Design and Performance Evaluation of Box-Type Solar Cooker with Energy Storage

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1 Introduction

Amongst the renewable energy technologies, solar energy is recognized as one of the most potential choices since it is free and provides environmentally clean energy. The major energy requirements of domestic consumers include lighting, cooking, and heating. Among these, cooking accounts for substantial amount of primary energy demand. There is an increasing consideration over the renewable energy options to meet the cooking requirements in developing countries. Solar cooker is a cost-effective device for harnessing solar energy. It is environment-friendly and helps in reducing deforestation and air pollution. The box-type cooker designs have been studied and modified since the 1980s and different designs and their characteristics are investigated. The method for performance evaluation of the box-type solar cooker was first proposed by Mullick et al. [1]. The main problem associated with simple box-type solar cooking system is the impossibility of cooking food during the late hours of the day. This problem can be solved by storing solar energy during the sunshine period and utilized later. There are three methods for storing heat energy, namely; sensible, latent and thermo-chemical [2]. Sensible heat storage method is used for some of the solar energy applications. However, the main limitation of drawback of a sensible heat storage unit is the large volume requirements. The latent heat storage system is a better way of storing thermal energy. The latent heat storage materials are generally referred to as phase change materials (PCMs). Although the study of PCM was initiated by Telkes and Raymond [3] in the 1940s, but, the phase change materials received large attention only after the energy crisis of the late 1970s

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and early 1980s. Better design of Box-type solar cooker with phase change material for storage of *t* energy will be more appropriate for cooking the food during late hours of the day.

There has been a significant attention in the development of solar cookers with phase change materials. Ramadan et al. [4] constructed a simple flat-plate box solar cooker with focusing plane mirrors and using locally available sand in Tanta University to store energy. In this design, a jacket of sand (0.5 cm thick) placed around the cooking pot which improved the cooker performance. Six hours per day (3 h/day outdoor and 3 h/day indoor) of cooking time has been reported. Overall energy conversion efficiency up to 28.4% had been obtained. Domanski et al. [5] designed a multi-step inner reflector box-type solar cooker. In this design, they replaced the absorber plate with reflective surfaces; these surfaces were tilted at different angles around the cooking vessel holder. The cooking vessel was made with two concentric cylinders of aluminium. The outer wall has a diameter of 18 cm and height of 12 cm, and the inner cylinder has a diameter of 14 cm and height of 10 cm. The tests were conducted by filling the gap between the vessels/cylinder with 1.1 kg stearic acid and 2 kg magnesium nitrate hexahydrate, respectively. They reported that charging time and storage efficiency strongly depend on solar intensity and the melting point of PCM. The overall utilization efficiency was reported about 3–4 times higher than the steam and heat-pipe solar cooker. Buddhi and Sahoo [6] used stearic acid as a storage medium for a box-type solar cooker. They filled the stearic acid below the absorber plate of the cooker. The absorber plate has 28 $\times$ 28 cm dimension at the bottom, 40 $\times$ 40 cm at the top and vertical depth in the absorber plate is 8 cm, where the cooking pot is placed for cooking. They designed this cooker for a cooking capacity of 0.75 kg. They reported that after solar radiation cut-off the temperature of PCM and absorber plate decreases at a faster rate in the first two hours and thereafter at a slower rate. The rate of heat transfer from the PCM to the load during the discharging mode of the PCM is slow, and more time is required for cooking an evening meal. Vigneswaran et al. [7], Sharma et al. [8] and Buddhi et al. [9] used simple box-type solar cookers with PCM storage unit made of two concentric cylinders and the space between concentric cylinders filled with PCM. Vigneswaran et al. [7] used 2.9 kg of oxalic acid dehydrate (melting point 101 °C), for energy storage by considering the energy required to cook 0.5 kg of rice. The overall utilization efficiency was reported to be 15.74% with a single reflector for 0.4 kg of water load and this efficiency increases to 25.47% with four reflectors for 0.8 kg of water load. Sharma et al. [8] used 2.0 kg of acetamide (melting point 82 °C) and reported that the second meal of food could be cooked if it is loaded before 15:30 h. Buddhi et al. [9] used 4 kg of acetanilide as PCM and reported that 0.5 kg food was cooked if loaded at 19:00 h. Mallikarjuna Reddy et al. [10] designed two solar cookers with circular trays, one with energy storage and one without energy storage system. The diameters of trays were 68 cm with height of 9.8 cm and the wax was filled in the gap of 1.0 cm. In energy storage system the space between the two trays filled with paraffin wax (melting temperature 55 °C) with fin arrangement to increase heat transfers from top absorber plate to bottom wax surface. They reported that cookers with energy storage are more useful than without energy storage system and has higher temperature during evening time.

