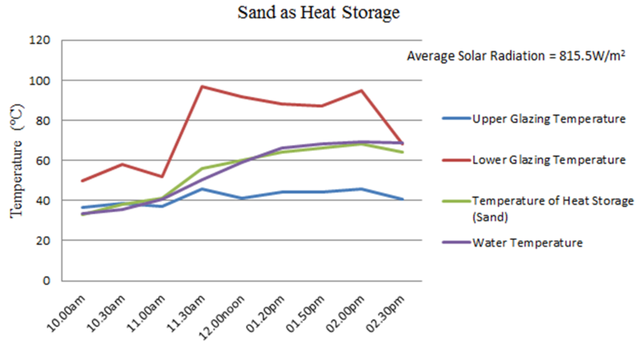


*Figure 11. Temperature at various points v/s time of day for cooker with sand as TES*

From the graph, it is observed that the increase in water temperature is very slowly as in the previous case, which used water as TES. The maximum temperature attained is around 70 °C. Initially, solar radiation helps in heating of sand, resulting in slower rate of increase of water temperature. The limitation was that the sand adds weight of solar cooker and hence manual tracking becomes difficult. Since river sand is used, water content was present in the sand and hence, as the solar radiation increases, the water gets evaporated and gets escaped, which may result in thermal losses initially.

## III. RESULTS AND DISCUSSIONS

In this project, four set of experiments were performed, which are, (i) solar cooker with unfinned absorber plate, (ii) solar cooker with finned absorber plate, (iii) solar cooker with water as TES, and (iv) solar cooker with sand as TES.

When the solar cooker with unfinned and finned absorber plate are compared, the maximum temperature is attained for the one with finned absorber plate and the value is 88 °C, whereas for unfinned one, it is 73 °C. Fig.12 shows the curves of water temperature in both experiments.

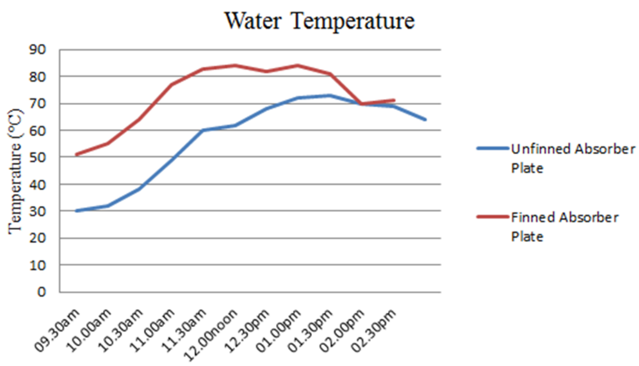


*Figure 12. Water temperature in case of finned and unfinned absorber tray*

But, the solar radiation is different in two cases. Hence a comparison based on efficiency of both systems is to be made. Efficiency of solar cooker is given as:

$$\eta = \frac{E_{out}}{E_{in}} = \frac{M_w C_w (T_{wf} - T_{wi})}{GA\Delta t} \quad (1)$$

Where, $E_{out}$ is the energy output of solar cooker, $E_{in}$ is the input energy of solar cooker, $M_w$ is the mass of water in kg, $C_w$ is the specific heat of water in (kJ/kg K), $(T_{wf} - T_{wi})$ is the temperature difference in °C between initial and final water temperature attained within the time period $\Delta t$ seconds, $G$ is the incident solar radiation in W/m$^2$ and $A$ is the aperture area in m$^2$ of solar cooker [6].

Using equation (1), the efficiency of box type solar cooker with unfinned absorber plate gives efficiency of 4.102%, whereas the efficiency increases to 5.103% when the unfinned absorber tray is replaced by a finned absorber plate. Even though the increase in efficiency is too low, it is quite significant as natural convection occurs in the process. Hence, the finned system is preferred, when the high temperature is to be attained for short time period.

The performance curves showing the comparison of two systems, which used water and sand as TES is shown in Fig.13.

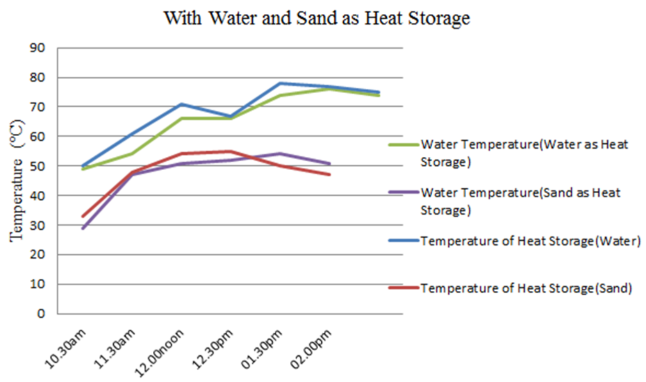


***Figure 13. Water and TES temperature in case of systems using thermal energy storage***

It is inferred from the graph that the temperature of system with water as TES and the corresponding water temperature is higher than the system with sand as TES. This is due to the reason that the sand stores heat in it very slowly when compared to water. Hence comparison is to be done based on the efficiencies of both systems. Using equation (1), the efficiency of solar cooker which used water as TES is found to be 2.06% and that which used sand as TES gives an efficiency of 4.145%. Even though the increase in efficiency is too low, it is quite significant as natural convection occurs in the process. Hence, the system with sand as TES is preferred over water, when the high temperature is to be attained for short time period.

### 3.1. Applicability of results

From the experiments, it is found that the maximum temperature is attained in case of finned absorber plate. But it occurs only when the solar radiation has reached its peak value, and the temperature dropped suddenly due to decrease in insolation. But in case of system which used TES, the maximum attained temperature remains the same for a long duration, when compared with both systems without TES. Hence, the finned system is preferred for boiling and pasteurization purposes. Solar cooker employing thermal storage can be used for cooking purposes. For example, for cooking rice, the temperature is to be maintained constant for a long period. In such cases, thermal storage can be incorporated with the solar cooker. For long period cooking at same temperature, sand is preferred since the heat retention capacity is more for it than the water. All these results are valid at the local climatic conditions under which the experiment was conducted, i.e., Kanjirappally (9.5500 °N, 76.7833 °E). As the climatic conditions vary, these experimental validations may change accordingly.

## IV. CONCLUSION

The principal objective of this project was to analyze the performance improvement of a box type solar cooker when finned absorber plate is used instead of unfinned one and to find a better solution for off-sunshine hour cooking. Experimental studies conducted indicate that while using the finned absorber plate instead of unfinned absorber plate, the efficiency increased from 4.102% to 5.103%. Hence a finned system is preferred over unfinned one. Also, the results of experiment using TES shows that efficiency increased from 2.06% to 4.145% when water is replaced by sand. Hence sand performs well as energy storage material than water. While considering the economics of this project, the only cost incurred is that of the aluminium sheet required to make the fins. Since sand and water, which are easily available, are used as TES, and the incorporation of fins to the solar cooker is easy and cheaper, the methods adopted in this project to improve solar cooker performance can be implemented in practical cases too.

The solar cooker performance investigation can be carried out at different season so as to understand the cooking profile of various periods in the year. In this experimental study, only water is used. The experiment can be repeated for different food materials like rice, meat, dal, etc. Latent heat storage materials/phase change materials (PCMs) can also be used and the performance analysis can be done.

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