

# A Review on Solar Cooker Geometries with Different Phase Change Materials

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**Abstract - Energy consumption for cooking is unavoidable, though there is continuous increase in the fuel price as well as scarcity of exhausting fossil fuels. Cooking contributes a major part in sharing of total primary energy consumption in India. Hence it needs an alternative energy source for this purpose. Solar cooking is one of the most promising techniques to meet the cooking needs as solar energy is freely and abundantly available. Solar cookers are the best substitute for heating, cooking and pasteurizing applications. Phase change materials are used to increase the efficiency of the cooker. The use of a latent heat storage system using phase change materials (PCM) is an effective way of storing thermal energy and has the advantages of high-energy storage density and the isothermal nature of the storage process. This paper throws light on features, limitations and feasible applications of different solar cooker geometries using different PCMs. This helps the consumer in selecting the most effective and appropriate solar cooker.**

**Keywords:** Solar cooker, Phase change materials, latent heat storage.

## I. INTRODUCTION

Energy requirements for cooking in the countries like India and China are very high, particularly due to the large population [1]. Wood is the primary energy source which is used all over the world. Due to use of wood as a substance for energy production, problems like deforestation and pollution occur. In urban regions, Liquid Petroleum Gas is the primary energy source [2]. A major concern of today is the rapidly depleting natural resources. So it is the urgent need of time to reduce the dependency on non-renewable sources, judiciously using the remaining sources and at the same time switching to new and better alternatives and renewable sources of energy [3][4]. Cooking by using solar energy is the best substitute over wood and fuel all over the world since solar energy is the most promising alternative energy which is available freely and abundantly. It is free of pollution and as well high

nutritional value of the cooked food [5][7]. Solar cooker is a device that cooks food using only sun energy in the form of solar radiation. In most parts of India, solar energy is available almost throughout the year and can be used as alternate input to meet energy needs. Solar energy can be used for various domestic and agricultural requirements including cooking, drying, dehydration, heating, cooling and solar power generation [6][8].

Energy storage is a key issue to be addressed to allow intermittent energy sources, typically renewable sources, to match energy supply with demand. PCMs are latent thermal heat storage materials that use chemical bonds to store and release heat. These solid-liquid PCMs initially function like conventional storage materials. Their temperature rises when they absorb solar heat. When the PCMs reach the temperature at which they change their phase (their melting point), they absorb large amounts of heat without heating. When the ambient temperature in the space around the PCM material drops, the PCM solidifies, releasing its stored latent heat [9].

## Nomenclature

MP - Melting Point  
PCM - Phase Change Material  
SBC - Solar Box cooker  
TES - Thermal Energy Storage  
HTF - Heat Transfer Fluid  
ETSC - Evacuated Tube Solar Collector

## II. SOLAR COOKER

### 2.1 Principle

*Concentrating sunlight:* Some devices, usually a mirror or some kind of reflective metal, are used to focus the light and warmth of the sun onto a small cooking area, making the energy more concentrated and therefore more powerful.

*Converting light to heat:* Anything that is black in a solar cooker, as well as some pot materials, will improve the

efficiency of converting light to heat. A black pan absorbs almost all of the sunlight and converts it to heat, which significantly improves the efficiency of the kitchen.

*Trapping heat:* Isolating the air in the kitchen from the outside air makes a big difference. Light can penetrate through the use of a transparent solid such as a plastic bag or glass cover. Once the light is absorbed and converted to heat, a plastic bag or cover can be used [10]. It minimizes convection loss of heat energy in the solar cooker [11].

## 2.2 Operation

Food cooks faster when it is in smaller pieces. Usually, small pieces of food are placed in the solar cooker. If we have to cook different foods, then they are put in different containers. After that container is placed inside the solar cooker. Food that cooks quickly should be placed later. Rice for lunch might be started early in the morning. Depending on size and capacity of solar cooker, quantity of cooked food, family can use one or more cookers. Solar cooker is turned towards the sun and left until and unless food is cooked. Food in a solar oven is generally not stirred. Solar oven may be checked every one and two hours, to turn the oven towards the sun. Cooker being used, quantity of food, air temperature, wind and latitude also affects the performance [11].

## 2.3 Types of solar cookers

There are four basic types of solar cookers

1. Box solar cooker
2. Parabolic solar cooker
3. Panel solar cooker
4. Evacuated tube cooker

The common feature of each design is the glossy reflective surface that directs the sun's rays into the cooking zone and the dark inner walls of the cooking zone and pan. [8].

### 2.3.1 Box solar cooker

It is the most common type of solar cooker made for personal use. It is very simple in construction, consists of a box casing painted black from inside and insulated from all sides except the window side, which is double glazed. Up to four black painted vessels are placed inside the box with the food to be cooked [8]. The space between the cooking vessels and outer casing is filled with the insulation like glass wool. The two reflecting mirrors are placed on the upper side of the box. The face of the cooker is to be placed perpendicular to beam radiation to collect the maximum energy.

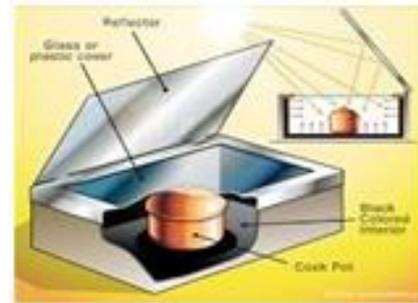


Figure 1: Box type cooker [8]

This perpendicular position can be easily achieved simply by the rotation of the cooker towards the sun [10].

### 2.3.2 Parabolic Solar Cooker

A solar parabolic cooker simply consists of a parabolic reflector with a cooking pot [10]. It uses the principles of concentrating optics. The concentrating solar cooker primarily consists of a reflector to focus the incident solar radiation on the cooking pot along with a support with turning mechanism to keep the reflector facing the sun and a cooking pot. Hence the cost and size of reflector is determined by heating capacity desired [8]. Parabolic reflector type solar cooker can heat the pot quickly at a very high temperature [11].

