Performance Evaluation of Solar Box Cooker with Phase Change Materials

Md. Riyaz Anwer, Naiem Akhtar, and Md. Reyaz Arif

Abstract Solar cooker uses solar radiation to cook the food. These are good alternative for cooking as it uses solar radiation which is free and does not cause any environmental pollution. Normally, the box type cooker can cook the food in day time only. On the other hand, the solar box cooker that utilises phase change material (PCM) is able to prepare food both during the day and in the evening. In this study, simulations of box solar cookers with three distinct PCMs have been conducted to compare the performance of the cooker with different PCMs. The 3D model of the box solar cooker has been prepared, grid independence test has been done and the simulations have been performed using ANSYS FLUENT package. In the simulation the maximum temperature achieved by the absorber plate during the charging mode and time to achieve this maximum temperature have been evaluated. Using the maximum temperature achieved the other thermal performance parameters have been calculated. Through the simulation it is found that maximum temperature of the absorber plate is achieved with PCM Erythritol. The drop in temperature of the absorber plate during the discharging mode is more with PCM Quinone. Also, during the discharging mode, the energy provided by Acetanilide and Quinone is less than the energy required for evening cooking, so Acetanilide and Quinone do not support evening cooking. However, the analysis shows that the evening cooking is possible by using Erythritol as the phase change material. All the performance parameters are high with Erythritol as compared to Acetanilide and Quinone. Thus, the performance of the cooker is better with Erythritol.

Keywords Solar box cooker · Phase change material · Simulation · Thermal performance · ANSYS FLUENT

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1 Introduction

Solar energy is one of the most significant renewable energy sources. It is available in a limitless quantity worldwide. Due to the decline of nonrenewable energy sources, the significance of solar energy increases. Solar energy is a pollution free environment friendly energy source. Lighting, cooking and heating are the major energy requirements of domestic consumers. A solar cooker is a device that uses the energy of the sun to cook food. Sunlight warms the cooking pot which is used for cooking food. Solar cookers are classified into two types; Box solar cooker and Concentrating type solar cooker. The box solar cooker is made up of an insulated box, metallic cooking pots inside the box, an absorber tray, a double glass top on the cooking tray, and a reflecting mirror mounted on the box's edge. Incoming solar rays strike the glass cover, pass through it, and reach the cooking tray. The heat is absorbed by cooking tray and transfers this heat to cooking pots to facilitate cooking. The reflector mirror reflects the solar radiation falling on it into solar cooker. In most cases, up to four cooking pots are placed within the box type solar cooker. Depending upon the availability of solar radiation the solar box cooker takes 2–3 h to cook vegetables, rice, dals, etc. [1]. The solar box cooker can typically only make food during the day. Food cannot be prepared by it in the evening or at night. If we somehow store solar energy during day time and use that energy later, then the cooking in the evening is possible. The three techniques of solar energy storage are thermochemical, sensible heat, and latent heat [2]. Latent heat storage is a more efficient way of storing thermal energy for the solar box cooker. The materials that are capable of storing latent heat are referred to as phase change materials (PCMs). Different PCM materials have been identified which can be used in solar box cooker. Material for storing solar energy is generally placed below the cooking tray in the solar cooker. The amount of PCM used depends on the energy required to cook food.

