

Thermal Performance and Analysis of Evacuated Tube Based Solar Cooker with Phase Change Material

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Abstract – The objective of the present work was to evaluate the thermal performance of evacuated tube based solar cooker with transformer oil as working fluid. Acetamide is used as phase change material (PCM) to store heat and pass on to the cooking vessel during and after sunlight. Transformer oil is used to transfer heat from evacuated tube to cooking vessel. In the cooking vessel design, there are two concentric cylindrical vessel with insulation provided around the outer cylinder. The outer vessel is having PCM and inner vessel as cooking vessel. In the vessel design, copper coil is wrap around the cooking pot. In this work, the system is tested for different load conditions in the cooking vessel during receiving and releasing heat to the PCM. The results are plotted in the form of cooking vessel temperature, PCM temperature, and working fluid temperature in the experimental unit. That gives an idea that the system is capable enough for faster and evening time cooking.

Keyword: Solar Cooker, Evacuated Tube Collector, Transformer oil, Phase Change Material, Discharging

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1. INTRODUCTION

A thermal storage unit is used to compensate the gap of off sunshine time by storing the energy during the solar energy supply and meet the solar energy demand. Energy for cooking is one of the basic requirements for developing countries. In India 36% of total energy consumed is required for cooking. A lot of work has been done on direct type solar cooker like box type, concentric type and indirect solar cooker like evacuate tube collector and flat plate solar collector. The limitation of box type cooker is that the temperature above 150°C is difficult to achieve and in concentric type solar cooker tracking is the main problem. The main limitation of solar energy is its intermittent behavior and unavailability in the evening and night time. Here the requirement of PCM arises. Ramdhan [1] designed a simple flat plate solar cooker with focusing plane mirrors and sand is used as a sensible heat storage unit. The use of sand in the collector provides the consistent amount of heat to the cooker under clouds or with other reasons of non-availability of sunlight in day time. Phase change materials are the substance which takes the heat from solar system and change their phase from solid to liquid. In the absence of sun light they release their heat to the working medium

and again attain solid phase from liquid. PCM stores the heat in the form of latent heat or combination sensible and latent heat. Phase change materials have an edge over sensible heat storage material is that the latent heat has a high heat storage density as compared to sensible heat and a small temperature variation during receiving and releasing of heat. With the help of PCM the cooking can be possible even after the sunshine hours i.e. in evening and night. Domanski et al. [2] designed two concentric cylindrical vessels and the gap was with filled with PCM for evening and cloudy hours cooking. Buddhiet al [3] introduced the PCM below the cooking in a box-type cooker and made cooking possible in the absence of sun rays. Sharma et al [4] used Acetamide as a latent heat storage medium to cook food in the evening hours. The modified design of cooking vessel has two concentric cylinder with the space in between. The space is filled by PCM to improve the heat transfer rate. It was found that the evening cooking with PCM is somewhat faster as compared to day cooking. Sari et al [5] used fatty acid and expanded graphite (EG) combination as phase change material (PCM) and analyze the receiving/releasing properties of the PCM. Sebail et al [6] studied on the acetanilide and magnesium chloride hexa-

hydrate and found that acetanilide is best for indoor cooking. The working fluid has an important role in cooking temperature and cooking time. Water as working fluid in solar collector based cooker has a limitation of maximum temperature of 100°C. Heat taking fluid is the medium that carry and transfers heat from the evacuated tube to cooking vessel. Further, the heat is transferred to PCM and cooking load during charging and from PCM to cooking load during discharging of PCM. Sharma et al [8] designed an Evacuated Tube Collector System with forced circulation. To achieve better circulation of Heat Transfer Fluid a pump is used. In their experiments, Erythritol is used as a PCM and water as heat carrying fluid. It is concluded that for effective cooking at night, high melting point PCM are suitable.

In the present study, acitamide is used as PCM and transformer oil is used as functioning fluid in evacuated tube based solar cooker system. Copper coils are used to transfer heat directly to the cooking and PCM. The system is developed for fast cooking in the day as well as in night time. Pump is used to provide the better circulation of transformer oil because thermos-syphon effect does not provide much circulation in the system.

2. EXPERIMENTAL SETUP

The experimental setup was designed to examine the effect of solar cooker during sunlight and evening hours with PCM. The system includes the subsequent components viz. evacuated tubes, header, phase change material, pump, reflector, gate valve, heat carrying fluid.