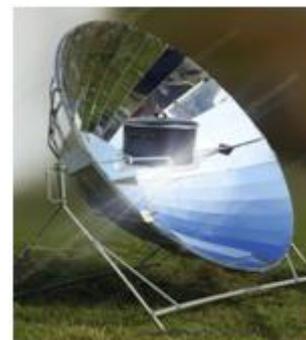


Figure 2: Parabolic solar cooker [13]

### 2.3.3 Panel solar cooker

The plate cooker is quite similar to the solar cooker in operation. The same principles are used, but instead of a simple insulated box, the plate oven is generally based on large reflective plates (often varied) that concentrate the sunlight in a pan. Panel kitchens are the easiest and cheapest to manufacture and only require four reflective panels and a cooking pan. However, they are unstable in strong winds and do not store as much heat when the sun is hidden behind the clouds [8]. Kitchens have a flat screen that reflects and concentrates sunlight for cooking and heating. This solar cooking method is not very desirable because it offers limited cooking performance [11].



Figure 3: Panel Solar Cooker [12]

### 2.3.4 Evacuated tube cooker

The vacuum tube literally means that the baking chamber consists of two layers of blown glass in the form of a sealed tube, with the air removed between the layers. Heat loss happens primarily by conduction and convection through a medium. [14]



Figure 4: Evacuated tube Solar Cooker

The heat can be stored whenever sun energy is available and can be used for cooking during off sun shine time. And cooking is possible for two times a day i.e. at noon and at evening time. And during the evening, cooking rate is faster than noon due to use of PCM storage heat energy. [7]

## III. PHASE CHANGE MATERIALS

PCMs are latent heat thermal energy storage materials which use their chemical bonds for the storage and releasing of energy. When PCMs reach the temperature at which they melt, they absorb large amounts of energy without getting heated. PCMs solidify and release energy when the surrounding temperature drops. Phase change materials for energy storage should have high thermal conductivity and large latent heat. Additionally, the melting point of the substances should lie within realistic range of application; materials should be chemically stable and should melt congruently with least super cooling. [16] Chemically, the materials must be non-toxic and non-corrosive. Financially, PCMs should be available and very cost effective. According to the researches done over the last few decades- types of

paraffin, salt hydrants, fatty acids and sugar alcohols are suitable for usage as Phase Change Materials though none of those materials possess all the properties of an ideal PCM [16].

### 3.1 Classification of PCMs

Wide varieties of phase change materials are available based on a range of temperatures required. PCMs are generally classified into three types: Organic, Inorganic and Eutectics [15].

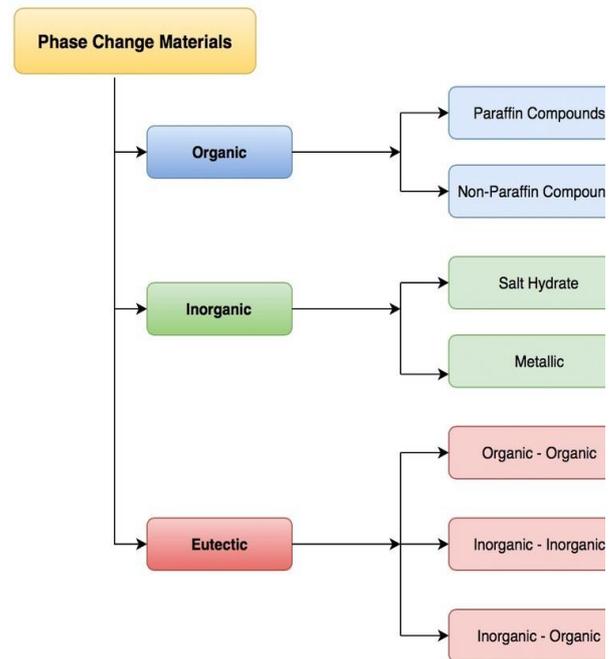


Figure 5: Classification of PCM [15]

#### 3.1.1 Organic PCM

Organic materials are generally categorized into paraffins and non paraffins. Usually, this type of materials melts and solidifies congruently, i.e. under repeated melting or solidification cycles, there is no phase segregation. Organic PCMs present self-nucleation, which is the property of crystallizing with little or no super cooling, and they are not corrosive in nature [15].

##### i. Paraffin

Paraffin qualifies as heat of fusion storage materials due to their availability in a large temperature range and their reasonably high heat of fusion. Due to cost consideration, only technical grade paraffins may be used as PCMs in latent heat stores. Paraffins like other mineral oil products are complicated mixtures of several organic compounds and contain one major component called alkanes [9].

ii. Non-paraffin compounds

The non-paraffin compounds are the most numerous of the phase change materials with a wide variety of properties. They are flammable in nature hence they are not applicable for high-temperature storage. Non-paraffin compounds are further distinguished as Fatty acids, Glycols, and Polyalcohols [15].

3.1.2 Inorganic Compounds and Eutectics

Apart from many inorganic salt hydrates there are many inorganic compounds, which undergo solid liquid phase transformation with high latent heat of fusion at higher temperature [9]. A eutectic is a material composed of two or more components. They solidify congruently and without segregation at a temperature that is normally lower than the one at which a single component solidifies, called "eutectic temperature" [15]. Also apart from the pure compounds, eutectics of organic or inorganic compounds can be used to obtain the desired melting point. It is possible to get a fixed melting or freezing point eutectic mixture of inorganic salts [9].

IV. SOLAR COOKING USING PCM

4.1 Solar box cooker

Vigneswaran V S et al. (2017) [17] in the year 2017 evaluated the performance of a solar box cooker with a varied number of reflectors. The cooking experiments were conducted with a double glazed (glass covers) SBC whose area is 0.49 X 0.49 m with 0.07 m depth. It consists of an absorber plate made of aluminum coated with black paint. The experiments were carried out for both types, with and without additional reflectors. A stainless steel kitchen container was used for cooking in the SBC. It was also painted with a matte black paint to absorb incoming sunlight. The temperatures of the absorbent plate and the top glass plate were also measured using thermocouples.

