SOLAR COOKERS WITH THERMAL ENERGY STORAGE SYSTEMS- A REVIEW

[1]Mohammad Tausif N Ansari,[2]Dr.Kalpesh V. Modi
[1]Research Scholar& Lecturer,[2]Associate Professor
[1]Mechanical Engineering Department,
[1]Government Polytechnic, Valsad,India

Abstract :Food is the basic requirement for human being but raw form of food is not suitable for the consumption. Hence, need to cook a raw food with higher nutritional value but conventional cooking leads to environmental pollution as well as food with lower nutritional value. Solar energy is the best alternative to cook a food with higher nutritional value and it is available in abundance. The most economical, effective and simple way to utilize the solar energy for domestic purpose is solar cooking. Solar cookers are the most convenient and extensively used for cooking the food. Numerous types and designs of solar cookers are available at present. But due to the higher cooking time cycle and less effective during the cloudy weather and off-sunshine hours, the solar cookers are not popular in regular cooking or spreaded worldwide application. Thermal energy storage is essential whenever there is a mismatch between the supply and consumption of energy. Latent heat storage in a phase change material is very attractive because of its high storage density with small temperature swing. The choice of PCM plays an important role in addition to heat transfer mechanism in the PCM. Hence, the present review emphasis on the performance of solar cookers with the aid of thermal energy storage material. The possibility and performance of cooking during off sunshine hours using PCMs as storage media are collected in this study.

I. INTRODUCTION

Wood, petroleum and natural gas are the main energy sources for cooking, frying and baking in India. These activities represent the major portion of energy consumption in the domestic sectors in our country. As the world becomes more environmental conscious, there is a rising concern regarding deforestation and finding renewable energy options to fossil fuels. Currently, solar energy is meeting the vital energy requirements for a large percentage of the world's population particularly in developing countries like India. Most of the thickly populated countries, specially India are blessed with abundant solar radiation with a mean daily solar radiation in the range of 5–7 kWh/m^2 and have more than 275 sunny days in a year **[1]**. Solar cooker are generally used to cook the nutritious food using solar energy. One of the problems of many solar cookers is the thermal storage where cooking during cloudy periods and late afternoon is not possible. Recently, a very few papers have appeared concerning the use of phase change materials (PCMs) as storage materials inside direct and indirect solar cookers.

Though there is a history for solar cooking since 1650, the interest in solar cooking was fuelled by the aftermath of the Second World War with its fuel shortages and rationing. Hence, solar cookers have a high potential of diffusion in these countries and offers a viable option in the domestic sector. It is identified as an appropriate technology as it has numerous advantages such as no recurring costs, potential to reduce drudgery, high nutritional value of food and high durability. In spite of these advantages, the main hurdle in its dissemination are resistance to acceptance a new technology, intermittent nature of sunshine, limited space availability in urban areas, higher initial costs and convenience issues. The growing urban lifestyle also warrants faster cooking. Moreover the use of solar cookers would result in the reduction of the release of CO_2 in the environment. These solar cookers use the amount of energy available directly from the sun instead of non-renewable energy sources (charcoal, wood, fossil fuels). There is a large variety of solar cookers which focus the sunlight directly on the cooking pot. Thus their use is limited to sunny days in warm areas and also not possible to cook in evening. To overcome this problem and improve the development of solar cookers, a heat storage unit is necessary. It can then be theoretically possible to cook during the night or on a cloudy day. Thermal energy storage (TES) systems can alleviate the mismatch between energy supply and demand particularly in cases where intermittent energy resources like solar energy are concerned. The two main contenders for domestic scale TES applications are sensible heat TES (SHTES) and latent heat TES (LHTES). SHTES is cheaper than LHTES for small storage volumes but its energy storage density is lower. Low thermal conductivities, degradation of phase change materials (PCMs) after numerous charging and discharging cycles and the expense in manufacturing of PCMs are added disadvantages of PCMs as compared to SHTES materials for small scale domestic usage. Sensible heat storage materials include thermal oils, rocks, water, metals and salts. Solid particulate matter requires a heat transfer fluid to store thermal energy at medium to high temperatures. Water as a heat transfer fluid should be pressurized to store energy at temperatures above its boiling point. Thermal oils have the advantage that they act both as the heat transfer and the heat storage medium for medium to high temperature domestic applications. These applications include steam generation and cooking of food. Although thermal oils are more expensive than water which is in abundance, the use of water in medium to high temperatures is limited by its boiling point. For small scale domestic applications which require non-sophisticated heat exchangers, thermal oils can be utilized. For domestic cooking, the temperature range of the storage medium should be around 100 °C to 250 °C, whereas for water heating the temperature range should be around 50 °C to 90 °C. These domestic applications are particularly more relevant to the developing world where poverty, disease and malnutrition are of particular concern. Thermal oils can be stored in simple non-pressurized vessels and can be used for these two mentioned applications to reduce the use of electrical energy for these processes. Thermal oils can be heated solely with renewable energy sources like solar energy or biogas, or they can be combined in hybrid systems with convectional energy resources like liquid petroleum gas (LPG) and electrical energy **[2]**. Apart from various design of solar collector and efficiency studies, energy storage is a fundamental requirement of all solar energy systems and among various storage techniques, latent heat thermal energy storage is particularly attractive due to its ability to provide high-energy storage density and its characteristics to store heat at constant temperature corresponding to the phase transition temperature of phase change material (PCM). PCMs have to be chosen considering their thermodynamic, kinetic, chemical and economic aspects and should have desirable properties such as high density, specify heat, latent heat of fusion, thermal conductivity, chemical stability, non-corrosive to containment materials and low cost **[3]**.