Sharma et al. [11] designed and tested an evacuated tube solar collector and PCM storage unit consisting of two evacuated tube solar collectors. The PCM storage unit fabricated by means of two hollow concentric cylinders of aluminium. The inner and outer diameters are 30.4 cm and 44.1 cm, respectively, with height of 42 cm. The space between both the cylinders is filled with 45 kg Erythritol. This system was able to cook two meals in a single day, noon meal and evening meal. However, the quantity of the phase change material (Erythritol) used was huge.

From the literature, it is clear that the thermal energy stored in the box-type solar cooker with the PCM is kept either in the space between two concentric cylinders or below the absorber plate with some deepness in absorber plate for cooking pot. Also, the performance of the Box-type solar cooker increases with the use of materials having higher melting temperature (specifically above 100 °C). In the present work, the design of the existing Box-type solar cooker has been modified. The Box-type solar cooker available in the market has the opening on the top side. The glass frame at the top is opened to keep the cooking pot on the absorber plate. It causes heat loss from the top. Moreover, when the food is cooked in the pot the absorber plate temperature is above 100 °C and inside air temperature is also high which can be harmful to human skin of the operator. It may become more dangerous if some amount of water spill out on the absorber plate during cooking.

In the present design, the top glass cover frame is fixed and a window is provided on the backside of the cooker for keeping the cooking pots on the absorber plate, which prevents the energy loss from the top. Moreover, energy storage using Erythritol (melting temperature 118 °C) is provided below the absorber plate for cooking during evening time.

2 Proposed Design

The box-type solar cookers available in the market generally have 0.25 m^2 aperture area, generally designed according to the BIS STANDARD, part II of "Solar cooker-Box-type-Specification *Second Revision* of IS 13429" [12]. These cookers are used for cooking one meal during the day and don't have any energy storage material. Also, the available cookers in the market have the opening for keeping/taking out the cooking pots is at the top. It causes heat loss from the top. Moreover, when the food is cooked in the pot the absorber plate temperature is above 100 °C and inside air temperature is also high which can be harmful to human skin of the operator. It may become more dangerous if some amount of water spill out on the absorber plate during cooking.

In the present design, the top glass cover has been fixed and a window is provided at the backside of the cooker for keeping the cooking pots on the absorber plate, which prevents the energy loss from the top. Apart from this modification, the second aim is to store thermal energy by using phase change material and use this energy during the late hour of the day. The selection of the material depends on the melting temperature, the latent heat of fusion, density and other properties, for example, toxicity and cost of the PCM. For the purpose of cooking using a box-type solar cooker, the PCM should have melting point above 100 °C. The phase change material; commercial-grade Erythritol ($C_4H_{10}O_4$) which is easily available in the Indian market at low cost (Rs. 325/kg) has been selected. The feasibility of charging of PCM has been checked and the quantity of PCM required is estimated. The calculation of heat losses during the charging and discharging period has been carried out.