The study of PCM was started in the 1940s, but the usage of PCM in the solar cooker was started during 1990s. A simple solar box cooker with focusing plane mirrors was constructed by Ramadan et al. [3]. They employed locally available sand as an energy storage medium around the cooking pot. The cooking time attained with using sand as an energy storage medium was six hours per day (3 h of indoor cooking and 3 h of outdoor cooking). Buddhi and Sahoo [4] had developed an energy-storing solar box cooker. They used steric acid as energy storage material. The PCM was kept below the absorber plate which has a depth of 8 cm. The cooking capacity of the cooker is designed for 0.75 kg. Evening cooking is quite slow as the energy stored by steric acid is low. In order to cook evening meals, Sharma et al. [5] have designed a solar cooker that stores energy during the day. They have used acetamide as PCM. The energy storage unit is in cylindrical shape which surrounds the cooking pot. They have used 2 kg of PCM and the result shows that second meal can be cooked if we put the meal in the cooker before 3:30 pm. Vigneswaran et al. [6] have developed a simple solar box cooker with an energy storage unit. The energy storage unit of PCM was made in concentric cylinder shape. Cylinder interspace was filled with oxalic acid dihydrate. It has a melting point of 101 °C. The amount of PCM was calculated according to the energy required for cooking 0.5 kg rice. They have used single and double reflector and compared the performance for both reflectors. The overall utilization efficiency for the double reflector (25.74%) is more as compared to the single reflector (15.74%). Sharma and Rai [7] have performed the experiment on the two models (model-1 and model-2) of the box solar cooker. They used Magnesium nitrate hexahydrate as PCM. The PCM was also placed below the absorber plate. Both the maximum temperature of the cooking pot as well as the overall utilization efficiency of the model-2 was found to be higher which has finned attached at base. Sharma et al. [8] had designed an evacuated tube collector that stores energy. Two hollow, concentric cylinders were used to create the PCM storage component. These hollow cylinders measured 30.0 cm in diameter on the inside and 44.0 cm on the outside. The height of the cylinder is 42.0 cm and 45 kg of Erythritol was used to fill the space between cylinders. This cooker can cook two foods one in daytime and one in evening. However, it requires huge quantity of PCM. Ali and Akhtar [9] have designed and analysed the performance of an energy-storing box cooker. They have used Erythritol having a melting point of 118 °C for storing solar energy. They have also modified the design. Generally, the opening is provided on the top side for keeping the cooking pot, but they have fixed the top glass cover. A rectangular window is provided on the back side for opening and for keeping the cooking pot. By fixing the top glass cover the energy losses from the top decreases.

From the literature it has been discovered that solar cookers operate better when PCM has a greater melting point. All the performance analysis of the box type solar cooker has been done experimentally and simulation work is not reported in the literature. Additionally, there is no information on how changing the PCM quantity may affect the cooker's performance. Therefore, the main objective of the present work is to simulate the performance of the box type solar cooker by selecting different PCMs and also to study the effect of varying the amount of PCM on the performance of cooker.

The performance simulation has been carried out using the ANSYS-FLUENT academic package. First, the 3D model of the box type solar cooker was made. Then that model was imported into ANSYS FLUENT and simulation was performed after mesh validation. The performance of the cooker with three distinct PCMs, Erythritol, Acetanilide and Quinone, were compared. The effect of changing the PCM quantity from 5 to 4 kg on the performance of the solar cooker is also studied. The performance of the solar cooker with these three PCMs on the basis of maximum temperature achieved by the absorber plate, time taken to reach maximum temperature, charging time of PCM, PCM storage efficiency and temperature of the absorber plate during the discharging mode has been compared.

2 Description of Proposed Solar Box Cooker

Generally, the solar cooker available in the market is used to cook food only during day time. It is not able to cook food in the evening since it lacks an energy storage unit. These cookers have opening in the top for keeping the cooking pot so it causes lots of heat losses from the top. The proposed PCM solar cooker has aperture area of 0.5 m^2. It has a double glass cover of length 71.5 cm and width 70 cm. The cooking tray as well as the PCM tray is made of GI sheet. The front side height of the absorber plate is 10 cm and the back side height is 22 cm. The height of the PCM tray was 9 cm and it was placed below the absorber plate. The PCM tray was filled with PCM. The outer box (casing) is composed of wood. The heights of the front and back sides that face the sun are 27 and 41 cm. The inner side of the wooden box is filled with insulation at the bottom and sides. The shape of the cooking pots is cylindrical with a flat base having a diameter of 18.0 cm and a height of 7.5 cm. A rectangular window of width 26.0 cm and height 13.0 cm is provided behind the cooker for placing or removing the cooking pots. A reflector mirror is attached to the top cover. The space between the wooden cover and reflector mirror is filed with insulation to minimize the top heat loss. The absorber plate measures 59 cm in length, 10 cm in front height, 22 cm in back height, 65 cm in front width, and 57 cm in back width. The PCM tray has a length of 64 cm. Considering the dimensions of the above PCM box solar cooker, a 3D model has been developed as shown in Fig. 1.