II. LITERATURE REVIEW ON SOLAR COOKERS WITH THERMAL ENERGY STORAGE SYSTEMS:

D.Buddhi and L.K.Sahoo**[4]** designed and fabricated a box-type solar cooker with latent heat storage for climatic conditions of India. The experimental results demonstrated the feasibility of using a phase change material as the storage medium in solar cookers and made it possible to cook the food even in the late evening with a solar cooker having latent heat storage. The experimental results were compared with results of a conventional solar cooker. Commercial grade stearic acid (melting point : 55.1 °C and latent heat of fusion : 160 kJ/kg) was used as a PCM. Generally, phase change materials have positive volumetric expansion on melting, therefore, the container should provide an extra volume. Figure 1 shows the sketch of a box-type solar cooker for one vessel having a PCM to store the solar energy. The cooker consists of an aluminium absorbing tray ‘A’ of dimensions 0.28 m x 0.28 m at the bottom, 0.40 m x 0.40 m at the top for the double glass lid, and the vertical depth of the tray was 0.08 m. The thickness of the aluminium sheet was 0.006 m. In the centre of the absorbing plate, a cylindrical container of 0.165m diameter and 0.02 m in depth was welded (shown in Figure 1 by ‘C’), and the cooking pot was kept tightly in it. Aluminium fins were also provided at the inner side of the tray and cylindrical container. The outer tray ‘B’ of size 0.40 m x 0.40 m x 0.108 m was also made from the same aluminium sheet. The distance between tray ‘A’ and tray ‘B’ was kept at 0.025 m on the bottom side. Tray ‘B’ was filled with 3.5 kg of commercial grade stearic acid and it was made sure that the PCM should be in good contact with the bottom side of tray ‘A’. These two trays were placed in an aluminium box of dimensions 0.5 m x 0.5 m x 0.14 m. The space between tray ‘B’ and the casing was filled with glass wool to provide thermal insulation to the bottom and sides of the solar cooker. The absorbing tray was provided with a double glass lid (0.4 m x 0.4 m) hinged to one side of the casing at the top. The aluminium cooking pot (0.16 m in diameter and 0.06 m in height) with cover was kept in the pot container ‘C’. The aluminium tray ‘A’, cooking pot and its cover were painted with a dull black paint on the outside.

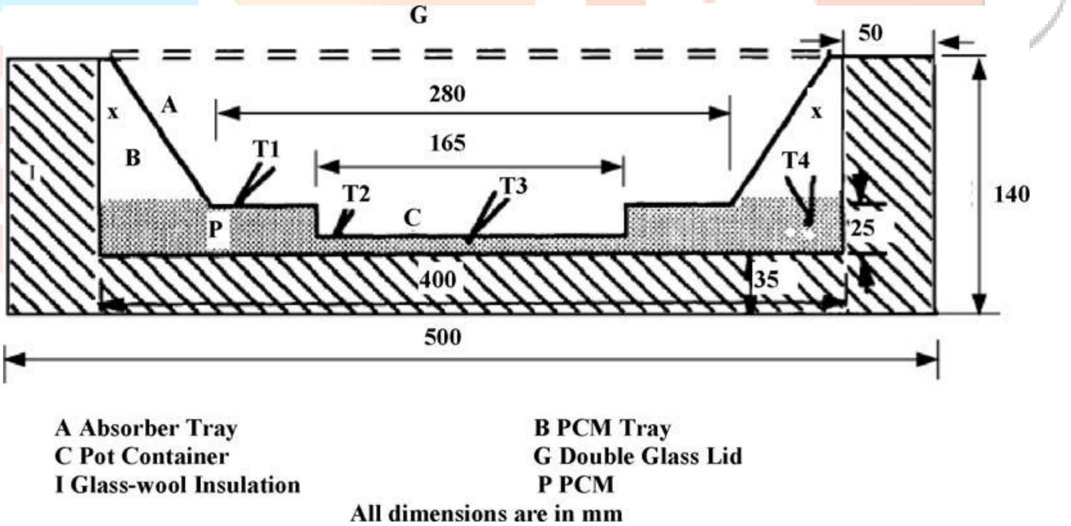

Fig. 1. Schematic diagram of the box of a solar cooker with storage. [4]

Sharma et al. **[5]** developed and investigated the performance of a solar cooker with latent heat storage unit for late evening cooking. They used commercial grade acetamide (having melting point : 82 °C and latent heat of fusion : 263 kJ/kg) as a latent heat storage material. They designed, fabricated and tested a cylindrical PCM storage unit for a box-type solar cooker to cook the food in the late evening. This unit surrounds the cooking vessel. As the rate of heat transfer between the PCM and the food is higher, cooking can be faster. For this purpose, a PCM container to hold the cooking vessel was designed and fabricated as shown in Fig. 2.