Oxalic acid dihydrate is used as a PCM to store heat from the sun. The required amount of PCM oxalic acid was rated at 2.9 kg, taking into account the energy required to cook half a kg of rice. The PCM storage unit is manufactured from two hollow aluminum cylinders with a diameter of 25.5 cm and 17.5 cm, which are arranged one inside the other. The outer surface of the PCM storage unit was painted with dull black paint and the top cover was also covered with aluminium sheet, coated with dull black paint.

Properties of Oxalic acid dihydrate:

1. Density-1.65 (kg/m<sup>3</sup>)
2. Latent heat of fusion-370 kJ/Kg
3. Phase change temperature-101°C

4. Specific heat capacity-1.62 kJ/Kg°C

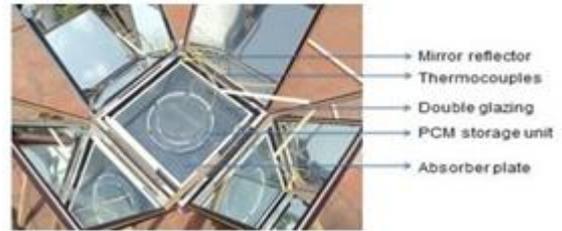


Figure 6: Photographic view of SBC PCM storage unit with dimensions [17]

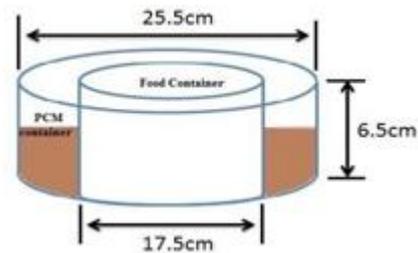


Figure 7: Schematic diagram of with multiple reflectors [17]

- Initially, the experiment was carried out for a load of 400g of water in the SBC consisting of a single reflector. The mean temperature of water was found 77.5°C with ambient temperature 31°C- 33°C. The overall utilization efficiency of the SBC was found to be 15.74%.
- The experiment was repeated for a higher load of 800g water hold-up in the SBC with four reflectors. Both the experiments were conducted in the afternoon, between 13.25 hrs and 15.15 hrs. The mean temperature of water was found 81.6°C. The overall utilization efficiency of the SBC was found to be 25.47%.
- Tests were carried out by heating 250g of palm oil in the SBC with booster mirrors on four sides. The experiments were conducted at 1.00 p.m. and the palm oil attained a maximum temperature of 136.8°C at 14.45 hr, thereby ensuring that Oxalic acid dihydrate PCM can be melted using the SBC with four reflectors.
- Tests were carried out for rice with a PCM storage unit. Charging the PCM started at 12.30 hrs with an ambient temperature of 32°C. The temperature of PCM attained a maximum of 121°C (without load), which is beyond its melting temperature. After charging the PCM up to 16.15 hrs, the total energy stored in the PCM was calculated as 759.12 kJ at a temperature of 121°C. 140g of rice with 360g of water was loaded and cooked in the SBC by using energy stored in the PCM. The amount of energy spent to cook the food item was calculated as 410.63 kJ. The time taken for cooking in the SBC and storage unit was 45 minutes. The food was found to

be well cooked using PCM. The discharging efficiency of the latent heat energy storage system was calculated as 57% [17].

**Abhishek Saxena et al. (2013)** [18] in 2013, he showed that it is possible to cook in the sun in sunshine hours by operating the kitchen with various PCMs in solar cookers, which are filled under the suction tank to act as a heat store. Two similarly designed solar cookers (stoves A and B) were considered in order to deliberately evaluate the heat storage performance of the solar cooker. The specific dimensions of the outer and inner boxes were approximately  $540 \times 540 \times 160 \text{ mm}^3$  and  $455 \times 435 \times 65 \text{ mm}^3$ .

The space between the outer tray and the outer box was filled with glass wool. The inner tray and outer boxes have been painted matt black to absorb as much solar energy as possible. A 4 mm thick flat specular reflector was attached to the housing for additional thermal energy. The absorbent bowls in the two kitchens were painted black on both sides and designed for at least two cooks. Aluminum alloy containers 16 cm in diameter (9 cm high and 0.5 mm thick) in the furnaces. The pans were round and painted black on the outside. Both ovens were tested under load and no load to evaluate the performance of PCM (stearic acid). In the case of the solar cooker A, 1500 g of stearic acid was filled between the lower isolated base (in tin) of the box cooker and the absorption tank of the base Al, and in the case of the solar cooker B, PCM was missing. Each kitchen was loaded with 1 kg of water (500 grams in two similar cooking vessels).

Properties of stearic acid: [19]

1. Density- 847-965 (kg/m<sup>3</sup>)
2. Latent heat of fusion- 169 (kJ/kg)
3. Melting temperature- 52°C
4. Specific heat- 1.590 (kJ/kg K)

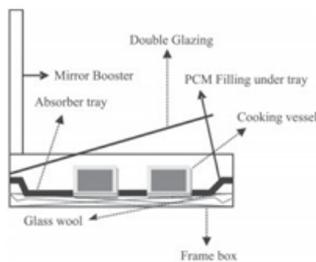


Figure 8: Solar box type cooker with latent heat storage [18]

Temperature of cooker B was found maximum 124°C at 15:00 Hrs with ambient temperature as 32°C; On the same day cooker A successfully reached a maximum temperature 134°C at 16:00 hrs. Ambient temperature was measured near about 19°C with 53°C temperature of cooker B at the end of the day. In the evening at 19:00 Hrs, temperature of cooker A was

noted 64°C when ambient temperature was near about 19°C. In comparison to kitchen B, kitchen A could offer a warm environment so that the cooking medium remains hot / hot for a long time after the end of the cooking process. This temperature (approx. 64 ° C) can also be used to heat / heat certain drinking substances such as milk, soups and water, etc. in kitchen a after hours of sunshine thanks to the heat storage capacity of stearic acid. It has been found that the cooking time of cooker A is reduced by 15 minutes compared to a cooker without heat storage [18].