2.1 Description of the Proposed Box-Type Solar Cooker

The PCM-cooker is designed for 0.5 m^2 aperture area. It consists of an absorber plate and a PCM-tray, constructed of GI-sheet of 0.5 mm thickness. The absorber plate and PCM-tray have an isosceles trapezoidal base. The height of the frontside of the cooker, facing the sun, is kept low, whereas the height of the backside is kept high so that the size of the opening is sufficient for keeping/taking out the pots. The frontside and backside heights of the absorber plate are 10 cm and 22 cm, respectively, and PCM-tray has 8.5 cm height. The PCM-tray is filled with a known quantity of heat storage material, employed under the absorber plate. The sides and bottom of the trays are encased in a box made of wood. The outer dimensions (length and width) of the base of the wooden box are 81.5 cm and 80.7 cm, respectively. The heights of the frontside (facing the sun) and backside are 27 cm and 41 cm, respectively. The space provided between the PCM-tray and encasing is filled with glass wool to provide thermal insulation. A double glass cover unit of glazing having length and width of 71.5 cm and 70 cm, respectively; is fitted in the wooden box at the top. A rectangular window/opening of dimensions 26 cm and 13 cm width and height, respectively, is provided at the backside of the cooker for keeping/taking out the cooking pots. A flat reflector mirror is encased in a wooden frame which serves as a reflector. To reduce the top heat loss during off-sunshine hours, the cooker is closed with reflector mirror frame by putting it on the glass cover frame. Glass wool of 3 cm thickness is provided between the wooden cover and the reflector mirror to further reduce the top heat loss during off-sunshine hours. The cooking pots are cylindrical in shape and have flat bases with 18 cm diameter and 7 cm in height. The cooking pots are provided with tight-fitting flat covers. The absorber plate and cooking pots are painted black. A secondary reflector is also used to increase incident solar radiation on the absorber plate. The isometric view of the PCM-cooker designed is shown in Fig. 1 and the backside view is shown in Fig. 2.

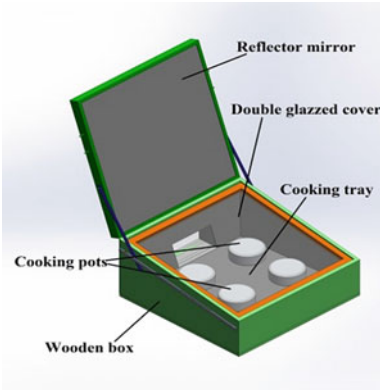


Fig. 1 Isometric view of PCM-cooker

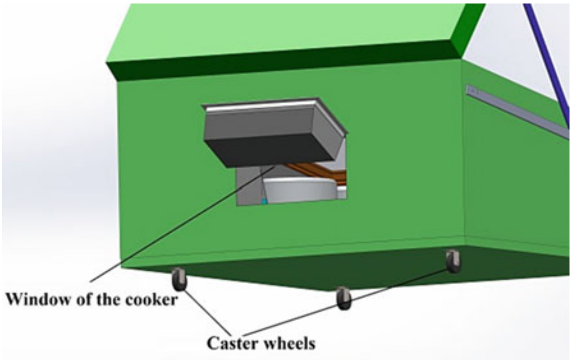


Fig. 2 Backside window view of PCM-cooker

2.2 Operation of Box-Type Solar Cooker with Phase Change Material

During the charging period, the solar radiation incident on the box-type solar cooker is transmitted through the double glass cover and reaches the absorber plate. The beam radiation reflected by the reflector mirror is also transmitted through glass cover and reaches the absorber plate. The solar radiation received on the absorber plate is converted into thermal energy and raises the temperature of the interior of the cooker. When there is no load on the absorber plate, a part of this thermal energy is utilized to increase the temperature of the interior of the cooker plus the heat supplied to the PCM and remaining energy lost to the surroundings. When there is a load on the absorber plate one part of thermal energy is also supplied to the load. As the temperature of the absorber plate increases the heat loss to the surrounding is also increased. During the late hour of the day, there is no solar radiation available and the cover of the cooker is closed (with reflector mirror). During this period only PCM is the source of thermal energy in the cooker. During off-sunshine hour, a part of the thermal energy supplied by PCM to the load, raise its temperature and a part of thermal energy is lost to the surrounding. After some time the load temperature becomes equal to the PCM temperature, the energy loss to the ambient by the cooker is the sum of the energy loss by the load and energy loss by the PCM.

2.3 Thermal Analysis of Proposed Design

The thermal performance of PCM-cooker is assessed in terms of charging-discharging time. The time required for complete melting of PCM is taken as charging time with initial temperature of PCM is equal to ambient temperature. The discharging time is defined as the time required for the solidification of PCM during off-sunshine.