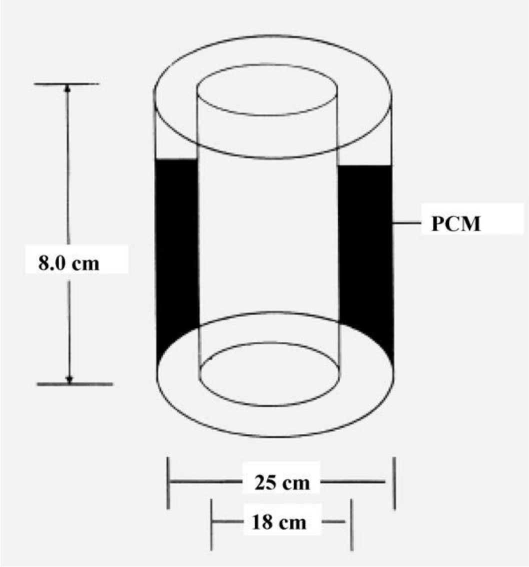

Fig. 2. Schematic diagram of latent heat storage unit. [5]

It has two hollow concentric aluminium cylinders of diameters 0.18 m and 0.25 m, and is 0.08 m deep with a 0.002 m thickness. The space between the cylinders was filled with acetamide as a PCM. The dimensions of the vessel used for cooking were 0.175 m diameter and 0.10 m height, and it can be inserted inside the PCM container for cooking purposes. Also eight fins of dimensions (0.01 m x 0.03 m) were welded at the inner wall of the PCM container to enhance the heat transfer rate between the PCM and the inner wall of the PCM container. They concluded that by using 2.0 kg of acetamide as PCM, the second batch of food could be cooked if it is loaded before 3:30 p.m. during the winter season. Cooking of three batches a day during summer and two batches a day during winter was successfully achieved with the designed storage unit.

Hussein et al. **[6]** constructed and tested novel indirect solar cooker with outdoor elliptical cross section wickless heat pipes, flat-plate solar collector and integrated indoor PCM thermal storage and cooking unit under actual meteorological conditions of Giza, Egypt. Two plane reflectors were used to enhance the insolation falling on the cooker's collector. They used magnesium nitrate hexahydrate (Tm = 89 °C, latent heat of fusion = 134 kJ/kg) as the PCM inside the indoor cooking unit of the cooker. It was found that the average daily enhancement in the solar radiation incident on the collector surface by the south and north facing reflectors was about 24%. Different experiments were performed on the solar cooker without load and with different loads at different loading times to study the possibility of benefit from the virtues of the elliptical cross section wickless heat pipes and PCM in indirect solar cookers to cook food at noon and evening and to keep food warm at night and in early morning. Cross sectional views of the indirect solar cooker under investigation are shown in Figs. 3-5. It consists of three main components: (i) outdoor flat-plate solar collector, (ii) indoor PCM cooking unit and (iii) closed loop wickless heat pipes network. The evaporator section of the wickless heat pipes network is incorporated into the outdoor collector, while its condenser section is incorporated into the indoor PCM cooking unit as shown in Fig.3

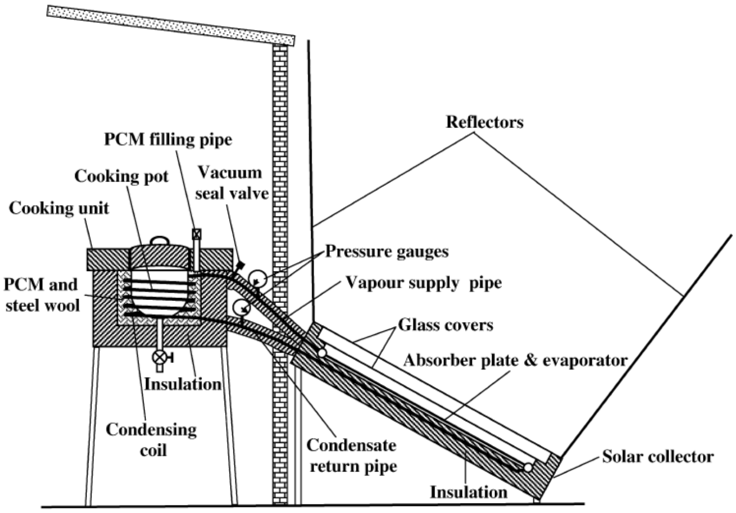

Fig. 3. Cross sectional side view of the solar cooker showing its main components. [6]

To manufacture the evaporator section of the wickless heat pipes network, 15 commercial copper tubes of 0.016m nominal diameters were cut to 0.75 m length. Copper tubes were deformed to have elliptical cross sections of 0.022 m x 0.014 m major and minor diameters, respectively. These tubes were arranged vertically, parallel to each other, as risers with a pitch distance of 0.13 m and brazed from their ends to two horizontal headers made of copper tubes of 0.0254 m nominal diameter to form the evaporator assembly as shown in Fig. 4.

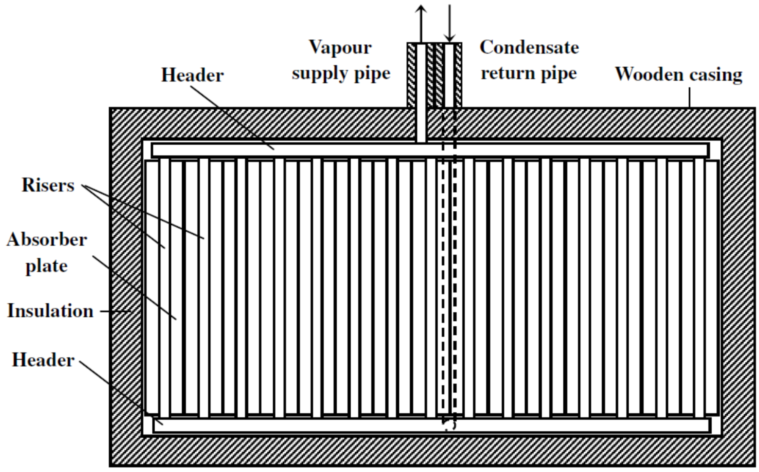

Fig. 4. Cross sectional front view of the wickless heat pipes flat plate solar collector. [6]