**Arabacigil.B et al. (2015)** [20] in 2015, he examined the possible use and effectiveness of paraffin wax in a new solar cooker box that was used during the day and at dusk. For these experiments, a kitchen with a reflective inner surface was designed, which was built by filling with paraffin wax and metal shavings. This box solar cooker with three-level internal reflectors consists of an external housing, an internal housing and external reflectors. The rectangular solar cooker has external dimensions of 643 mm × 520 mm × 290 mm and internal dimensions of 406 mm × 374 mm × 121 mm. The outer housing is made of 10 mm thick wood and is insulated with a double-glazed cover. The inner box consists of the reflective inner surfaces, the absorbent surface and the other surfaces and is made of 3 mm thick aluminum foil. Two of the inner surfaces are arranged at angles of 30 °, 45 ° and 75 ° [21, 22]. The box solar cooker closes with a double glass cover of 18 mm thickness. Four rectangular shaped reflectors with dimensions of 520 mm × 950 mm and 643 mm × 950 mm are used. The external reflectors are made of cardboard and the surfaces are covered with aluminum foil, which was selected as a reflective material due to its good reflectivity.

The space between the two aluminum sheets is filled with 5 kg of the PCM (paraffin wax) and 3.5 kg of the metal shavings. These shavings are used to ensure the homogeneous distribution of paraffin wax, and to make thermal contact with the inner absorber surface.

Properties of paraffin wax: [22-27]

1. Latent heat of fusion- 189 (kJ/kg)
2. Melting temperature- 58-60°C

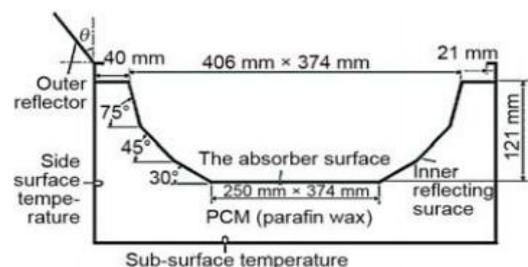


Figure 9: Schematic diagram of box-type solar cooker with inner and outer reflectors [20]

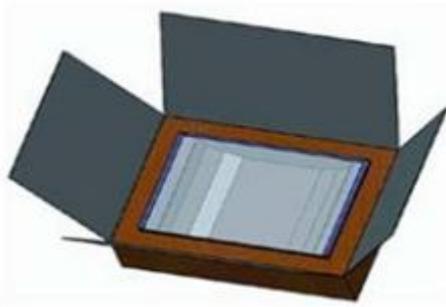


Figure 10: The outer box and reflectors [20]

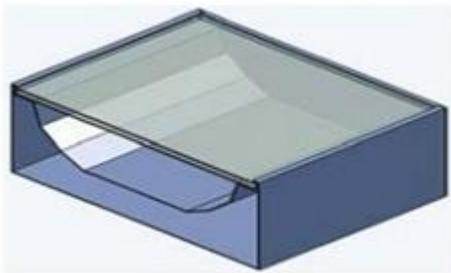


Figure 11: Inner box [20]

A series of experiments with and without the outer reflectors were performed on the box type cooker filled with paraffin wax. Instead of changing the position of the cooker, four reflectors were arranged at different angles on different days. The angle of the outer reflector can be varied between  $0^\circ$  and  $90^\circ$  with respect to the vertical axis. With the outer reflector angle of  $30^\circ$ , the solar cooker also receives reflected radiation from the inner reflectors. The maximum temperature of the paraffin wax decreases with an increase of the reflector angle of  $30^\circ$ . The reflected radiation makes a maximum contribution of 9.26% to the temperature of the paraffin wax.

For the reflector angle of  $30^\circ$  the maximum temperatures of the paraffin wax are  $71.6^\circ\text{C}$ ,  $83.4^\circ\text{C}$ , and  $75.5^\circ\text{C}$ , respectively. For a reflector angle of  $60^\circ$  and  $45^\circ$ , the maximum temperature of the paraffin wax is in the range of  $69.4^\circ\text{C}$  to  $74.5^\circ\text{C}$ . The maximum temperature obtained by paraffin wax was  $92.6^\circ\text{C}$ . The efficiency of the solar cooker without the reflectors is in the range of 46.20% to 50.80%. For reflector angles of  $30^\circ$ ,  $60^\circ$ , and  $45^\circ$ , the thermal efficiencies are approximately 68.70%, 50.10%, and 51.50%. The minimum contribution of the reflector on the thermal efficiency of the solar cooker is found to be approximately 17.9%. It is found that when the optimum angle of the outer reflector is  $30^\circ$ , the designed solar cooker gives the best performance. The heating time is found to decrease by one hour. The paraffin wax is capable of keeping PCM temperatures (near  $56^\circ\text{C}$ ) by the next morning. The efficiency of the solar cooker and the cooking times are found to depend strongly on the paraffin wax, the reflector angle, insulation,

and the solar intensity. The metal shavings are to provide a uniform temperature distribution inside the paraffin wax [20].

S.D. Sharma et al. (1999) [28] in the year 1999 designed and developed a PCM storage unit for a solar cooker to store solar energy during sunshine hours. The size of the cooking vessel is 18 cm in diameter and 6 cm in height and it can be inserted inside the PCM container for cooking purposes. The PCM container has a diameter of 25 cm and is 8 cm deep with 2 mm thickness. To enhance the rate of heat transfer between the PCM and the inner wall of the PCM container, 8 fins (1 x 3 cm) were welded at the inner wall of the PCM container.