The solar cooker receives solar energy that reaches the absorber plate while it is in the charging mode. Additionally, the radiation that is reflected by the reflector mirror is received by the absorber plate. As a result of the radiation being absorbed on the absorber plate, the temperature within the cooker ultimately rises. At the time of no-load condition some part of energy received on the absorber plate is used to increase the temperature of the cooker and some energy is transferred to PCM. During loading conditions, a portion of the energy is also used to raise the load's temperature. During the hours when solar radiation is unavailable and the lid of the cooker is closed. Throughout this time, the cooker can prepare food using energy stored in the PCM during the charging time. During evening cooking, some

Fig. 1 3D model of box cooker

of the energy stored in the PCM is used to cook the meal, while some is lost to the environment.

3 Modelling of Solar Box Cooker

The solar box cooker equipped with PCM storage unit is shown in Fig. 1. The energy storage material was placed in the PCM tray, which is placed below absorber plate. During day time the solar energy is absorbed by the absorber plate. Some portion of the absorbed energy is transferred to PCM, and that energy is stored by PCM. In the late evening, PCM uses its stored energy to cook the food.

3.1 Energy Balance for PCM Cooker

The performance of the box type solar cooker with energy storage is defined in terms of charging- discharging time, temperature attained by load, time to attain maximum temperature, storage efficiency, and PCM utilization efficiency. The charging time is the amount of time necessary to completely melt PCM. Discharging time is the amount of time it takes for PCM to solidify completely.

Charging time of PCM:

$$\tau_{\mathrm{ch}} = \tau_{\mathrm{sh}} + \tau_m \tag{1}$$

Discharging time of PCM:

$$\tau_{\mathrm{dis}} = \tau_{\mathrm{sc}} + \tau_s \tag{2}$$

where

τ_{ch} Total charging time of PCM
τ_{sh} Sensible heating time of PCM with initial temperature equal to ambient
τ_m Melting time of PCM
τ_{dis} Total discharging time of PCM
τ_{sc} Time of sensible cooling of PCM
τ_s Solidification time of PCM

The energy stored in the PCM is evaluated by

$$Q_{\mathrm{stored}} = \int_{T_{\mathrm{pi}}}^{T_{\mathrm{pm}}} mC_{\mathrm{ps}} dT + mL + \int_{\mathrm{pm}}^{T_{\mathrm{pf}}} mC_{\mathrm{pl}} dT \tag{3}$$

Energy supplied to the cooker:

$$Q_{\text{in}} = I_{\text{av}} A_p \eta_o \tau_{\text{ch}} \tag{4}$$

where,

m	Mass of PCM
C_{ps}	Specific heat capacity of PCM in solid state
L	Latent heat capacity of PCM
C_{pi}	Specific heat of molten PCM
T_{pi}	Initial PCM temperature
T_{pm}	Melting temperature of PCM
T_{pf}	Maximum temperature of PCM during charging
A_P	Solar cooker aperture area
η_o	Optical efficiency of double glass cover
I_{av}	Average intensity of solar radiation

The storage efficiency of solar cooker is given by:

$$\eta_{\text{stored}} = \frac{Q_{\text{stored}}}{Q_{\text{in}}} = \frac{\int_{T_{\text{Pi}}}^{T_{\text{Pm}}} mC_{\text{ps}}dT + mL + \int_{T_{\text{Pm}}}^{T_{\text{pf}}} mC_{\text{pl}}dT}{I_{\text{av}} A_p \eta_o \tau_{\text{ch}}} \tag{5}$$