Two copper tubes of 0.0127 m nominal diameter (vapour supply and condensate return pipes) were brazed to the headers of the evaporator assembly to connect it with the condenser section of the closed loop wickless heat pipes network as shown in Figs. 3 and 4. Each riser of the evaporator assembly was then welded to a copper absorber plate of 0.3 mm thickness, 0.13 m width and 0.73 m length. The upper surface of the absorber plate/evaporator assembly was then treated and painted black. The absorber plate/evaporator assembly was incorporated into a wooden casing insulated on the back and sides by 0.1 m thick glass wool insulation. The collector wooden casing was covered by ordinary tempered double glass covers of 4 mm thickness. To enhance the insolation falling on the collector, two plane reflectors (facing south and facing north reflectors), made of polished stainless steel sheets, were mounted on the top and bottom edges of the collector. The condenser section of the closed loop wickless heat pipes network was made of a copper tube of 9.5 mm nominal diameter and about 7 m length in the form of a helical coil as shown in Fig. 5.

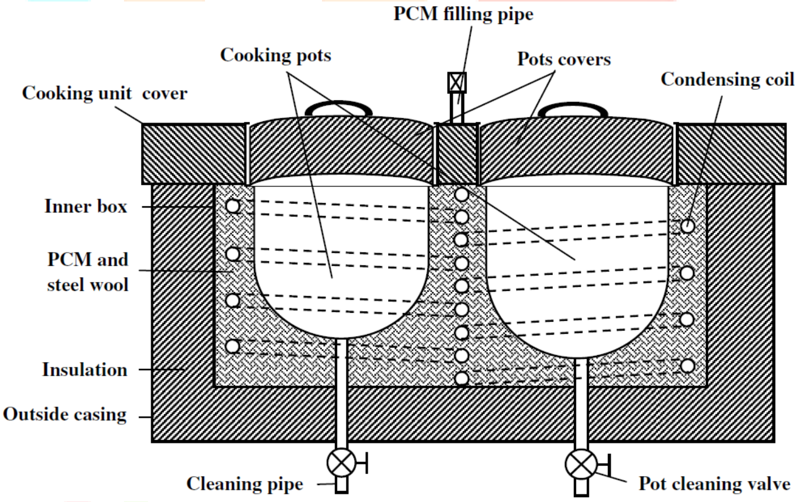

Fig. 5. Cross sectional front view of the indoor PCM cooking unit. [6]

The condenser section was then flame heated, and its inner surface was cleaned and rinsed by the procedures performedon the evaporator assembly. It was then incorporated into an indoor cooking unit that has an inner galvanized iron box of 0.56 m length, 0.28 m width and 0.165 m height. Two cooking pots of 3 and 4 litre capacities were built in the inner box of the indoor cooking unit inside the helical condensing coil. Each pot was equipped with a cleaning pipe, a cleaning valve and a vapour tight cover insulated by 0.1 m thick glass wool insulation. The space between the pots and the inside surface of the inner box was filled with magnesium nitrate hexahydrate {$Mg(NO_3)_2.6H_2O$} as PCM and steel wool. The steel wool was imbedded in the PCM with 20% volume ratio to improve its thermal conductivity. The inner box/pots assembly was then incorporated into a galvanized iron casing insulated on the back and sides by 0.1 m thick glass wool insulation. Then, the cooking unit assembly was covered by an insulated galvanized iron cover of 0.1 m thick glass wool insulation.

El-Sebaii et al. **[7]** investigated the influence of the melting / solidification fast thermal cycling of commercial grade magnesium chloride hexahydrate ($MgCl_2.6H_2O$) on its thermo-physical properties; such as melting point and latent heat of fusion, to be used as a storage medium inside solar cookers. One thousand cycles were performed in a sealed container under the extra water principle. The thermo-physical properties were measured using the differential scanning calorimetric technique. It was indicated that $MgCl_2.6H_2O$ with the extra water principle and hermetically sealing of the container is a promising phase change material for cooking indoors and during low intensity solar radiation periods. It was also found from the melting / solidification behaviour of $MgCl_2.6H_2O$ that it solidifies almost without supercooling ; except in few cases of 0.1–3.5 °C of supercooling.

Mussard et al. **[8]** conducted comparative experimental study of two solar cookers : (i) the widespread SK14 cooker and (ii) the prototype of a solar concentrator (parabolic trough) using a storage unit. The SK14 is a direct solar cooker where the cooking pot is placed on the focal point of a parabolic dish; in the trough system heat is transported from an absorber to a storage unit by means of a self-circulation loop filled with thermal oil. Cooking takes place directly on the top of the storage. Cooking experiments were conducted to compare the performance of these two methods of heat extraction. Both boiling and frying were tested to estimate the cooking efficiency of the heat storage system. Simulations were conducted to optimize and improve the system. The SK14 is a solar cooker developed by the Foreign Aid Group Solar Cooker ot the State Technical College Altoettinge.V in Germany (Fig. 6), the system is a parabola made with reflective strips, its diameter is 140 cm. The parabola is held by a structure which allows rotation to follow the sun. A holder is placed so that the vessel is exactly at the focal point. A special pot painted black is provided with the system. The aperture of the collector was 1.54 m^2.

