

Performance Comparison of Different Geometries of Thermal Energy Storage Unit for Solar Cooker



B. C. Anilkumar, Ranjith Maniyeri, and S. Anish

Abstract Many researchers have been interested in solar energy as an unlimited energy resource over the last few decades due to its vast range of applications, including household cooking. The present work aims to design, optimize, fabricate, and test different geometries of thermal energy storage (TES) units for solar cooker (SC) using paraffin wax as the phase change material (PCM). The optimum amount of PCM necessary for different geometries (cylindrical, square, and hexagonal) of TES units surrounding the cooking vessel is computed using a computational approach. The TES units developed in this study have the provisions for filling the PCM on all sides, including the lid, enhancing the heat transfer to the cooking load. The performance comparison of different TES units is carried by conducting the indoor test. The experimental findings show that after 6 h, all geometries of TES units maintain the temperature of the cooking load at the melting point of PCM. However, cylindrical-shaped TES unit performs best in comparison with hexagonal and square. A cylindrical box solar cooker performance test is also carried out with an optimized cooking vessel surrounded by the PCM-filled TES unit and lid.

Keywords Cylindrical box solar cooker · Thermal energy storage unit · Phase change material · Cooking pot

Nomenclature

T_{mp} Melting temperature of PCM
 M_{pcm} Mass of PCM
 U Overall heat transfer coefficient

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Greek Symbol

λ Latent heat of fusion of PCM

1 Introduction

Renewable energy systems, particularly solar cookers (SCs), are viable for meeting global cooking needs. SC converts the insolation into useful thermal energy for cooking. Solar energy has become more prominent in the present worldwide debate on energy and the environment. Today, growing awareness for the benefits of renewable energy and increasing prices of fossil fuels drive the SC market. Many modifications were made to SCs over the last four to five decades across the world [4, 5]. In a recent study, we examined the effects of various box shapes on solar cooker performance by using numerical analysis, including rectangular, trapezoidal, cylindrical, and frustums of cones [3].

The evening or night cooking is possible with the provision of the heat storage facility in SCs. Thermal energy can be stored in the SC as sensible or latent heat. Generally used sensible heat storage materials (SHSMs) in SCs are sand [13], engine oil [10], and carbon [15]. In our recent study [1], we experimentally investigated the effects of the optimum mixture of SHSMs such as sand, iron grits, brick powder, and charcoal on the performance of solar box cooker (SBC). In the latent heat storage (LHS) units, energy stored during a phase change is used for cooking. Generally, phase change materials (PCMs) are used to store heat energy in the latent form. The cooking pot incorporated with the LHS system contains two concentric cylindrical vessels made of aluminium or steel with an annular cavity filled with PCM (Fig. 1). The PCMs contained in the cooking vessel are heated and solidified by the SBC or concentrated/indirect SCs. Recently, several review papers [12, 17] are reported on the developments of SCs incorporated with PCMs. Nkhonjera et al. [11] reviewed the heat storage units, materials, and performance of SCs included with thermal energy storage (TES) units. They recommended that the shape and heat transfer properties of TES units need be optimized.

In general, the TES units surrounding the cooking vessel were filled with PCM along the lateral side [6–9, 16, 18]. In the present work, we aim to introduce a new design of the TES unit that includes the facility for filling the PCM at the bottom part of the cooking pot and on the lid. This will enhance the cooking performance as heat is transferred to the load through all sides of the pot. Therefore, the primary objective of this research is to design and develop the TES units of different geometries incorporated with the cooking pot. The present study also compares the cylindrical, square, and hexagonal geometry of TES units by conducting the indoor test. Another goal of this research is to conduct outdoor tests to evaluate the performance of the improved TES unit with the cylindrical box solar cooker (CBSC). The optimum