The PCM utilization efficiency is given by:

$$\eta_{\text{pu}} = \frac{Q_u}{Q_{\text{storage}}} = \frac{m_f C_f (T_{\text{maxf}} - T_{\text{fi}})}{\int_{T_{\text{Pi}}}^{T_{\text{Pm}}} mC_{\text{ps}}dT + mL + \int_{T_{\text{Pm}}}^{T_{\text{pf}}} mC_{\text{pl}}dT} \tag{6}$$

m_f	Mass of cooking food
C_f	Specific heat capacity of cooking fluid
T_{maxf}	Maximum cooking fluid temperature
T_{fi}	Initial temperature of cooking fluid

4 Numerical Aspects

After importing geometry and naming the component name the next step is to generate the mesh. High quality unconstructed mesh was generated using ANSYS Meshing. First, very fine meshing of the solar cooker was generated. After that element size of the mesh was increased. As very fine mesh will give more accurate result but it will take more computing time so mesh validation or grid size independency test was carried out for obtaining a mesh size which will give an optimum result in an optimum computing time. Figure 2 depicts the mesh of a solar box cooker with an element size of 18 mm.

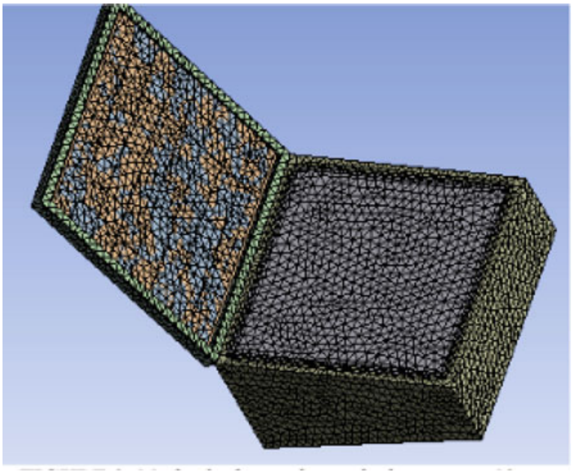

Fig. 2 Mesh of solar cooker with element size 18 mm

Table 1 Grid independency test

Grid size (mm)	No of elements	Temperature of absorber plate (°C)
10	227,470	129.07
14	128,509	128.68
18	69,162	128.32

4.1 Grid Independence Test

Grid independency test is conducted to obtain a suitable mesh size for the simulation. For grid independency test the absorber plate temperature at different grid sizes is calculated. Table 1 shows the result of the grid independence test.

From Table 1 it is concluded that the mesh with element number 128,509 (grid size 14 mm) is optimum for simulation of the cooker.

4.2 Boundary Conditions

The assigning of the material to each component of the solar cooker is done by the inserting material with their properties. In the input solar loading on the cooker has been applied by inserting the latitude and longitude of the location, date and month and starting time of the solar loading. For the present case the location is Aligarh with latitude and longitude 27.8974° N and 78.0880° E, respectively. The selected date is 10th June with starting time 9:30 am. The data available for the solar radiation on 10th June at Aligarh has been considered which varies from 723.74 W/m^2 at 9:30 a.m. to 835.5 W/m^2 at 1:30 p.m. The overall heat loss factor for the charging mode is calculated for different temperatures using Akhtar and Mullick correlation [9] and then an average heat loss factor was inserted. The same boundary conditions were applied for each PCM material. In the output absorber plate temperature with time and load temperature with time are obtained.

4.3 Validation of Numerical Model

The selected model is validated by Abid et al. [9] with the experimental results obtained on the same model with Erythritol as the PCM material having quantity of 6 kg. The maximum temperature obtained with 6 kg of Erythritol with simulation on 11 march is 116.1 °C while through the experimental result the maximum temperature of the absorber plate is 115.7 °C. The variation of temperature of the absorber plate by experiment and simulation is shown in Fig. 3.