Commercial grade acetamide (melting point  $82^\circ\text{C}$ ) is used as a latent heat storage material. The required mass of PCM was calculated to be 2.0 kg for cooking capacity of 0.75 kg. A double glazed box type solar cooker with reflector having 50x50 cm aperture area and 15 cm deep was used. To compare the thermal performance of this 'PCM Cooker', a similar box type solar cooker of 50x50 cm aperture area and 10 cm deep with standard cooking vessel was used as a 'Reference Cooker'. The orientation of the solar cooker was adjusted towards the sun after every 15 min.

Properties of commercial grade acetamide: [28]

1. Melting temperature of acetamide-  $82^\circ\text{C}$
2. Latent heat of fusion of acetamide-  $263 \text{ kJ/kg}$
3. Density of solid acetamide-  $1.159 \text{ g/cm}^3$
4. Density of liquid acetamide-  $0.998 \text{ g/cm}^3$
5. Specific heat of the acetamide-  $1.94 \text{ kJ/kg}^\circ\text{C}$

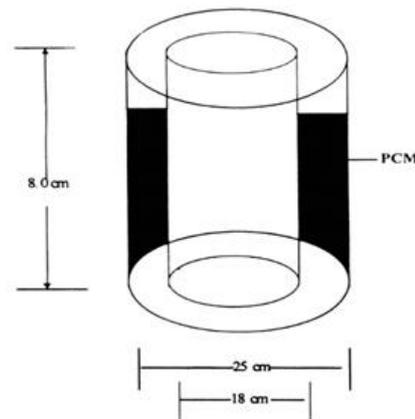


Figure 12: Schematic diagram of latent heat storage [28]

Cooking experiments were conducted using the 'PCM Cooker' and 'Reference Cooker' with the same quantity of load. They conducted the experiment in three batches in the month of June loaded with 0.1 kg rice and 0.2 kg water. The first batch was conducted between 10.30 am and 2 pm and the rice was found to be well cooked in both the cookers. The day was cloudy and hence the time taken for cooking was about 3

hours. The second batch was conducted between 4 pm and 4.35 pm. It was found that the rice was well cooked in both the cookers. The plate and PCM temperatures at the loading time were 136.1°C and 128.58°C, respectively. In the third batch the cooker was loaded with 0.15kg of rice and 0.25kg of water which was conducted between 6pm to 6.50pm. The plate and PCM temperatures at the loading time were 127.8°C and 130.68°C, respectively. It was found that the rice of the 'PCM Cooker' was well cooked and that of the 'Reference Cooker' was not cooked. Similarly experiments were conducted with different loads in the month of October.

It was found that during the month of June (summer), there was a possibility of cooking three batches (two noon and one evening) a day, while during the month of October (winter), cooking of two batches (noon and evening) of food were possible in the 'PCM Cooker'. However, evening cooking was not possible in the 'Reference Cooker'. It can be said that for evening cooking, the temperatures of the PCM and absorbing plate should be higher than 120°C at the time of loading for a PCM having a melting point of 82°C. During cooking experiments with the 'PCM Cooker', it was found that the time taken for evening cooking is about one hour. It was also observed that the rice was well cooked if maintained at about 95°C for 15 min [28].

Gianluca Coccia et al. (2020) [29] in the year 2020, conducted outdoor experimental tests on portable solar box cooker coupled with thermal energy storage based on a PCM. The proposed solar box cooker is composed of a wooden box containing a zinc-coated steel frame with the function of a cooking chamber. The box is surrounded by 8 booster mirrors that allow an additional amount of solar radiation to be reflected and concentrated towards the cover and the cooking chamber. The system is composed of two cylindrical stainless steel pots. The outer pot has a diameter of 23 cm and was painted with a black coating. The inner pot, has a diameter of 19 cm and was filled with the testing fluid (water or silicone oil). Four bolts were used to connect the two pots, and the corresponding annulus was filled with the PCM. The black paint is used for absorbing the maximum amount of solar radiation and protecting the metal parts from oxidation. With respect to the black paint, the selective coating shows a solar absorptance factor of about 90%. The cooking chamber metal walls were thermally insulated to reduce heat losses and obtain higher operating temperatures. The cooker prototype has a maximum height of 75 cm and a mass of about 20 kg. The PCM used in thermal energy storage is erythritol with mass 2.5 kg.

Properties of erythritol: [29]

1. Melting temperature of erythritol- 117.7°C
2. Latent heat of fusion of erythritol- 339.8 kJ/kg

3. Density of solid erythritol- 1480 kg/m<sup>3</sup>
4. Density of liquid erythritol- 1300 kg/m<sup>3</sup>
5. Specific heat of solid erythritol- 1.383 kJ/kg K
6. Specific heat of liquid erythritol- 2.76 kJ/kg K

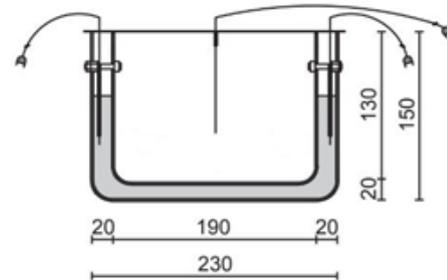


Figure 13: Schematic diagram of thermal energy storage

Outdoor tests were conducted from May to October during the years 2017, 2018, and 2019. To guarantee a proper tracking of the sun, the cooker alignment with the sun was adjusted about every 5– 10 min. Two different tests were carried out; tests without load where the maximum temperature attained by the solar cooker was determined. Another was tests with load where the tests were carried out by loading the solar cooker with a testing fluid, water or silicone oil. This allowed us to study the behavior of the cooker in the presence and absence of the erythritol based TES.