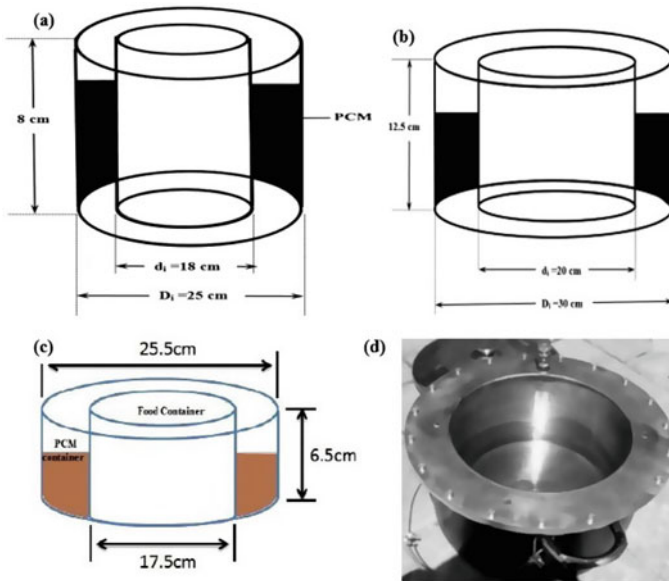


Fig. 1 Schematic of TES units for solar cooker **a** Buddhi et al. [7] **b** Sharma et al. [16] **c** Vigneswaran et al. [18] **d** Photo of TES unit [8]

mass of PCM and dimensions for the different geometries of TES units are found following our recently developed computational procedure [2].

2 Methodology

Latent Heat Storage Medium: Paraffin wax can reach a wide range of temperatures, thus making it a useful heat storage material in several applications. Paraffin wax is considered as good heat storage material because of its fast-charging properties and high latent heat of fusion. Furthermore, they are non-corrosive, compatible with many materials, chemically stable, non-toxic, and do not segregate. In general, the paraffin wax used as PCM is of technical grade. This grade of paraffin wax is also cost effective, feasible, and widely used. However, they also present some disadvantages, such as low thermal conductivity, more significant volume changes between the solid and liquid phases, and the possibility of flammability.

The solid–liquid phase transition temperature should be around 100 °C or higher for practical cooking. Paraffin wax is available in different fusion temperatures. The melting temperature and latent heat of fusion of paraffin wax tested in SCs by Saxena et al. [14], Yuksel et al. [19], and Lecuona et al. [8] are, respectively, 41–44 °C, 58–60 °C, 100 °C and 250 kJ/kg, 189 kJ/kg, and 140 kJ/kg. Paraffin wax shows a decrease

Table 1 Thermo-physical parameters of commercial-grade paraffin wax

Properties		
Melting temperature (°C)		55–60
Latent heat of fusion (kJ/kg)		220
Density (kg/m ³)	Solid	818
	Liquid	760
Specific heat (kJ/kg °C)	Solid	2.95
	Liquid	2.51
Thermal conductivity (W/m°C)		Liquid 0.22

in latent heat of fusion with increasing melting temperature. In the present work, we used paraffin wax with fusion temperature of 55–60 °C and latent heat of 220 kJ/kg.

Design of TES Unit: The TES units of cylindrical, hexagonal, and square geometries are designed using the previously developed computational procedure [Anilkumar et al. 2021]. The dimension of the TES container depends on the properties of the heat storage material to be used, and the time for the evening or night cooking is required. The thermo-physical parameters of commercial-grade paraffin wax, which is employed as the PCM for heat storage in all geometries, are given in Table 1. For maintaining the temperature of the cooking vessel at PCM's melting point for a specific duration of time, latent heat rejected by the PCM and energy loss from the container should be equal. This is expressed by the equation [13]

$$M_{pcm}\lambda = U(T_{mp} - T_a)t \quad (1)$$

The procedure to be followed in the design of TES unit is as follows: [3]

Step 1: Initially guess the temperatures of PCM, the inner and outer surface of the TES unit, and ambient air.

Step 2: Compute air and PCM's thermal properties (Pr , k , and ν) at the corresponding mean temperature.

Step 3: Calculate the Nusselt number and convective heat transfer coefficient at the inner and outer surface of the TES unit using analytical correlations.

Step 4: Guess the dimension of the TES unit of each geometry.

Step 5: Compute U-value for each geometry of the heat storage container.

Step 6: Compute the mass of PCM required using Eq. (1).

Step 7: Update the dimension of the TES unit.

Step 8: Compare the updated and previous dimension value and repeat the step 5 to 7 until it converges.

Step 9: Update the temperature at the inner and outer surfaces of the TES unit.