Fig.1 Experimental setup

2.1 Evacuated tube collector (ETC)

Evacuated tubes are the one ended glass in glass concentric tube with vacuum between them. They are made up of strong borosilicate glass and have the heat absorbing coating over the inner tube outer surface. Due to the presence of vacuum it has very less convection and radiation heat losses. Evacuated tubes are coupled to header from open end and the closed end is resting on the frame. Connecting pipes is used to make the connection between the header and cooking vessel.

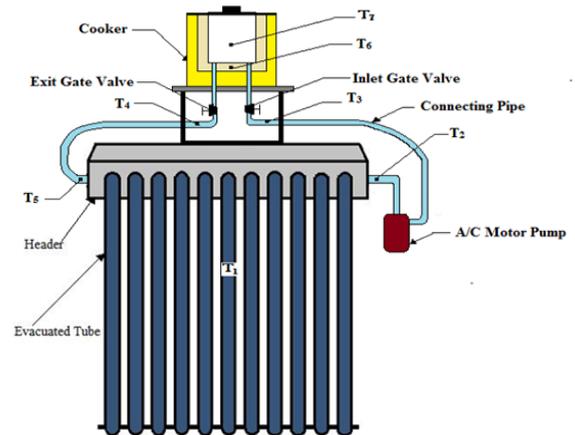


Figure 2: Schematic diagram of Experimental setup

Eleven evacuated tubes are used in the collector and placed south faced with the 30° inclination to receive the maximum amount of solar energy. After receiving heat from the tube, the hot transformer oil rise upward towards header and transported to the cooking vessel with the help of pump.

2.2 Solar cooker

Solar Cooker composed of two hollow container one inside the other as shown in figures 2 (a) and 2 (b). The outer vessel is made of aluminum and inner vessel is made up of copper. The inner container specifications are 0.11 m diameter and height 0.135 m. Outer container has 0.21 m diameter and 0.17m height. The hot transformer oil (HTF) transfer heat through copper tubes to cooking vessel and PCM. To reduce heat losses from outer vessel an insulation of 0.025m thickness is inserted between the outer vessel and the outer casing. Two PCM holes are made on top surface of the vessel one for inserting the RTD PT100 thermocouple and another for filling the PCM.

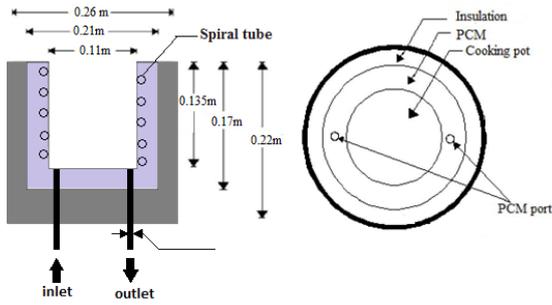


Fig. 3 Side and top view of cooker

2.3 Phase Change Material

Phase change materials are the substance which changes their phase after taking the heat from the sun. They carry the heat by changing their phase from solid to liquid in the presence of sun rays and give it back in the evening during discharging process. Acetamide used as a PCM because of its high capacity to store heat i.e.263 kJ/kg. The properties of the acetamide is given in the table 1.

Table 1: Acetamide details

Melting point	82 °C
Specific heat	1.94 kJ/kg K
Density	1159 kg/m ³

2.4 Measuring devices

RTD PT100 thermocouple measures the temperatures of heat transfer fluid, PCM temperature and food temperatures solar radiation received on a horizontal surface are measured by Pyranometer.

Table 2: Details of instruments

Device	Measured parameter	Type	Accuracy	Range
Pyranometer	Global Radiation	LP-Silicon-Pyra-04	± 5%	0-2000W/m ²
Temperature sensor	Temperature	RTD PT 100	± 0.2%	0-200°C

2.5 System Operation

Solar cooker is connected with evacuated tubes through the pipes with gate valve to control and stop the flow of heat carrying fluid in the system. The on/off valves is placed at inlet and outlet of system. The valves are kept open during the sunshine hours to transfer heat from tubes to the cooking vessel through the PCM. The system used is shown in figure 3. Heat is absorbed throughout the day in the presence of sunshine. To absorb the maximum amount of sunlight, reflector is placed below the evacuated tubes to reflect back the sunlight goes through the vacancy between the tubes. The heat

accumulated in the glass tubes is moved to cooking vessel by heat carrying fluid through connecting pipe which connects the header outlet with vessel inlet and vessel outlet with header inlet. The pump circulates the transformer oil throughout the unit. The transformer oil gives its heat to cooking pot and PCM simultaneously to raise their temperature. In evening, to find the discharging behavior of PCM with different loading condition, gate valve were kept closed.