Fig. 6. SK14 system [8]

Fig. 7. Heat storage based system with parabolic trough [8]

The prototype was a solar concentrator with a heat storage unit. A closed loop self circulating oil system transfers the heat from an absorber to a storage unit. The absorber (part of the loop) was a copper tube, 1 m long and 22 mm diameter, painted black. The energy from the sun is focused on the absorber by a parabolic trough. The collector aperture is 1 m^2 and the focal length 20 cm. The aperture is lower than the SK14, so if storage is included, we can consider that the two systems have a similar bulk. Fig. 7 shows a picture of the prototype. The oil used was the Duratherm 630. Its thermal properties at 25 °C :

Heat capacity : $C_{PO} = 1.933$ kJ/kg K.

Density: $\rho_0 = 833$ kg/m^3.

The storage unit is a steel cylinder with a diameter of 0.202 m, insulated with 0.08 m of Pyrogel. It is full of oil and closed with a 1 cm-thick lid made of aluminium; this lid has 8 tubes containing a $NaNO_3$–KNO_3 binary mixture (called molten salts) having melting temperature around 210–220 °C.The evolution of the water temperature was linear for the SK14 due to the constant energy flux while the water temperature increase for the heat storage system slows down when reaching higher temperatures due to the (almost) constant temperature in the storage as shown in Fig. 8.

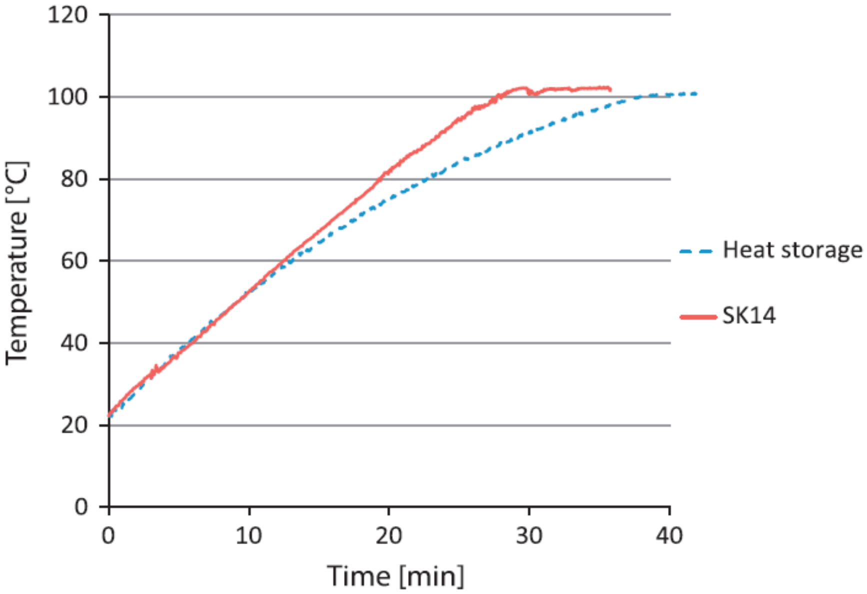

Fig. 8. Evolution of the water temperature during a boiling test – SK14 and heat storage-based system [8]

For the frying experiment, the temperatures of the oil and the meat were recorded as a function of the time until it reaches a temperature of 80 °C in the meat (Fig. 9). The middle of the meat reaches the cooking temperature in less than 20 min. With improved surface contact, this time would be reduced and in the range of acceptable times for food preparation.The system was able to keep heat during several hours and was perfectly suitable for cooking during the evening (up to 3 h after sunset) on a sunny day.

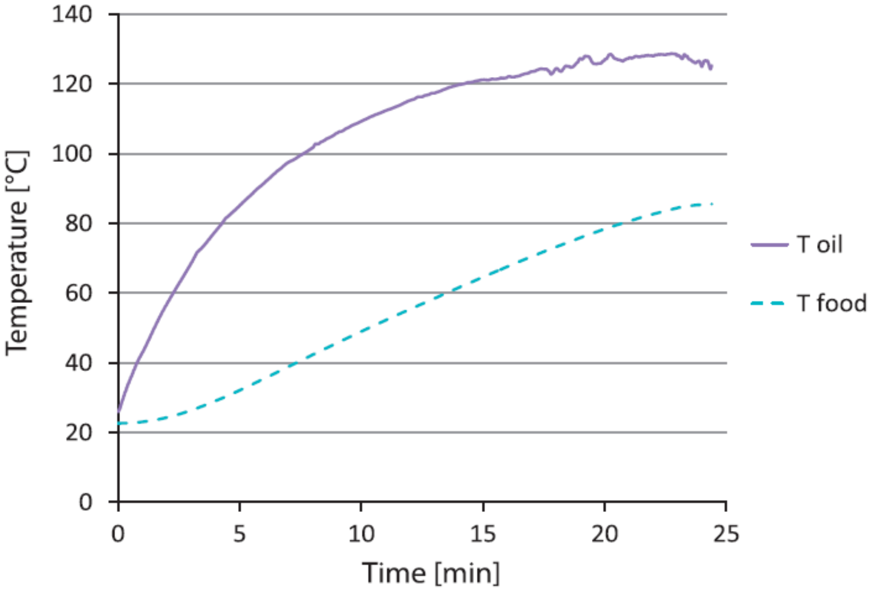

Fig. 9. Frying experiment results. [8]