Step 10: Compare the updated and previous temperature values and repeat the step 2 to 9 until it converges.

The mass of paraffin wax required and dimensions of heat storage containers of different geometries surrounding the cooking vessel of diameter 16 cm and height

Table 2 Dimensions of different geometries of TES units and required mass of PCM

Geometry	Dimension of TES container (cm)	Mass of PCM (kg)		
		Lateral side	Bottom side + Lid	Total
Cylindrical	18.7	1.01	0.416	1.426
Hexagonal	10.7	1.32	0.452	1.772
Square	17.5	1.44	0.464	1.904

18 cm are given in Table 2. The optimum mass of PCM required for 6 h is found to be maximum for square followed by hexagonal and minimum for the cylindrical geometry. Therefore, a cylindrical-shaped TES unit is considered the optimum geometry as it uses the minimum mass of PCM for maintaining a constant temperature for a specific duration of time.

Fabrication of TES Unit: The TES units of cylindrical, hexagonal, and square geometries (Fig. 2) are fabricated using a stainless steel sheet of 1 mm thickness. The sheet is cut into the required shapes and dimensions by using the automatic CNC machine. Bending and rolling works are carried out using hydraulic press brake bending and rolling machines, respectively. Then the parts are joined by spot/resistance welding at different locations to form the required geometry. Afterwards, the joints are entirely welded by the tungsten inert gas (TIG) welding process. Finally, the grinding process is carried out for the smooth and consistent appearance of the welded parts. Two holes are drilled on the vertical surface of the container facing in the opposite direction for inserting PCM into the cavity. The PCM can be filled in the annular cavity between the inner pot and outer TES container on the lateral side and at the bottom. The lid for all the geometries of TES units is fabricated with provisions for filling the PCM. For this, two holes are provided at the top of the lid in opposite directions.

The designed quantity of PCM should be filled into the TES unit to expand and solidify completely in each cycle. The TES unit is first kept vertically and partially placed in hot water during PCM filling. PCM is filled through one of the provisions at the top. At the same time, the other provision on the opposite side was kept open for the escape of air during filling. After filling at the hole level, one of them is closed, and the container is kept in a horizontal position. Then the PCM is filled, and another provision is also closed. The lid is also filled with PCM by following the same procedure. During the complete filling procedure, PCM is maintained in the liquid state by keeping the TES unit in a hot water bath.

Performance Test: The performance comparison of different geometries of TES units is carried by conducting indoor and outdoor experiments. The indoor test is performed to validate the computational approach used to design the TES containers of all geometries, whereas the outdoor experiment is performed by testing the optimized TES container charged with CBSC.

Indoor test. The experimental set-up for the indoor test is shown in Fig. 3. The temperature of cooking pot surfaces and water is measured by using the K-type

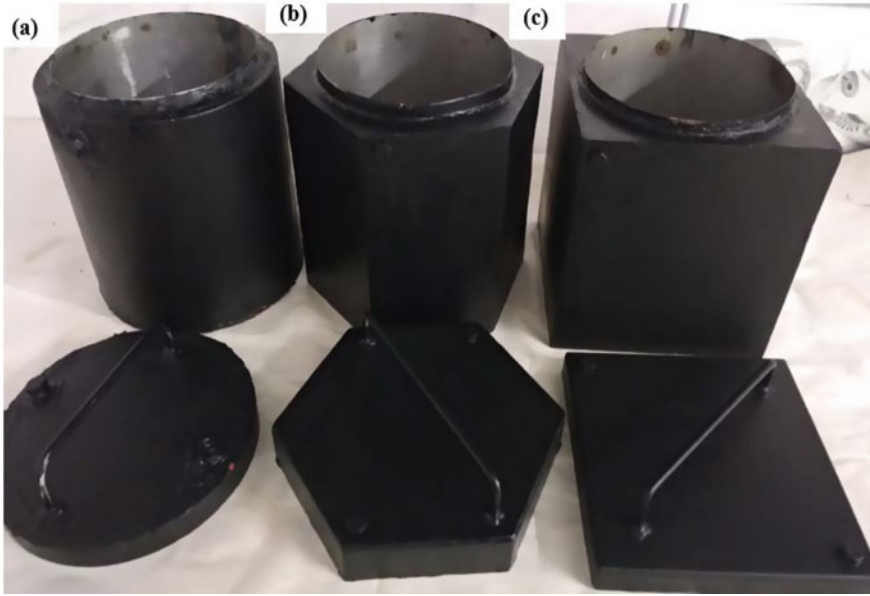
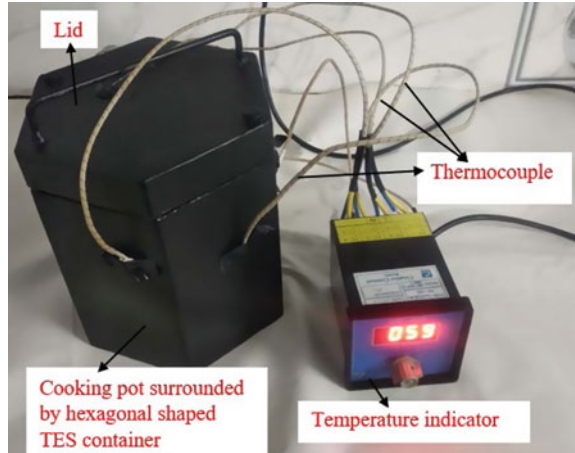