3. PERFORMANCE PARAMETER AND UNCERTAINTY ANALYSIS

The system output is recorded in the form of temperatures achieved in the cooking vessel, PCM and heat carrying fluid.

Kline and McClintock root-mean-square method is used for the uncertainty analysis (Kline & McClintock, 1953). The error can be analyzed by the given equation

$$\Delta z = \left[\left(\frac{\partial f}{\partial y_1} \right)^2 (\Delta y_1)^2 + \left(\frac{\partial f}{\partial y_2} \right)^2 (\Delta y_2)^2 + \dots + \left(\frac{\partial f}{\partial y_n} \right)^2 (\Delta y_n)^2 \right]^{1/2} \quad (1)$$

$$\frac{\Delta z}{z} = \left[\left(\frac{\partial f}{\partial y_1} \right)^2 \left(\frac{\Delta y_1}{z} \right)^2 + \left(\frac{\partial f}{\partial y_2} \right)^2 \left(\frac{\Delta y_2}{z} \right)^2 + \dots + \left(\frac{\partial f}{\partial y_n} \right)^2 \left(\frac{\Delta y_n}{z} \right)^2 \right]^{1/2} \quad (2)$$

Where f is an independent variable function, y_1, y_2, \dots, y_n , are the function variables, $\Delta y_1, \Delta y_2, \dots, \Delta y_n$ is the error associated with variables, and $\Delta z/z$ is the relative error. The test errors of working fluid temperature, PCM and cooking vessel temperature are found to be ±3.9% and ±4.19% respectively.

4. RESULTS AND DISCUSSION

The experimental work is to carried out to examine the performance of evacuated tube solar cooker. Transformer oil is taken as a heat carrying fluid and acetamide as PCM to carry heat. The evacuated tube collector was installed at U.I.E.T., K.U.K in the north-south direction. The change in temperature and solar radiation intensity for the evacuated tube based solar cooker with time were found out for the following cases:

Case-I Variation in temperature during charging of PCM in presence of sunlight

- Change in temperature and solar radiation intensity with time with no load.
- Change in temperature and solar radiation intensity with time having load (600 ml. water).

- Change in temperature and solar radiation intensity with time having load (200g rice + 400ml. water)

Change in temperature and solar radiation intensity with time having no load

The experimentation is done the month of July in north Indian climate. The unit is made ready half an hour before the experimentation and exposed to sunlight. The evacuated tubes receive and absorb major part of the sunlight on black coating provided over the inner tube's outer surface. Figure 3 revealed that temperature of PCM increases gradually as it takes heat from the transformer oil and store it in the form of heat of phase transformation. After complete melting of PCM there is a sharp increase in its temperature. This is due to the fact that the portion of the sunlight consumed by the PCM is utilized in the temperature gain of working fluid and PCM. The solar radiation intensity is mainly responsible for increase in temperature. The solar radiation intensity has an increasing behavior up to the solar noon and decreases as the day progresses to evening. The maximum intensity lies in the range of 900-950 W/m² and the ambient temperature varies from 24.5°C to 40°C. The highest temperature in tubes lies in the range of 130-125°C at 14:30 hrs. The gate valves are closed at 17:00 hours because after that the transformer oil temperature becomes approximately equal or less than the PCM temperature.

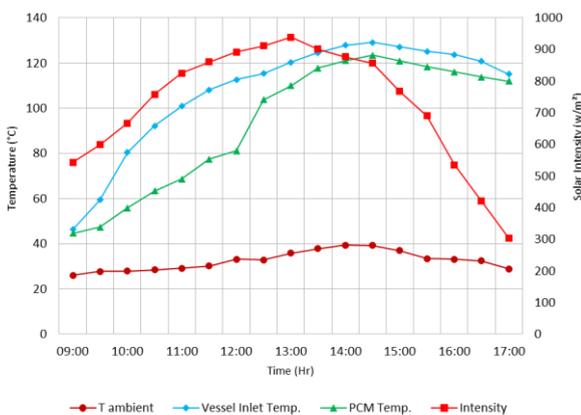


Fig.3: Change in Temperatures and Intensity with Time for no load condition.