5 Results and Discussion

The boundary conditions, as discussed above were applied and the simulation was initialized. After initialization calculation was run with a suitable time step. The initial temperature for the absorber plate as well as the load was taken as 27 °C. The change in the absorber plate temperature and load temperature with time for the measured

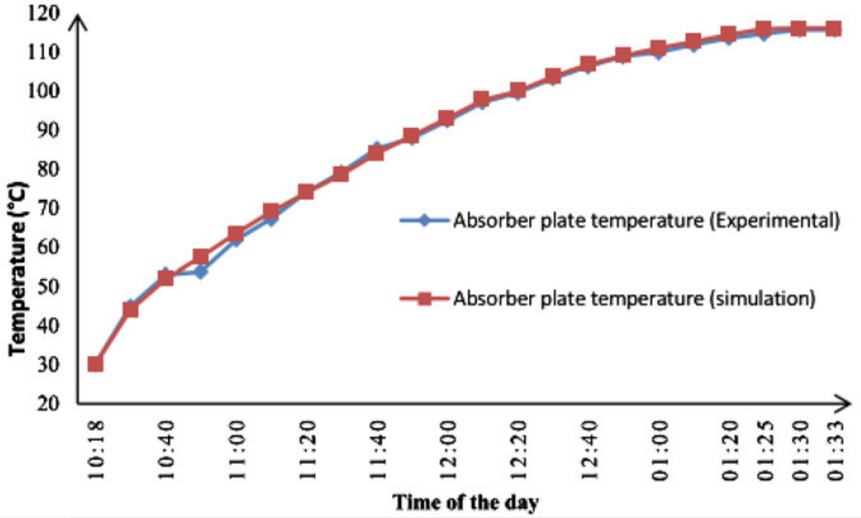

Fig. 3 Absorber plate temperature with the time of day with experiment and simulation

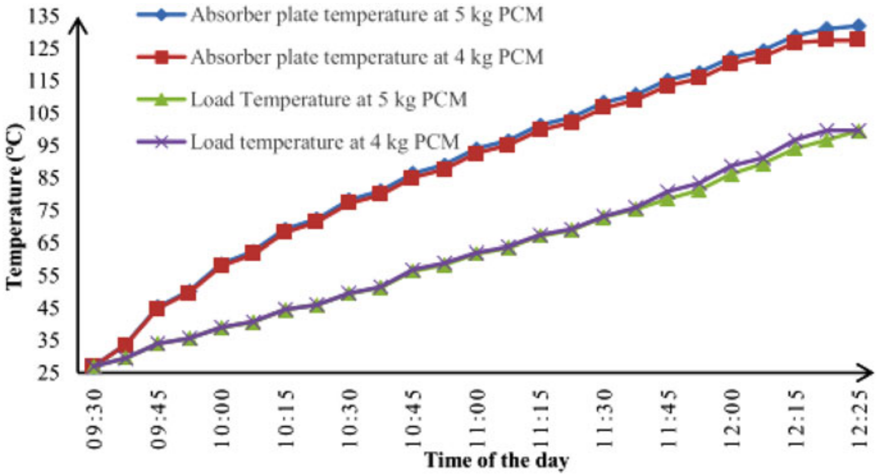

Fig. 4 Absorber plate temperature and load temperature with time of the day for Erythritol

values of solar radiation available on 10th June 2022 at Aligarh, considering 4 and 5 kg of Erythritol as PCM is shown in Fig. 4.

Figure 4 shows that the temperature of the absorber plate and the temperature of the load both rise with the passing of the day and reach their highest values around noon. For 5 kg of Erythritol in 2 h and 55 min, the absorber plate can reach a maximum temperature of 132 °C, and for 4 kg in 2 h and 50 min, it can reach a maximum temperature of 127.51 °C.