Mawire et al. **[9]** conducted charging experiments to evaluate energy and exergy based thermal performance of three thermal energy storage oils for solar cookers. The three thermal oils evaluated are Sunflower Oil, Shell Thermia C and Shell Thermia B. A new parameter, the exergy factor, was proposed which evaluates the ratio of the exergy content to the energy content. They concluded that Sunflower Oil performs better than the other thermal oils under high power charging. The schematic diagram of fig. 10 shows the operation of the charging cycles. In the charging mode, the charging flow direction is represented by the solid arrows. A positive displacement DC motor controlled pump (3) driven by a variable DC power supply (4) was used to circulate oil through a copper spiral coil that was in thermal contact with electrical heating elements (1). The DC motor of the pump was rated at 12 V operating at a maximum current of 6 A. An oval gear volumetric flow-meter (5) was connected in series between the charging pump and the bottom of a 20 L thermal oil storage tank (6) such that it records the volumetric flow-rate during charging of the storage tank. The charging pump extracts oil at the bottom of the tank (6) and pushes it through an electrical heater with an oil charging coil (1). The oil enters the charging coil at a temperature T_{in} and exits the coil at a temperature T_{out} after absorbing heat from the electrical heater controlled by a temperature controller (2). The temperature controller controls temperature of the heating elements by using a (ProportionaleIntegrale Derivative) PID control mechanism such that the temperature of the elements does not exceed by too much the set temperature of the controller. The PID temperature control mechanism involves calculating an error value as the difference between the measured temperature and the desired set-point temperature from the controller.

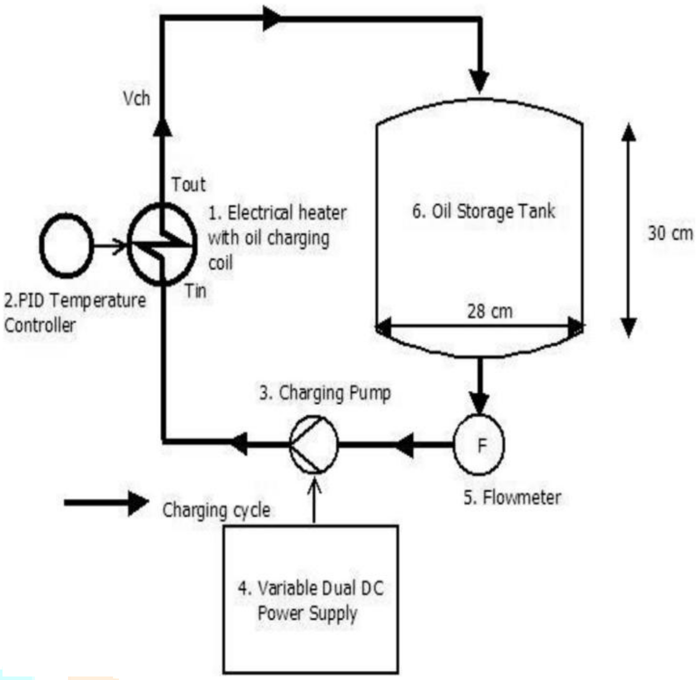

Fig. 10. A schematic diagram of the experimental setup and operation. [9]

Energy and exergy profiles for the three thermal oils at an average charging flow-rate of 4.2 ml/s are shown in fig. 11. Energy and exergy profiles are seen to peak to maximum values as the thermal gradient rises during the initial charging stages. Sunflower Oil with the highest density and heat capacity showed the highest energy and exergy values. Exergy values are lower than energy values and they start to rise after the average storage tank temperature becomes significantly greater than the ambient temperature. Exergy values thus depend on the ambient temperature. The exergy profile for Shell Thermia B starts to rise appreciably later as compared to the other thermal oils due to the lower initial storage tank temperatures which are lower than the ambient temperature. The energy and exergy profiles drop from their peak values due to the drop in the degree of thermal stratification as charging progresses. Due to the characteristic rises in the upper level temperatures after 80 min, the energy and exergy profiles are seen to slightly rise during the final stages of charging.

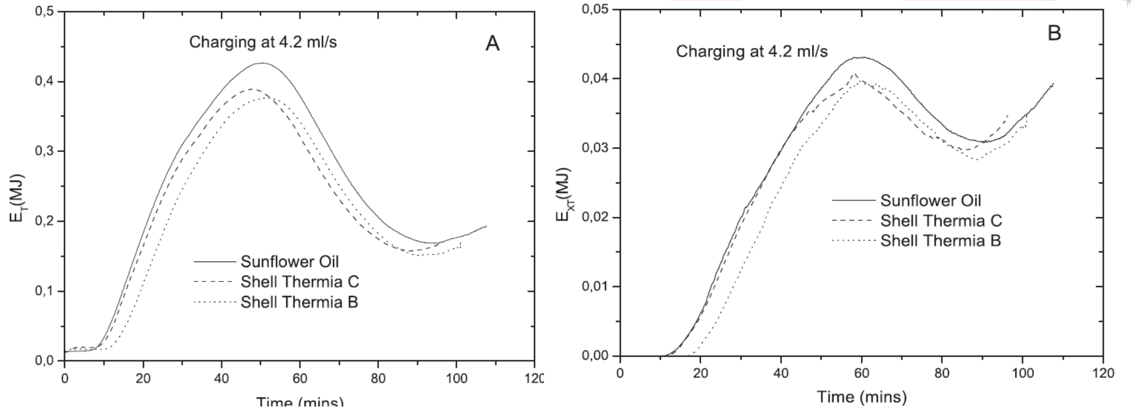

Fig. 11. (A) Energy profiles of different oils at a charging flow-rate of 4.2 ml/s. (B) Exergy profiles of different oils at a charging flow-rate of 4.2 ml/s. [9]