Change in temperature and solar radiation intensity with time having cooking load (600 ml. water).

In the morning, cooking vessel was loaded at 09:00 hours. Initially, the temperature of cooking material is approximately equal to ambient temperature as presented in figure 4. With increase in solar intensity, the temperature of transformer oil rises and it gives heat to the cooking pot and PCM simultaneously. The temperature rise is not that fast as was in previous case when no cooking load is there in the vessel. The temperature of the cooking container,

PCM temperature and the transformer oil is increasing slightly faster after getting in equilibrium conditions with cooking load by achieving the same temperature. The maximum temperature achieved by the PCM is 118.1°C whereas the maximum temperature attained by the cooking load 103.2°C. The temperature difference arises due to the heat absorbed by the cooking load.

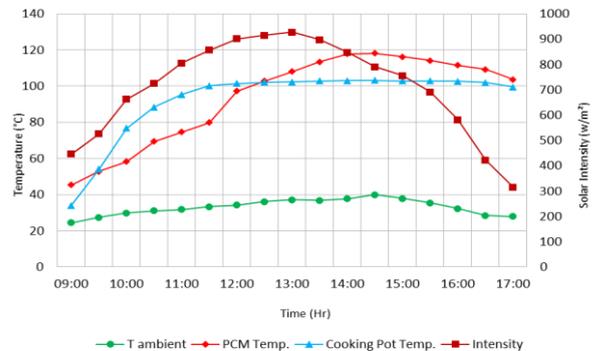


Fig. 4: Change in Temperature and Solar Intensity with Time when cooking pot loaded with 600 ml. water.

Change in temperature and solar radiation intensity with time for load 200g rice + 400ml. water.

The solar radiation intensity, cooking vessel temperature and PCM temperature have the same behavior as discussed previously. From the figure 5, the temperature of PCM and cooking vessel temperature variation shown with time and it can be clearly observed that the pace of temperature increase is less this time due to the extra cooking load. The cooking vessel temperatures were lies in the range of 95-100°C at 17:00 hours when the cooking pot with placed rice. The PCM temperature is trailing the vessel temperature in the first half of the day. This is due to the fact that the PCM is absorbing the heat initially and phase transformation takes place up to noon. Once the complete mass of the PCM gets melted then temperature rise in PCM takes place and becomes almost equal to the temperature of the vessel.

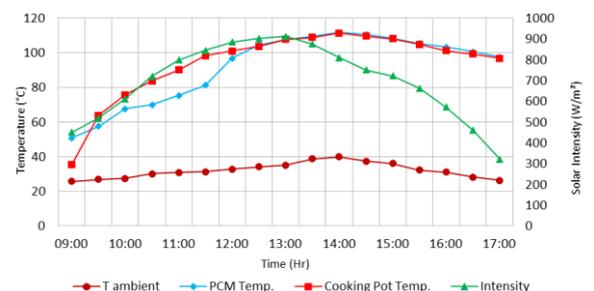


Fig. 5: Change in Temperature and Solar Intensity with Time when cooking pot loaded with 200 g rice + 400 ml. water

Case-II: Variation in temperature during Discharging in absence of sunlight

- Cooking Pot with no load
- Cooking Pot Loaded with 600 ml. Water.
- Cooking Pot Loaded with 200g Rice+400 ml. Water.

From the study of above cases we found that the temperature of transformer oil at 17:00hrs become approximately equal or less than the temperature of PCM. At that time, it start taking heat from the PCM. That's why for maintaining the sufficient temperature for evening cooking, the circulation is stopped by keeping valve closed. Discharging behavior of Phase Change Material was evaluated different loading conditions which are given below.

i. Cooking Pot with No Load

As there was no cooking load in the cooking pot, so there was very less heat loss from the PCM. At that time only air was in the cooking pot that draws very small temperature from the PCM and temperature rise takes place due to its low specific heat. It is clear from figure 6 there is very little difference in the temperatures of PCM and air in the vessel with time. The decrease in temperature of PCM is very less due to the absence of cooking load. The temperature of PCM at 20:00 hours is 89.7°C which is sufficient for cooking.