Fig. 2 Cooking pot with TES unit and lid of different geometry **a** cylindrical, **b** hexagonal, and **c** square

thermocouple and an indicator. The container is tested with water for the performance study. Initially, water is heated up to 100 °C and is poured into the vessel fully. Again, water in the vessel is replaced with newly boiled water. Before changing the water, the temperature of the previous water in the container is measured. Also, the temperatures of all the surfaces of the vessel are measured. This process is continued until all the surface temperature reaches the melting temperature of PCM and remains constant after that. This ensures that all PCMs in the container are melted. After PCM gets melted fully, water in the vessel is made empty, and again water at a temperature above the melting point of PCM is filled in the vessel and the lid is closed. The temperature at each surface of the vessel is measured in equal intervals of time. After six hours, the water temperature in the pot is measured and compared with the expected value.

Outdoor test. The performance test of the TES unit with optimum geometry is conducted by charging with CSBC (Fig. 4). The CSBC used in the present work consists of a mild steel cylindrical box with external and internal diameters 53 cm and 43 cm, respectively, and height 30 cm. A double glazed cover is provided at the top of the cooker to form the greenhouse effect, allowing solar radiation to pass into the cavity but preventing it from escaping. Since the glazing is opaque to longer wavelength radiation such as infrared waves emitted by the absorber plate, heat radiation will be trapped inside the cooker. The annular gap between the outer and inner cylinders is insulated with 5-cm-thick glass wool to reduce heat loss to the environment. The circular absorber plate made up of aluminium having a diameter

Fig. 3 Experimental set-up (indoor test)



of 43 cm and thickness of 2 mm painted with black is fixed at the base of the inner cavity of the cooker. The glass wool insulation of 5 cm thickness is also provided below the absorber plate to reduce the heat loss through the bottom surface. A small door is provided on the lateral surface of the cooker. A K-type thermocouple and an indicator are used to measure the required temperatures.