A major part of the incidence solar energy is lost to the ambient specifically when the cooker interior is at high temperature. For calculation of energy loss to the ambient, the calculation of the overall heat loss coefficient is required. The overall heat loss coefficient consists of two parts; one is the top heat loss coefficient and the second side and bottom heat loss coefficient. During the charging period, there is incidence solar radiation and the cover of the cooker is open. During discharging period there is no solar radiation and the cover of the cooker is closed. So, top heat loss coefficient has two cases. In charging mode, the top heat loss is from the absorber plate to the surrounding through the glass cover. The top heat loss coefficient of the cooker is calculated by using the analytical procedure proposed by Akhtar and Mullick [13]. In discharging mode, the top heat loss coefficient is calculated by applying energy balance between the absorber plate and first glass cover, first glass cover to second glass cover, second glass cover to the wooden cover and from the wooden cover to ambient. An iterative procedure is used for solving the heat balance equations until the convergence is achieved. For fixed dimensions of the cooker and a constant velocity of wind, the top heat loss coefficient is a function of the plate and ambient temperature. The side heat loss coefficient and bottom heat loss coefficient are calculated with the help of Fourier's law of heat conduction. The overall heat loss coefficient is the sum of top heat loss coefficient and side heat loss coefficient and bottom heat loss coefficient. After calculation of the overall heat loss coefficient as a function of absorber plate temperature, the time taken to charge the PCM, duration of discharging and quantity of PCM required is calculated by applying energy balance on the absorber plate.

The thermal analysis of cooker with 6 kg of Erythritol as phase change material, considering the intensity of solar radiation as 700 W/m^2 is shown in Table 1.

The above results show that it takes approximately 7 h to charge 6 kg PCM. And it takes more than 3 h to solidify PCM along with heating the 4 kg of water up to 100 °C. Without load, complete PCM will solidify in more than 6 h.

Table 1 Result of thermal analysis of proposed design

Pre-charging time (ambient temperature to 118 °C)	1.05 h
Melting time (at 118 °C)	5.90 h
Charging time (pre-charging time + Melting time)	6.95 h
Total discharging time with load (4 kg of water)	3.23 h
Total discharging time without load	6.63 h

3 Experimental Setup and Instrumentation

The cooker was designed, fabricated and experiments were performed in the Department of Mechanical Engineering, Aligarh Muslim University Aligarh, India. The location of Aligarh city is (27.89° N, 78.08° E) and 178 m above mean sea level. Experiments were performed during the month of January to April-2019.

The experimental setup consists of two box-type solar cookers. One cooker is purchased from the market named as standard cooker, shown in Fig. 3. The second cooker is developed in the lab integrated with energy storage material named as PCM-cooker, shown in Fig. 4. Pyranometer (Kipp and Zonen CMP-11Secondary standard) is used for the measurement of solar radiation and T-type thermocouples with data-logger are used for measurement of temperatures.

Fig. 3 Standard cooker

Fig. 4 PCM-cooker

Table 2 Dimension of box-type solar cookers

		Standard cooker	PCM-cooker
Aperture area (m^2)		0.25	0.5084
Reflector mirror area (m^2)	Primary	0.348	0.5476
	Secondary	N.A	0.7972

The standard cooker has only a primary mirror reflector and PCM-cooker has a primary as well as secondary mirror reflector; both the cookers have black painted absorber plate. The dimensions of both the cookers are shown in Table 2.

3.1 Experimental Procedure

The experiments were conducted for: (i) Comparison of PCM-cooker with standard cooker and (ii) Performance evaluation of PCM-cooker.

3.1.1 Comparison of PCM-Cooker with Standard Cooker

In this test, PCM-cooker's performance is compared with a standard cooker to observed the effect of PCM used in the cooker. This test is carried out between 10:00 A.M. and 2:30 P.M. The test is carried out for no-load test and load test with two continuous loads. In standard cooker load is 1.5 L of water and the PCM-cooker load is 3 L of water in two and four pots, respectively.

3.1.2 Performance Evaluation of PCM-Cooker

The performance of PCM-cooker is evaluated with maximum load of 4 L of water. This test is conducted from 10:00 to 20:00 h. In this test two loads are placed; one in the morning which completed by the time of 13:00 h after that only charging is carried out of the PCM up to 15:40 h after 15:40 h PCM-cooker is placed inside the room and the second load is placed about 15:50 h and the test is carried out up to 20:00 h.