- *Tests without load:* Three tests without load were carried out under different environmental conditions. The maximum absorber temperature was about 189°C for the ambient temperature of 31.27 °C.
- *Tests with water:* Outdoor tests were carried out with water on different days. The cooker was loaded with 2kg of water. The ambient temperature was 25 °C during the interval. Water took about 1.68 hours to heat up in the range 40–90°C.
- *Tests with silicone oil:* Five tests were performed using the cooker loaded with 1.5 kg of silicone oil. The ambient temperature was 17.35°C. The test was divided into an initial heating phase and a following cooling phase. The former phase took about 1.58 hours to take the silicone oil temperature from 55 °C to 125 °C. When the silicone oil temperature was higher than 130°C, the solar cooker was closed to solar radiation and left cooling down. During the cooling phase, the average ambient temperature was 17.35 °C and the silicone oil required 0.31 hours to take its temperature from 125 to 100 °C.
- *Tests with silicone oil and PCM:* The behavior of the solar box cooker coupled with the PCM-based thermal storage unit was studied by carrying out 4 outdoor tests. The thermal storage system, including 2.5 kg of erythritol, was filled with 1.5 kg of silicone oil. The ambient temperature was 19.33 °C. When the solar cooker was used with the TES, the heating

process required about 1.58 to 2.52 hours to take the silicone oil temperature from 55 to 125 °C. The increase in the heating time is due to the presence of the additional mass of PCM. The cooling phase, instead, required 1.65 hours to decrease the testing fluid temperature from 125 to 100 °C. During this phase, the average ambient temperature was 19.87 °C. The silicone oil cooling time increased by more than 5 times with the use of PCM-based TES.

It was found that the presence of the erythritol-based TES stabilizes and extends the use of the portable solar box cooker when the solar source is absent or intermittent. When the solar cooker is coupled with the PCM, the heating time is increased by an average 114.41% respect to the average performance obtained with silicone oil only due to added mass of PCM. The average load cooling time in the range 125–100 °C was determined to be about 351.16% larger than that without the TES solution. This result proves the activeness of the proposed system [29].

#### 4.2 Parabolic Solar cooker

**L. Chitra et al. (2019)** [30] in the year 2019, carried out an experimental investigation on a solar cooker with heat storage. To make the usage of existing parabolic solar cookers more effective and efficient, PCM storage technology is incorporated in the cooking pot. The conventional parabolic collector is modified such that the compact parabolic collector which reflects the solar radiation to the boiling pot is placed at the center. A coaxial double layered boiling pot was fixed at the center of the parabolic collector. The gap between two layers of cooking pot will be filled with the specific PCM for heat storage during sunshine hours. Magnesium nitrate hexahydrate ( $Mg(NO_3)_2 \cdot 6H_2O$ ), an inorganic salt hydrate PCM is used as the storage medium [31].

The parabolic collector material is 3M Reflective film; base parabolic concentrator is made from aluminum sheet; the cooking pot - Aluminum or stainless steel coaxial cylindrical and insulation box from Polyurethane foam sheet. The diameter and height of the dish are about 52 cm and 13 cm. Focal length of the dish from the bottom of the solar concentrator is about 45 cm. The receiver is a two layered coaxial cylindrical container with a gap between the layers is about 1cm. The gap between the two layers will be filled with the PCM upto the vent of the receiver.

Properties of Magnesium nitrate hexahydrate: [32]

1. Melting temperature- 89°C
2. Density- 1.46 g/cm<sup>3</sup>

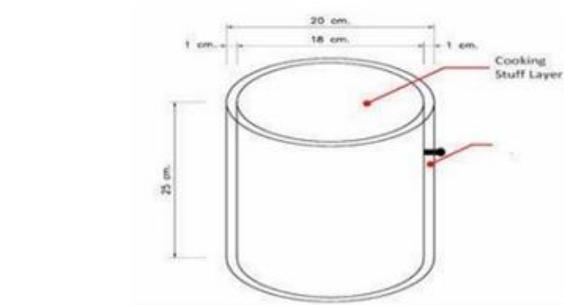


Figure 14: Thermal cycling process of PCM [30]

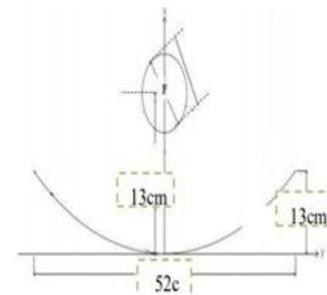


Figure 15: Geometric representation of the system [30]

After the PCM charging process during sunshine hours, the cooking pot is placed in an insulation box for the off sunshine cooking process. The amount of heat stored in the PCM is sufficient to cook one batch of food materials during off sunshine hours. The total cost of the system with materials available in the market is around Rs. 8500. The efficiency of the designed system is about 44% in the month of March. The time taken to boil 1.5 liters of water with PCM present in the gap of the cooking pot layers is around 10 minutes. From the results of the proposed system, it can be concluded that the designed portable parabolic boiler with PCM depository can be a good output for the fossil fuel free boiling technology [30].

**Kushal S et al. (2015)** [33] in the year 2015, reviewed relevant studies related with solar cooking using latent heat storage and performed experimental analysis on a solar cooker based on a parabolic dish collector with thermal storage unit. This system consists of parabolic dish collector, solar cooker, and insulator box. Acetanilide is used as a phase change material and it is filled in between the hollow space of the inner and outer wall of the solar cooker. In this system, segments of the reflecting material are joined to form the concentrator.