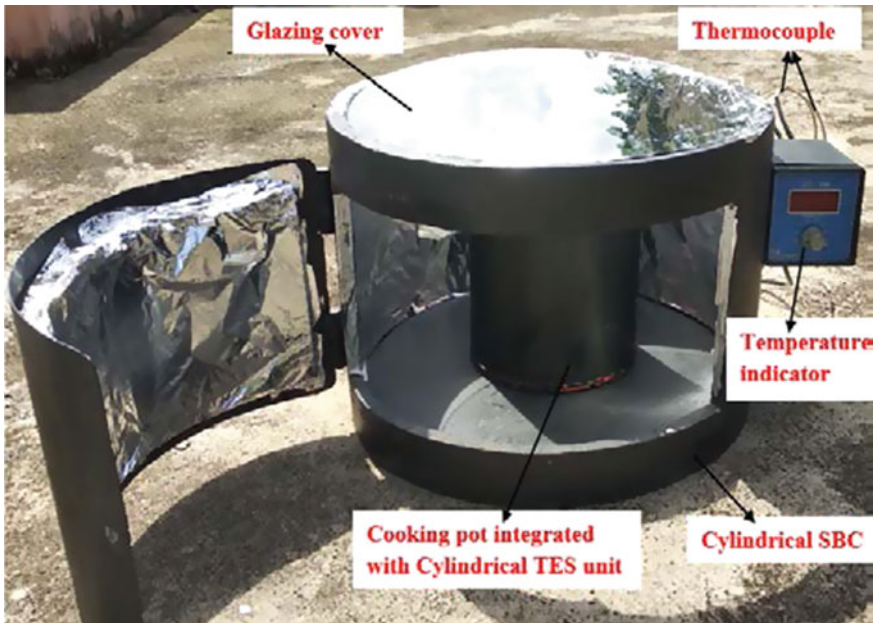


Fig. 4 Experimental set-up (outdoor test)

3 Results and Discussion

Initial Set-up: The cooking pot is filled with water that is hotter than the melting point of paraffin wax. To ensure the complete melting of paraffin wax, the poured water is replaced two to three times with fresh hot water. The temperature of the replacement (prior) water and the time is recorded. The temperature of the replaced and pouring water is the same during the first set. Initially, the cooking pot is filled with water at 91 °C. After 15 min, the water temperature has dropped to 68 °C. The water temperature drops to 66 °C on the third replacement. This means that the paraffin wax absorbs heat from the hot water. The water temperature increases to 76 °C during the fourth replacement, indicating that the paraffin wax melts fully and heat absorption diminishes. Figure 5 depicts the temperature variation of replaced water during the initial heating of the cooking pot integrated with cylindrical, square, and hexagonal TES units.

Indoor Test: Water at a temperature more than the melting point of paraffin wax is filled in the cooking pot and is covered with the lid. Every 30 min, the surface temperature is recorded. The temperature of the water is also monitored after 6, 7, and 8 h. The surface temperature of the cylindrical TES unit is increased from 43 °C to 62 °C after 45 min. At the same time, the lid temperature rises from 38 °C to the maximum of 56 °C after 1 h and 15 min. Figures 6–8 illustrate the variation in surface and lid temperatures of cylindrical, square, and hexagonal TES units. For the square-shaped TES unit, temperatures are measured at the four side faces denoted as surface 1, 2, 3, and 4, as depicted in Fig. 7. Similarly, for the hexagonal geometry, all the six side faces are considered for the temperature measurement denoted by surface 1, 2, 3, 4, 5, and 6, as shown in Fig. 8. The side faces for square and hexagonal geometry of TES units exhibit nearly equal temperatures at every time. The temperature of the surface and lid falls in small units after 1 h and 45 min

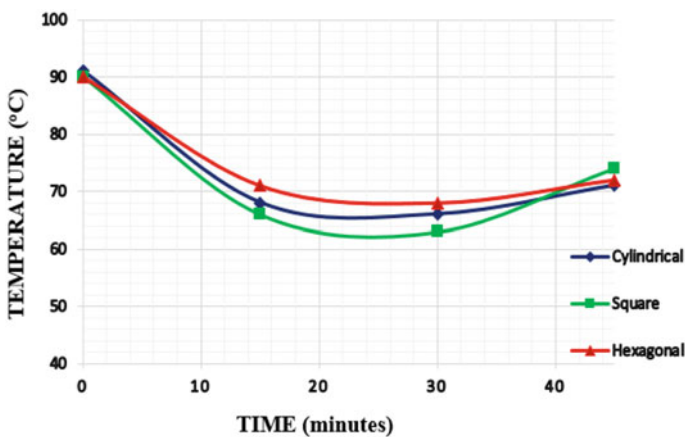


Fig. 5 Variation of temperature of replaced water during initial set-up

from the start of the test. This shows that paraffin wax maintains nearly constant temperature during the phase change. Figure 9 shows the water temperature variation for cylindrical, square, and hexagonal TES units. All of the TES units maintain the water temperature at 59 °C after 6 h of testing. However, compared to cylindrical and hexagonal TES units, square geometry exhibits a slight decrease in water temperature. For cylindrical, hexagonal, and square TES units, the water temperature on the second day (after 24 h) is 46 °C, 44 °C, and 41 °C, respectively. This shows that the heat loss across the cylindrical geometry is lower than other forms due to the small surface area-to-volume ratio.