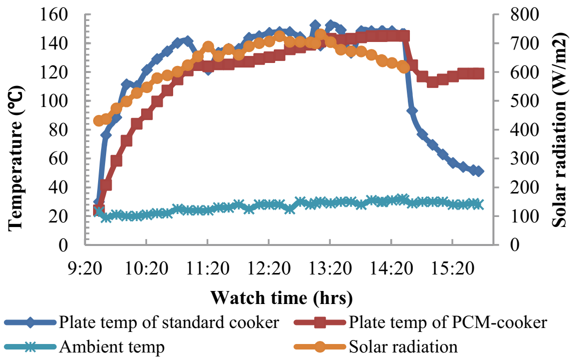


Fig. 5 Variation of plate temperature, ambient temperature and solar intensity with time of the day in no-load test on 23-February-2019

3.2 Experimental Result and Discussion

3.2.1 Comparison of Performance of PCM-Cooker with Standard Cooker in No-Load Test

Figure 5 shows the variation of plate temperature, ambient temperature and intensity of solar radiation with time of the day for standard cooker and PCM-cooker in no-load test performed on 23-February-2019. The test starts at 9:33 h, the cover of the cooker is closed at 14:32 h and cookers placed inside the room and test continue till 15:45 h.

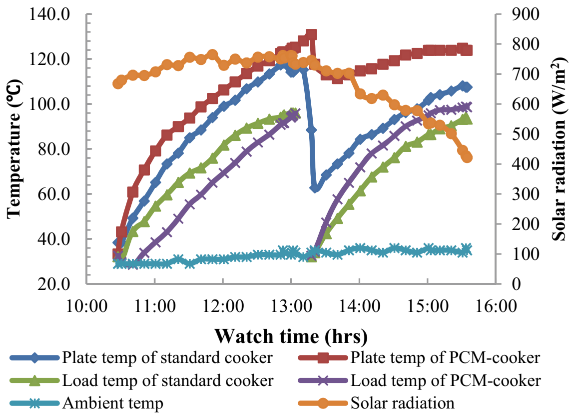
From the experiment, it is observed that the absorber plate of standard cooker attained maximum temperature, 152.5 °C, at 13:20 h and the absorber plate of PCM-cooker attained maximum temperature, 145.1 °C, at 14:20 h.

3.2.2 Comparison of Performance of PCM-Cooker with Standard Cooker in Load Test

Figure 6 shows the variation of plate temperature, water temperature and ambient temperature with time of the day in two continuous loads test conducted on 26-March-2019. The first load placed at 10:27 h in both the cookers. The loads on both the cookers are replaced with the second load at 13:17 h after attained maximum temperature. The test continues till second load in both the cookers attained maximum temperature.

From the experiments, it is observed that in standard cooker the first load attained maximum temperature, 96 °C, at 12:59 h. Then first load is replaced with second load at 13:17 h and the second load attained maximum temperature, 94.2 °C, at 15:33 h. In PCM-cooker first load attained maximum temperature, 95.9 °C, at 13:03 h, now first load is replaced with second load at 13:17 h and second load attained maximum temperature, 98.9 °C, at 15:33 h.

Fig. 6 Variation of plate temperature, load temperature, ambient temperature and solar intensity for two continuous load test on standard cooker and PCM-cooker on 26-March-2019



3.2.3 Performance of PCM-Cooker with Primary and Additional Reflector Without Load

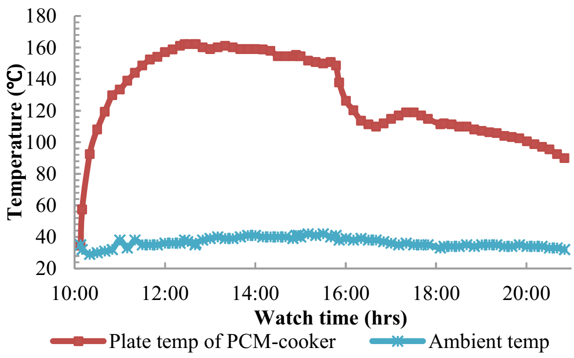
Figure 7 shows the variation of plate temperature and ambient temperature with time of the day for PCM-cooker with additional reflector in no-load test performed on 01-April-2019. The test started at 10:08 h, the cover of the cooker is closed at 15:47 h and cooker placed inside the room. The observations are continued till 20:50 h.

From the experiment, it is observed that during charging mode the absorber plate attained maximum temperature, 162.1 °C, at 12:26 h. During off-sunshine mode the absorber plate temperature drop to 109.9 °C at 16:40 h, then the absorber plate temperature starts increasing and attained 118.9 °C at 17:20 h. After that, the absorber plate temperature continuously decreases and the test is concluded at 20:50 h with absorber plate temperature of 90.0 °C.