Properties of Acetanilide:

1. Melting point - 118°C
2. Latent heat - 222 kJ/kg
3. Specific heat capacity– 2 kJ/kg°C

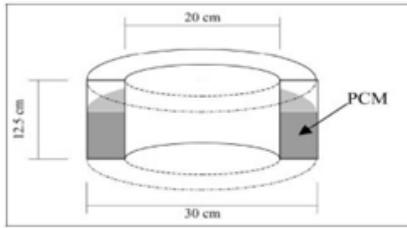


Figure 16: Latent heat storage unit for evening cooking in a solar cooker [34]

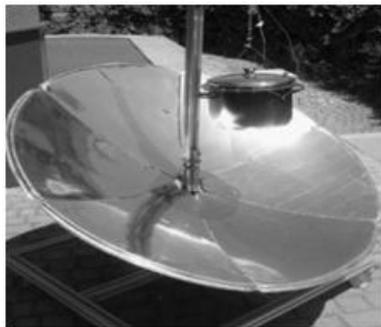


Figure 17: Complete system of solar cooker with PCM [33]

In the experimental setup, cooking experiments were conducted using a solar cooker based on a parabolic dish collector with thermal storage unit. Experimental setup was developed keeping provision for further likely modifications in future. The system was fitted with required measuring instruments with proper accuracy. PCM was poured in the cooking vessel in molten form before experimentation. The readings were taken for: without cooking load and with cooking load. Experiments were conducted on four different cases:

1. Solar cooker with cooking load and with glazing (loading at 10.30 am)
2. Solar cooker with cooking load and without glazing (loading at 10.30 am)
3. Solar cooker without cooking load and glazing (loading at 3.30 pm)
4. Solar cooker without cooking load and without glazing (loading at 3.30 pm)

In the case of the solar cooker with PCM and without glazing, the maximum temperature achieved by PCM is lower compared to the cooker with glazing. This cooker is 7 to 9% less efficient compared to the cooker with glazing due to loss of heat by air flowing around the cooker, which is minimized due to glazing. It is found that the system with full day cooking load and with glazing is more efficient than other systems because it stores more energy as compared to other cases and PCM temperature achieved is also more compared to other cases. Glazing helps to avoid heat loss to surrounding air due to air flow and improves performance. Efficiency

improvement due to glazing is about 6 to 8%. End temperature achieved in all four cases is 89°C, 81°C, 78°C & 72°C respectively. By possible use of glazing in the case of a cooker with evening loading; the end temperature achieved is 78°C which is more than the sterilization temperature of most of the food [33].

### 4.3 Evacuated Tube solar cooker

S.D.Sharma et al. (2004) [35] in the year 2004, investigated the thermal performance of a prototype solar cooker based on an evacuated tube solar collector with PCM storage unit. The setup consists of an ETSC, a closed loop pumping line containing water as the heat transfer fluid (HTF), a PCM storage unit, cooking unit, pump, relief valve, flow meter and a stainless steel tube heat exchanger. Two panels, each containing six collector tubes, were used. The absorbing plate of the ETSC was tilted at 20° facing due south. The PCM storage unit has two hollow concentric aluminum cylinders, and its inner and outer diameters are 304mm and 441mm, respectively, and 420mm deep with 9mm thickness. The space between the cylinders was filled with 45 kg erythritol for use as the PCM. The dimensions of the cooking vessel are 297mm in diameter and 300mm in height, this can be easily inserted inside the PCM storage unit. A pump (370W) circulates the heated water (HTF) from the ETSC through the insulated pipes to the PCM storage unit using a stainless steel tubing (diameter 21.6mm) heat exchanger that wraps around the cooking unit in a closed loop.

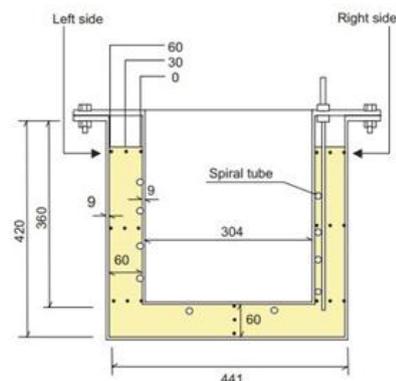


Figure 18: Vertical sectional view of PCM storage unit [35]

Cooking experiments were conducted using the ETSC and PCM storage unit. The collected solar energy transferred to the PCM raises its temperature from the initial temperature to the higher temperature around the melting point. In the case of a large temperature difference between the heated water (HTF) and the PCM, the initial change in temperature is a faster process because of the high heat transfer rate to the PCM. After this rapid increase, the temperature becomes somewhat constant during the melting period. A test run was

conducted without load with an average flow rate of 6.43 l/min.



Figure 19: Stainless steel tube around PCM heat storage unit [35]

The maximum temperature of PCM was observed as 138°C [35], which is higher than the lowest temperature (near 75°C) required for cooking most types of food [21]. This experiment was undertaken to see whether the PCM was capable of evening cooking or not. An experiment was conducted for noon and evening cooking with a load of 8 kg water and an average flow rate of 8.14 l/min. Almost all the PCM was melted except on the bottom with maximum temperature of near 130°C. PCM temperatures were found near 100°C the next morning, so once the food is cooked it can be kept warm until the next morning. During this experiment, the heat transfer rate from the PCM unit to the cooking vessel was found to be very poor as no water filled in the gap to increase the heat transfer, and because of the poor insulation around the PCM storage unit.

The PCM did not melt in January (winter) in Japan. In summer, PCM temperatures reached more than 110°C at the time of evening cooking. Hence, erythritol is a promising PCM for solar cooking. This system is expensive but shows good potential for community applications. It provides high PCM temperatures of up to 130°C without tracking and allows cooking in the shade and also in a conventional kitchen during non-sunshine hours or in the evening [35].

Surjeet Saini et al. (2017) [36] in the year 2017, performed experiments to investigate the thermal performance of solar cooker with thermal storage unit based on evacuated tube collectors. It consists of an evacuated tube collector, a solar cooker, gate valves, pump and connecting pipes. There are eleven evacuated tubes with the length 1.5m and diameter of the outer glass tube and coated absorber tube are 0.047m and 0.037m respectively. Solar cooker is made up of two hollow concentric cylindrical vessels. The outer vessel having diameter 0.21m is of aluminum and filled with 3kg of commercial grade Acetanilide(MP=119°C). The inner vessel having diameter 0.11m made of copper is used for cooking

and a lid is provided over the same. The dimensions of the reflector are 1.39m x 0.90m. It is basically zinc coated galvanized aluminum sheet with a reflectivity of 86%. The two gate valves are provided at the inlet and exit of the solar cooker. In the experimental setup, transformer oil is used separately as heat transfer fluid. In this setup a copper pipe is coiled around the copper cooking vessel and a pump is used which continuously circulates HTF from the header to the cooking vessel so that heat is transferred from ETC to the PCM with very low flow rate so that more heat is transferred.