Geddam et al. **[10]** investigated the thermal performance of a box type solar cooker along with phase change material and finned cooking vessel. They found out the two figures of merit F_1 and F_2 for the modified cooker. The solar cooker used in the investigation was of a double exposure type which consists of a box with a double glazed glass having an aperture of area 0.1344 m^2 that allows the absorber to receive solar radiation. The absorber consists of a galvanized steel sheet painted black on its surface. The cooking vessel was cylindrical in shape and was made of aluminium having a flat base provided with a lid of diameter 0.18 m and height 0.06 m. The effect of PCM was evaluated to improve the heating efficiency and to reduce cooking time. Variation of cooking vessels was made by introducing a central annular cavity filled with PCM to increase the effective area of heat transfer and latent heat storage capacity. The experiments were carried out by means of a finned aluminium cooking vessel with the diameter of 0.22 m and yet another aluminium vessel devoid of fins with a diameter of 0.18 m was inserted inside the finned box. It was fitted strongly with bolt to provide a spacing of 0.03 m between the two vessels. Paraffin wax of 60 °C was chosen as PCM to act as a heat storage component. The fig. 12 depicts the effect of PCM and shows that the temperature decrease cause time lag of 1 h for cooking vessel without medium for 0.5 kg water load. The initial rise in the temperature was slower with PCM medium when compared with the temperature of the vessel without PCM medium but as the time goes on the highest temperature (95 °C) was attained at the same time for both the vessels with PCM medium and without PCM medium.

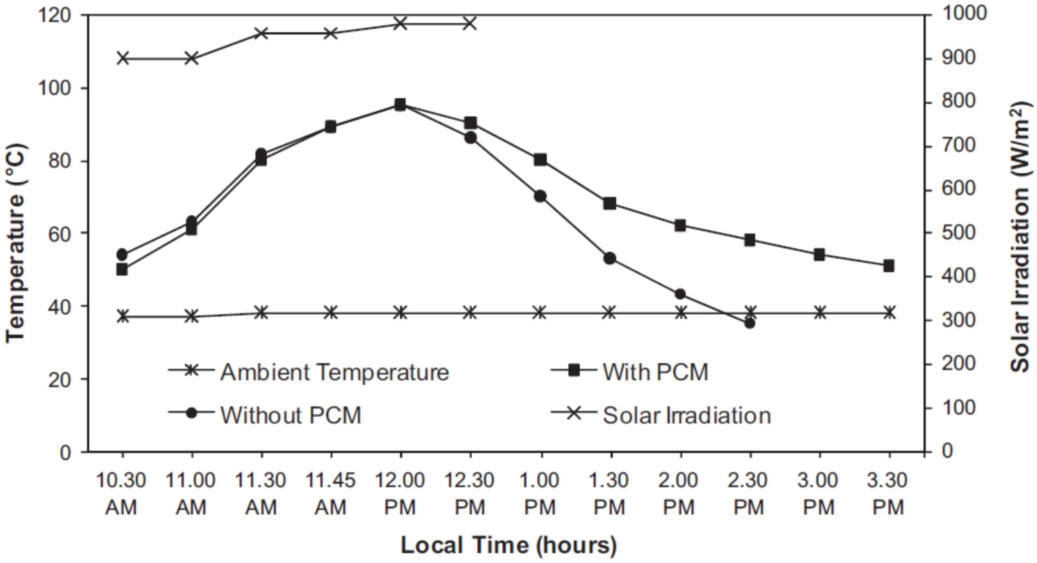

Fig. 12. Comparison of PCM vessel and without PCM vessel (0.5 kg load). [10]

For a minimal load of 0.5 kg of water, the temperature variations were tested under standard conditions. The temperature measurements were noted till 95 °C as it would reach the boiling point beyond that level subsequently causing inaccuracy. The F_2 values were found experimentally as 0.4508 and was found to be reasonably in good agreement with the predicted values as shown in Table 1. The results of the water heating test for different loads of water are given in Table 1 below:

Table 1 Figures of merit F_2 values for different loads of water.

Load of water (kg)	Experimental F_2	Predicted F_2
0.50	0.4508	0.4329
0.75	0.4650	0.5200
1.00	0.6398	0.5780
1.25	0.6411	0.6197
1.50	0.6425	0.6510

Zhang et al. **[11]** presented the recent developments and practical aspects of thermal energy storage. Classification of energy storage systems according to the working temperature is shown in fig. 13.