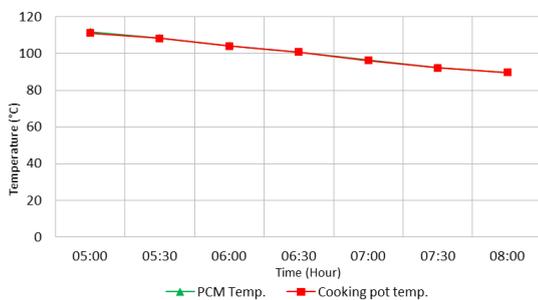


Fig.6 : Change in Temperature during discharging of PCM when no load condition.

ii. Cooking Pot with 600 ml. Water.

In the off sunshine hours, the cooking vessel is loaded at 17:00hrs. In the beginning, cooking container temperature is nearly ambient temperature. The PCM starts releasing the stored heat to the cooking container and further to water inside the vessel.

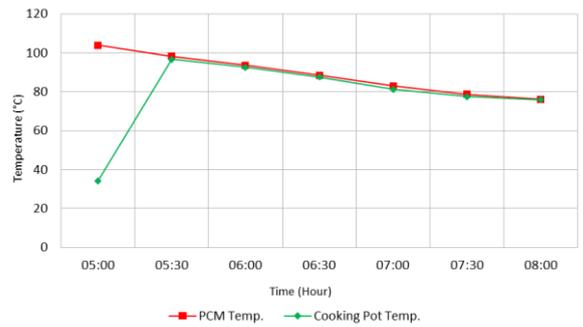


Fig. 7 : Change in Temperature during discharging of PCM when cooking pot has 600 ml. water.

Maximum temperature attained by the water in cooking vessel is 96.7°C at 17:30hr. It is clearly observed from figure 7, the temperature of PCM at 20:00hour is 75.8°C which is less as comparison to the 1st case when there was no cooking load. But the temperature decrease is slightly faster and still has the sufficient heat content in the late evening hours that can be utilised for cooking purpose in the late evening hours.

iii. Cooking Pot with 200 g Rice+400 ml. Water

In the evening, both gate valves were closed at 17:00hrs and rice along with water is placed in the cooker at that time. In the beginning, the temperature of cooking load is approximately equal to ambient temperature and start increasing with time by receiving heat from the PCM. The rice are well cooked at 19:00hrs and maximum temperature of rice is 89.6°C at 17:30hr. It could use the stored heat of PCM for further cooking also. The decrease of PCM temperature is fastest in this case as comparison to the above two cases because the quantity of load is maximum this time.

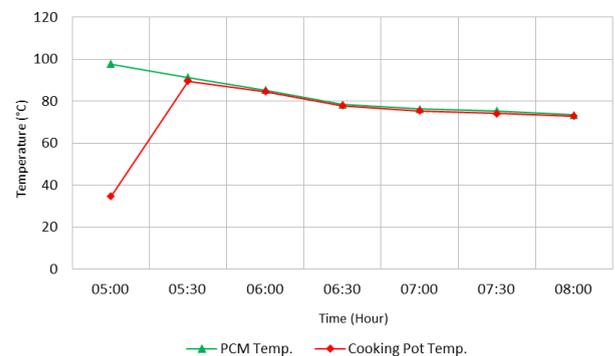


Fig. 8 : Change in Temperature during discharging of PCM when cooking pot was loaded with 200g rice+400 ml. water

It is observed from the above cases, the condition of cooking pot load conditions that the evening temperature of PCM was low in the second case. This is due to the load in the cooking pot takes the

heat to the PCM. The process of losing heat by the PCM is very slow due to its property to store the heat for long times when it start solidify.

5. CONCLUSIONS

The system is suitable for day time and evening time cooking. The conclusion arises from study are:

1. With transformer oil as heat carrying fluid, temperature of PCM at 17:00 hour varies from 110 to 115°C when the cooking pot was empty and 100-105°C when vessel is having water.
2. The successful cooking is carried out by forced circulation of transformer oil and showed the cooker can be used in day time and as well as in evening time.
3. The result shows that the system can be very efficient in cooking with transformer oil as working fluid in day time and PCM storage in evening cooking.

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