Discussion on variation of plate temperature after solar radiation cut-off

When solar radiation is cut-off and the cooker is placed inside the room the plate temperature falls below the melting temperature of PCM and after some time plate temperature starts increasing and reach at melting temperature of PCM. This

Fig. 7 Variation of plate temperature with time of the day in no-load test on PCM-cooker on 01-April-2019



happened because when solar radiation is cut-off by closing its cover the overall heat loss coefficient decreases to almost half.

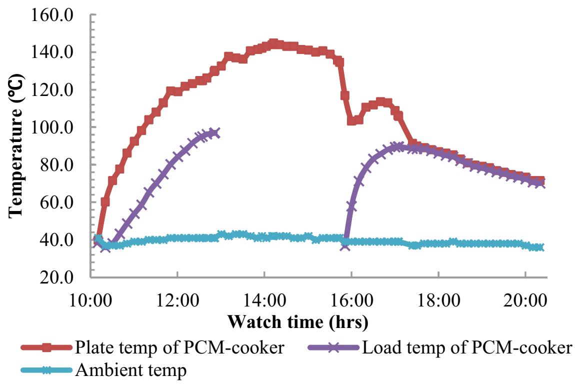
During the charging mode of PCM-cooker the top heat loss is through top glass covers to the atmosphere. This heat loss depends on the temperature difference between glass temperature and ambient temperature. Due to heat balance between two surfaces the heat loss from plate to inner glass is equal to heat loss from inner glass to outer glass and this also equal to heat loss from top glass to atmosphere. After solar radiation is cut-off by the closing cover, the heat loss from cooker is from outer surface of the wooden cover to atmosphere, this heat loss depends on temperature difference between temperature of wooden cover and atmosphere. And this heat loss also depends on the temperature difference between plate and inner glass. Since heat loss becomes almost half after closing the cover, the temperature difference between plate and inner glass decreases after solar cut-off. Hence, the temperature of inner glass increases. For this, some amount of heat is required. Also, the air medium requires some amount of heat to increase its temperature. This heat is supplied by the PCM. When the PCM starts supplying the heat, the temperature of PCM and the plate temperature start decreasing. Since the heat is supplied by the upper layer of the PCM adjacent to the absorber plate the top layer of PCM will initially solidify. As the heat capacity of PCM in a solid-state is low, the plate temperature goes below the melting point of PCM. Once equilibrium between plate and inner glass is achieved at a lower temperature the layer of solid PCM below the absorber plate will start taking heat from the liquid PCM below the solid layer of PCM. When solid layer gets heat from liquid PCM, it also supplies heat to the plate and the plate temperature increases and reaches the melting point of PCM. Thus, the absorber plate temperature increases and equilibrium at a higher temperature (melting temperature of PCM) is achieved and after that plate temperature starts decreasing gradually due to the continuous heat loss.

3.2.4 Performance of PCM-Cooker with Primary and Additional Reflector with Load

Figure 8 shows the variation of plate temperature, water temperature and ambient temperature with time of the day with the use of additional reflector performed on 27-April-2019. The test is performed with two loads. The first load of 4 kg water kept at 10:10 h in PCM-cooker, which is removed from the cooker after the maximum temperature, is achieved at 12:51 h and then the cooker is left for charging of PCM. The charging is continued till 15:43 h, then the cover is closed and the cooker is placed inside the room. After that, the second load of 2 kg water is kept in the PCM-cooker and observations are continued till 20:20 h.

From the experiment, it is observed that during charging mode the first load of 4 kg water attained maximum temperature, 97.1 °C, at 12:51 h, now first load is removed from the cooker at 12:51 h. After charging of PCM, the cover of the cooker is closed and placed inside the room. The second load of 2 kg water is placed at 15:51 h in the

Fig. 8 Variation of plate temperature, load temperature and ambient temperature with additional reflectors with time of the day in load test on PCM-cooker on 27-April-2019