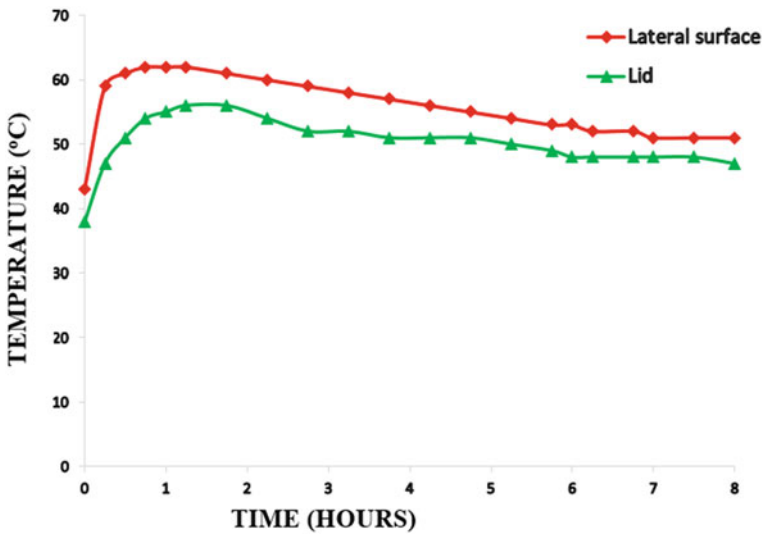


Fig. 6 Variation of surface temperatures of cylindrical TES unit with time

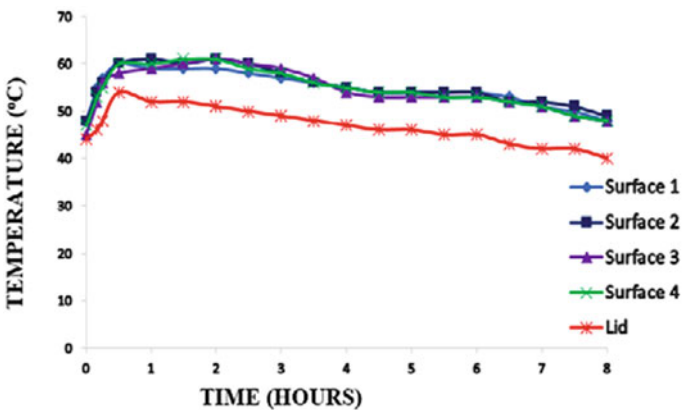


Fig. 7 Variation of surface temperatures of square TES unit with time

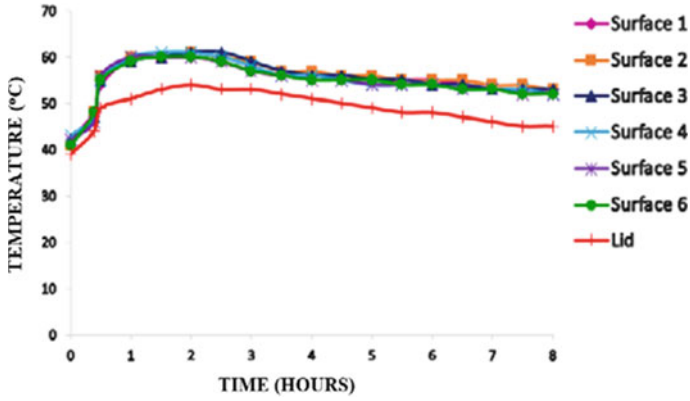


Fig. 8 Variation of surface temperatures of hexagonal TES unit with time

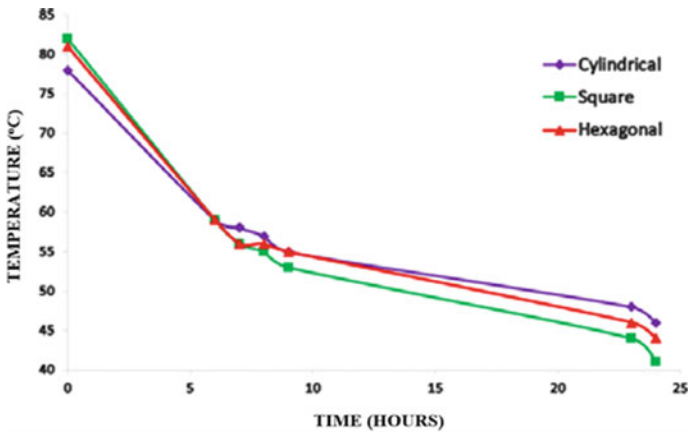


Fig. 9 Variation of water temperatures in different geometries of TES units with time

Outdoor Test: The outdoor test is conducted with the cylindrical-shaped TES unit charged with CBSC. The cooking pot having 1 kg of water is placed on the top of the absorber plate, and the whole assembly is open to direct sunlight. Figure 10 shows the variation of solar irradiance and temperatures of the absorber plate, cooking pot, water, and ambient air measured during the experiment conducted on 10 June 2021. The experiments began at 10 AM (IST) and took measurements at 15-min intervals. The ambient, water, TES surface, and absorber plate temperatures reached 32 °C, 86 °C, 91 °C, and 104 °C, respectively, at 1:15 PM, and the corresponding solar irradiance is observed to be 830 W/m². Later, the temperatures of the water, absorber plate, and cooking pot are decreasing. At 3 PM (IST), the cooking pot integrated TES unit is taken from the CBSC and placed in the thermal insulation box. Then, the water and TES container surface temperatures are, respectively, 62 and 65 °C.

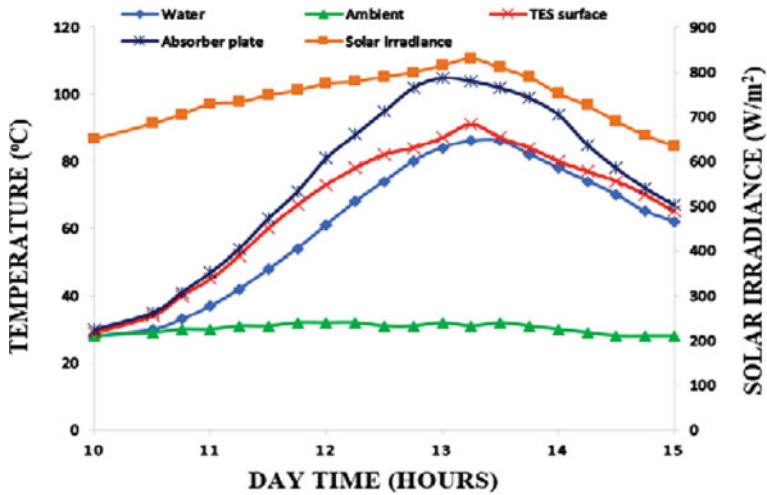