The change in the temperature of the absorber plate and load with time of the day for the measured values of solar radiation available on 10th June 2022 at Aligarh, considering 4 and 5 kg of Acetanilide as PCM is shown in Fig. 5.

The maximum temperature achieved by the absorber plate is 126.6 °C with 5 kg of Acetanilide in 3-h 20 min and 121.9 °C with 4 kg of Acetanilide in 3-h 19 min as shown in Fig. 5.

The change in absorber plate temperature and load temperature with time of the day for the measured values of solar radiation available on 10th June 2022 at Aligarh, considering 4 and 5 kg of Quinone as PCM is shown in Fig. 6.

Figure 6 shows that the maximum temperature achieved by the absorber plate is 122.91 °C in 3-h 19 min with 5 kg of Quinone and 119.5 °C in 3-h 15 min for 4 kg of Quinone.

Figure 7 illustrates how the temperature of the absorber plate varies during the day for each of the three PCMs. The greatest temperature of the absorber plate is achieved in the case of Erythritol rather than Acetanilide for the same boundary condition and for the same quantity of PCM that is employed, whereas the minimum temperature is achieved with Quinone for the same boundary condition. The absorber plate may reach a maximum temperature of 132 °C with Erythritol, 126.6 °C with Acetanilide, and 122.9 °C with Quinone.

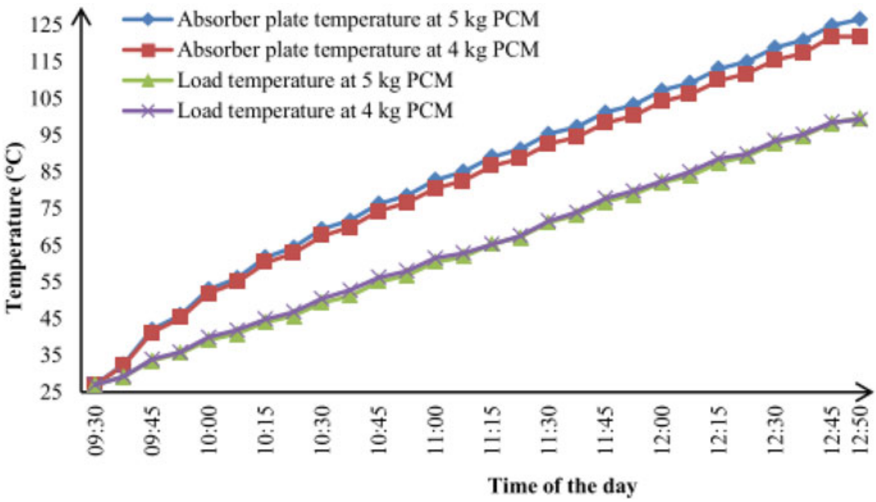

Fig. 5 Absorber plate temperature and load temperature with time of the day for Acetanilide

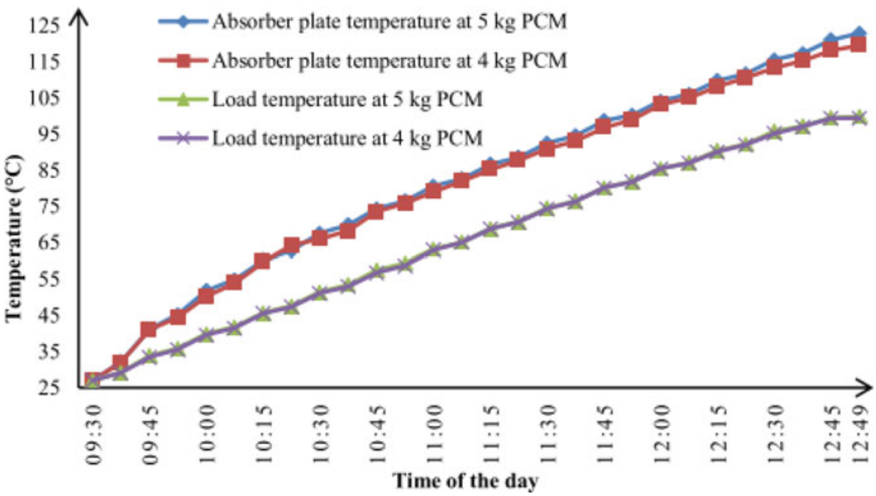

Fig. 6 Absorber plate temperature and load temperature with time of day for Quinone