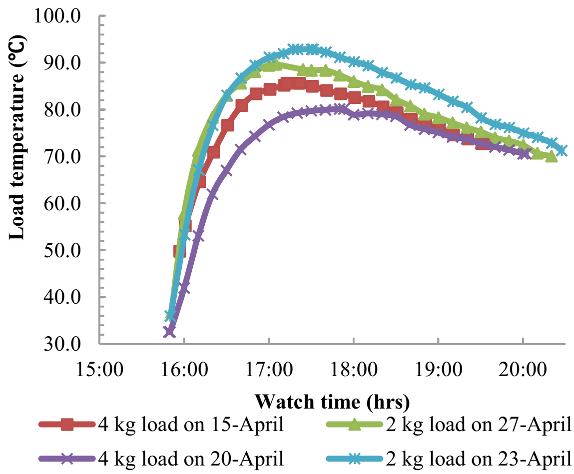
PCM-cooker. The second load attained temperature, 89.7 °C, at 17:04 h. The test is continued up to 20:20 h with load (water) temperature achieved is 70.1 °C.

Temperature of second load (during off-sunshine hours) in PCM-cooker at different load conditions

The cooker is charged during the sunshine hours and then placed in the room with the cover of the cooker in closed condition. The performance of the cooker is evaluated in terms of the rise in temperature in different load conditions. The variation of 2 and 4 kg of water on different days is shown in Fig. 9.

It can be seen from the plot that the temperatures achieved during off-sunshine hours for 2 kg and 4 kg of water are 92 °C and 85 °C, respectively.

Fig. 9 Variation of load temperature during off-sunshine hours on 15-April, 20-April, 23-April, and 27-April



3.3 *Cooking of Foods in Standard Cooker and PCM-Cooker*

The experimental study shows that the first load placed in the PCM-cooker during sunshine hour attained the boiling point of water, but when the second load is placed in cooker it does not achieve boiling temperature of water. The maximum temperature achieved by the second load is 85.6 °C and 92.2 °C when the cooker is loaded with full load (4 kg) and half load (2 kg), respectively. These results show that the second load does not attain the boiling temperature of water, which creates doubt regarding the cooking of the meal in the late hour of the day. A matter of curiosity, to clarify this doubt the PCM-cooker is tested by cooking two meals on the same day.

On 29-April and 30-April load tests with food were performed by placing rice and pulse in both the cookers. On 29-April 550 g load (100 g rice + 200 g water in one pot and 50 g pulse + 200 g water in the second pot) on the standard cooker and 1.1 kg load (200 g rice + 400 g water in one pot and 100 g pulse + 400 g water in the second pot) on PCM-cooker are placed at 10:00 h, which are prepared/cooked by 12:00 h. After that PCM-cooker is left for charging up to 15:50 h. Then the charged cooker is placed inside the room and then second meal of 1.1 kg is placed on PCM-cooker before 16:00 h and we get well cooked and hot food around 19:30 h.

Similar test again conducted on 30-April with increased loads: 1.3 kg load (200 g rice + 600 g water in one pot and 100 g pulse + 400 g water in the second pot) on the standard cooker and 2.6 kg load (400 g rice + 1200 g water in one pot and 200 g pulse + 800 g water in the second pot) on PCM-cooker at 10:00 h, the food was cooked by 12:40 h. Then the PCM-cooker is left for charging up to 15:50 h and after charging the PCM-cooker is placed inside the room and then second meal 1.95 kg load (300 g rice + 900 g water in one pot and 150 g pulse + 600 g water in the second pot) is placed on PCM-cooker before 16:00 h and at 19:30 h well cooked and hot food was ready.

4 Conclusions

On clear days with high intensity of incoming solar radiation, the absorber plate temperature of the standard cooker is higher than the temperature of PCM-cooker. This is due to the fact that when the absorber plate temperature of the PCM-cooker reaches higher than the melting point of the phase change material, it transfers the heat to the PCM and the rise in temperature is less. Although the overall efficiency of both the cookers is approximately same, the standard cooker is unable to cook the food in the late hours of the day. The cooker with phase change material can be used for cooking the food during the daytime as well as during the late hours of the day. The use of an additional (secondary) reflector during the charging time is beneficial for cooking the food when the solar radiation is moderate. During off-sunshine hours, the second load (second meal of the day) attains a temperature around 90 °C in the PCM-cooker. As the cover of the cooker is closed during the off-sunshine hours, the heat loss decreases and the temperature drop is slow and the temperature of the load is approximately 70 °C at 20:00 h. The cooking of rice and pulse is possible during the off-sunshine hours of the day using the PCM-cooker.

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