Fig. 10 Variation of water temperature and solar irradiance with time (10 June 2021)

Experimentation revealed that the cooking pot’s water keeps the temperature in the 55–60 °C range until 9 PM (IST).

4 Conclusions

Thermal energy storage (TES) units of various shapes (cylindrical, hexagonal, and square) incorporated with the cooking vessel used in solar cookers are designed, fabricated, and tested for the comparative performance study. In this work, we developed the TES unit to fill the heat storage material at the lateral and bottom sides and on the lid. Commercial-grade paraffin wax is used as the latent heat storage material. The results of the indoor test show that after 6 h, all geometries of TES units keep the water temperature at the same level as the melting point of paraffin wax (55–60 °C). However, cylindrical TES units perform best, followed by hexagonal, while square TES units perform least. The surface area-to-volume ratio is the lowest for cylindrical geometry and the highest for a square shape. The performance test on the cylindrical box solar cooker (CBSC) with the optimized cooking vessel incorporated with the TES unit is also conducted. The CBSC is used to charge the heat storage material during the daytime up to 3 PM (IST), and the TES unit discharges the thermal energy required for the night cooking. Research should focus on implementing solar cookers with efficient TES units by utilizing PCMs with high-energy density, high latent heat of fusion, and low-cost and low volume changes in future.

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