Figure 20: Photograph of the experimental setup [36]

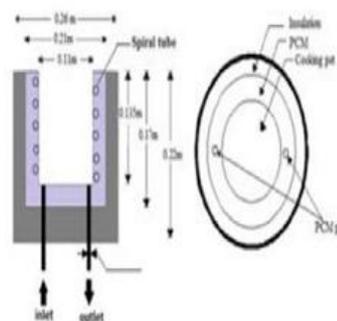


Figure 21: Schematic diagram of solar cooker [36]

**Evacuated tube solar cooker with transformer oil as heat transfer fluid:**

Day 1: Both gate valves were opened during discharging of PCM throughout the day. The experiment was performed with thermal oil as HTF with cooking load of 700ml of water. The maximum temperature inside the evacuated tube was 120.9°C at 13:00hr while at the same time, temperatures at header exit, header inlet, PCM, cooking port were 107.6°C, 104.4°C, 96.1°C and 95.7°C respectively. The maximum temperature attained by HTF inside cooker and PCM were 108.9°C and 106.3°C respectively. The cooking load attained maximum temperature of 84.8°C at 17:00 hrs.

Day 2: Both gate valves were closed during discharging of PCM. The solar cooker was loaded with same cooking load of 700ml of water. Ambient temperature was in the range of

23.5°C to 31.0°C. The maximum temperature inside the evacuated tube was 128.3°C at 13:00hr and at the same time temperatures at header exit, header inlet, PCM, cooking port were 107.8°C, 104.3°C, 98.7°C and 101.4°C respectively. The maximum temperature attained by HTF inside the cooker and PCM were 109.2°C and 101.9°C respectively. The cooking load attained a maximum temperature of 91.7°C at 17:00hrs.

**Solar cooker with transformer oil as heat transfer fluid and both valves closed:**

Day 3: With cooking load (200g pulse + 700ml water), ambient temperature was found in the range of 23.0°C to 31.5°C. The maximum temperature inside the evacuated tube was 141.2°C at 13:00hr while at the same time temperatures at header exit, header inlet, PCM, cooking port were 117.1°C, 111.1°C, 103.2°C and 89.7°C respectively. The maximum temperature attained by HTF inside the cooker and PCM were

117.1°C and 105.9°C respectively. The maximum temperature of food was 76.3°C at 16:00hr.

Day 4: With cooking load (300g pulse + 700ml water), the ambient temperature was found in the range of 23.0°C to 31.5°C. The maximum temperature inside the evacuated tube was 144.4°C at 12:30 hr while at the same time temperatures at header exit, header inlet, PCM, cooking port inlet were 113.7°C, 107.7°C, 99.3°C and 87.3°C respectively. The maximum temperature attained by HTF inside the cooker and PCM were 119.7°C and 111.5°C respectively.

The successful cooking was carried out with transformer oil as HTF and both pump ON and OFF showed the feasibility of solar cooker based on evacuated tube collector for day time cooking as well as evening time cooking in Indian climatic conditions. So overall it can be concluded that acetanilide is the most suitable phase change material for evening cooking in Indian summer climate as stored heat is maximum [36].

Table 1: Overview of Literature Survey

S. No	Year	Author	PCM	M. P °C	Latent heat of fusion kj/kg	Type of cooker	PCM temp achieved (°C)
1.	2017	Vigneswaran VS et al.	Oxalic acid dihydrate	101	370	SBC	121
2.	2013	Abhishek Saxena et al.	Stearic acid	52	169	SBC	134
3.	2015	Arabacigil.B et al.	Paraffin wax	60	189	SBC	92.6
4.	1999	S.D.Sharma et al.	Acetamide	82	263	SBC	130.68
5.	2020	Gianluca Coccia et al.	Erythritol	117.7	339.8	SBC	125
6.	2019	L. Chitra et al.	Magnesium nitrate hexahydrate	89	172	Parabolic	100
7.	2015	Kushal S et al.	Acetanilide	118	222	Parabolic	141
8.	2004	S.D.Shar ma et al.	Erythritol	117.7	339.8	ETSC	138
9.	2017	Surjeet Saini et al.	Acetanilide	118	222	ETSC	111.5

## V. CONCLUSION

The use of conventional Solar Cookers is limited because cooking of food is not possible during cloudy days or in the evening time. We can overcome this drawback by storing the solar energy in the solar cooker which can be used to cook the food whenever required. This is possible with the implementation of latent heat storage i.e PCM in the cooker. PCMs store energy during sunshine hours which can be utilized for evening/night cooking. The main objective of this paper is to explore the feasibility of various solar cookers with the thermal storage unit for late evening cooking.

1. Incorporating PCM surrounding the cooking pot and encapsulating it is an efficient way to effectively use the harnessed solar energy stored in the PCM.
2. Glazing the solar cooker is a good way to avoid heat loss due to air flow and thus improves the performance of the solar cooker.
3. The parabolic dish collector is one of the best ways to use solar energy efficiently due to its advantages to convert abundantly available solar energy into an effective and convenient form of heat energy which can be used for cooking.
4. Experimental analysis showed that Acetanilide and Erythritol achieved higher temperature range due to their high melting point temperatures when used in parabolic solar cooker and evacuated tube solar cooker respectively. Acetanilide achieved a maximum temperature of 141°C whereas erythritol achieved a maximum temperature of 138°C.
5. With the use of PCM in cooking, the heating time increases due to additional mass of PCM along with cooking load but the cooling period is longer as compared to conventional cooker, thus ensuring that the temperature inside the cooker is high enough for evening/night cooking.

Cooking energy plays an important role in sustainable energy management in Indian households. Solar energy is available almost throughout the year in most parts of India. Thus there is a lot of potential for solar cooking as an alternative to cooking based on LPG gas.

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