During evening cooking, the energy stored by the PCM material is the only energy source for cooking. Some amount of energy stored by PCM is used by load for cooking and some is lost to the environment; as a result the temperature of absorber plate continuously decreases. The variation of absorber plate temperature during the discharging mode is shown in Fig. 8.

During the hours when the sun is not shining, the only source of energy available to cook the meal is the energy that has been stored in the PCM. A part of stored energy

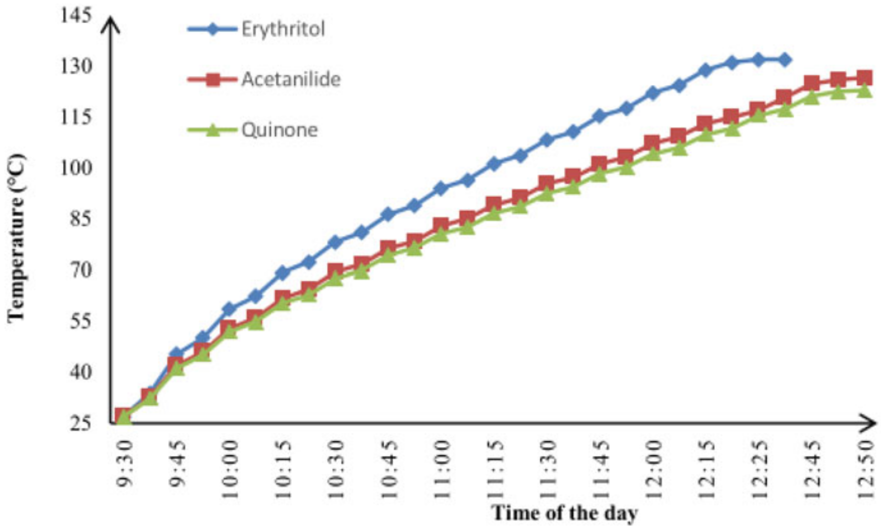

Fig. 7 Absorber plate temperature with time of day for all three PCM of quantity 5 kg

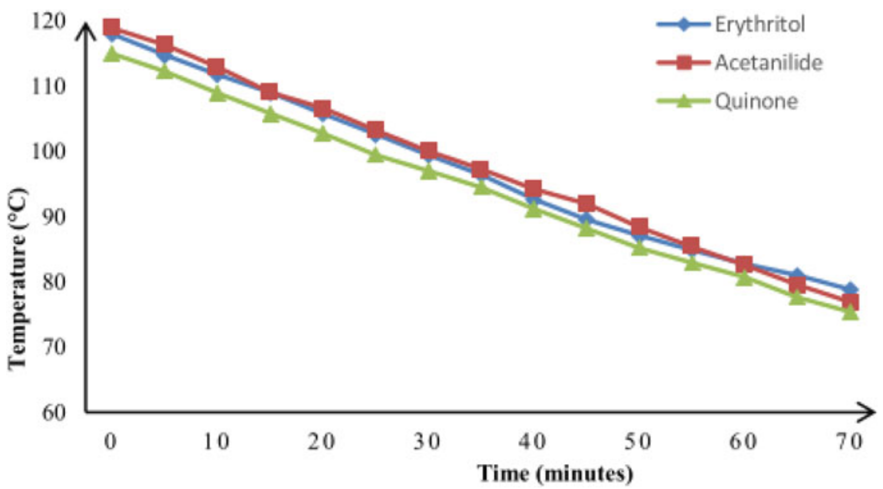

Fig. 8 Absorber plate temperature in discharging mode for all three PCM of quantity 5 kg

is used to cook food and the residual energy is lost to the environment. Hence the temperature of the absorber plate decreases. It has been found that during this period of 70 min duration with 5 kg of PCM the absorber plate temperature decreases from 118 to 78.82 °C for Erythritol, 118.9 to 76.9 °C for Acetanilide and 115 to 75.4 °C for Quinone. With the decrease in the amount of PCM the temperature of the absorber plate during the discharging mode further decreases as with 4 kg of PCM where the decrease in the absorber plate temperature is 118–66.1 °C for Erythritol, 118.9–65.5 °C for Acetanilide and 115–64 °C for Quinone. Hence, during the discharging mode the decrease in absorber plate temperature is minimum for Erythritol. So, the absorber plate with PCM Erythritol keeps the temperature high for a long duration as compared to the other two.

5.1 Thermal Performance with Different Material

The thermal performance of the Box type solar cooker with energy storage is evaluated based on the charging time (pre-charging time plus melting time), the amount of energy stored by PCM, the energy storage efficiency of PCM, the cooling time, and the solidification time. Pre-charging time is the time required to reach the melting point temperature of PCM from the ambient temperature and the melting time is the complete melting of PCM at its melting point temperature. Energy storage efficiency of PCM is the ratio of energy stored by PCM to the total incident radiation falling on the Box type solar cooker. Cooling time is the amount of time required to cool the PCM from its highest temperature to its melting point temperature. The amount of time needed for the PCM to completely solidify at its melting point is known as the solidification time. Thermal performance of each PCM has been investigated and compared with each other to obtain which of these three gives better performance. Thermal performance of box solar cooker with different PCMs is shown in Table 2.

6 Conclusions

According to the findings of the simulation, the absorber Plate can reach its maximum temperature of 132 °C when treated with PCM Erythritol of quantity 5 kg for a period of 2 h and 55 min. Energy stored by 5 kg of Erythritol is significantly greater than that of PCM Acetanilide and Quinone. Total charging time for PCM Quinone is less than other two. During the discharging mode the absorber plate of PCM Erythritol drops to 78.82 °C from 118 °C within a time duration of 70 min while the temperature drops to lower values with the other two PCMs. The energy needed to heat a 4 kg load with Acetanilide and Quinone is significantly more than the energy stored by them. As a result, Acetanilide and Quinone cannot be used to prepare meals in the evening. The performance of a solar cooker with 5 kg PCM is much superior to that of a solar cooker with 4 kg PCM. Overall, the performance of a cooker containing the PCM Erythritol is superior to that of a cooker containing the PCM Acetanilide and Quinone.

Table 2 Thermal performance of solar cooker with different PCMs

	Erythritol (5 kg)	Acetanilide (5 kg)	Quinone (5 kg)	Erythritol (4 kg)	Acetanilide (4 kg)	Quinone (4 kg)
Maximum temperature of absorber plate (°C)	132	126.6	122.9	127.51	121.9	119.5
Time taken to reach maximum temperature	2-h 55 min	3-h 20 min	3-h 19 min	2-h 50 min	3-h 19 min	3-h 15 min
Pre-charging time (min)	61	92	63	48	84	50
Melting time	6-h 29 min	4-h 28 min	2-h 53 min	5-h 11 min	3-h 35 min	2-h 18 min
Charging time	7-h 30 min	6-h	3-h 56 min	5-h 59 min	4-h 59 min	3-h 08 min
Energy absorbed by PCM (kJ)	2499.4	1971.7	1612.55	1999.56	1577.36	1290.04
PCM storage efficiency in percentage	38.65	37.6	47.11	38.18	36.2	46.8
Cooling time (min)	47	23	24	18	8	12
Solidification time	5-h 13 min	3-h 24 min	2-h 39 min	4-h 10 min	2-h 44 min	2-h 07 min

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