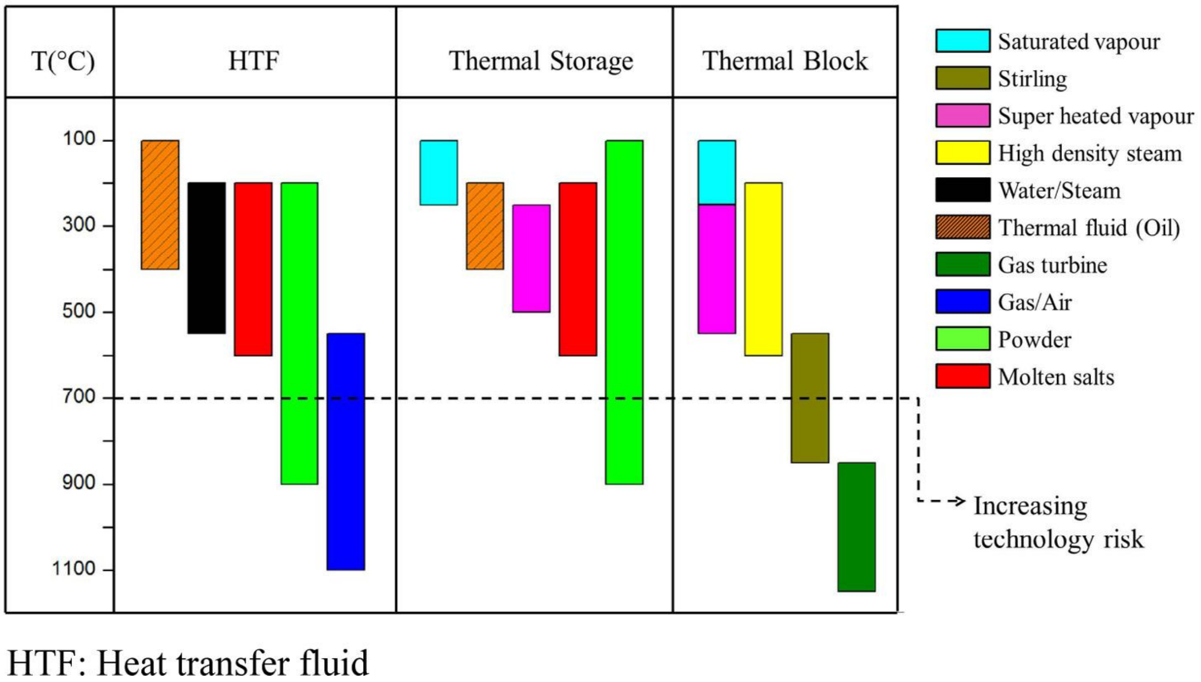

Fig. 13. Classification of energy storage systems according to working temperature. [12]

Within the high temperature thermal energy storage option using PCMs, various alternatives were investigated, as illustrated in Fig. 14. To illustrate the practical use of the results reported in previous sections, design approaches for thermal energy storage installations were further elaborated. This will be demonstrated by describing potential applications of high temperature thermal energy storage in three typical case studies:

- The encapsulated PCM is mixed within a high temperature concrete for passive heat energy storage.
- The encapsulated PCM is mixed in a liquid HTF.
- The encapsulated PCM is used in a solid–gas conveying system as heat carrier.

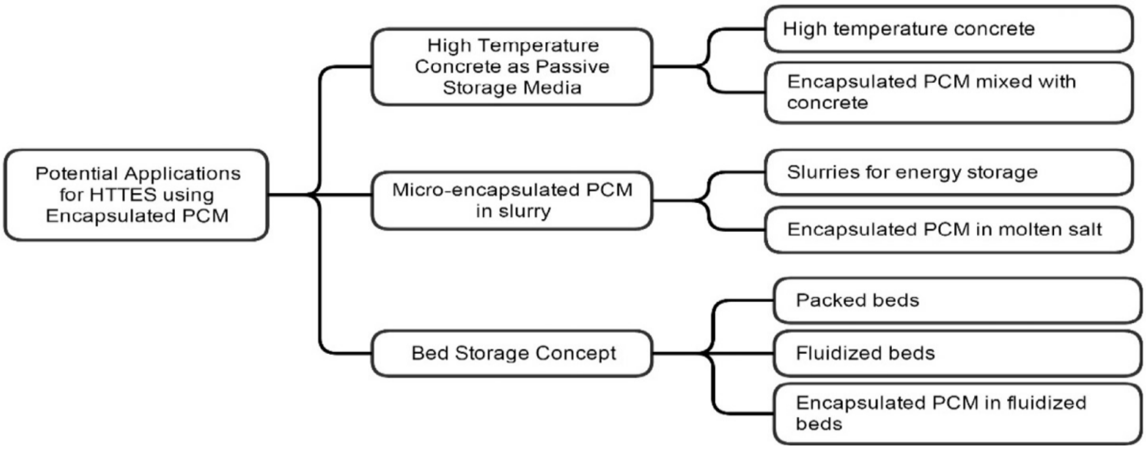

Fig. 14. Potential applications for TES using E-PCMs. [11]

III. CONCLUSION

From the detailed review and experimental results, it is concluded that (i) the storage of solar energy does not affect the performance of the solar cooker for noon cooking and (ii) if a phase change material (PCM) having a melting temperature between 105 °C and 110 °C is used, the cooking with the present design will be possible even during the night. Box type direct solar cookers are well suited to the farmers for their noon meal cooking. It is successfully commercialized in many parts of India. Solar steam cooking using parabolic concentrators are also successfully being utilized for community level large scale noon meal cooking. However, this system has no thermal storage units for cooking during off-sunshine hours. The experimentation to increase the thermal energy storage capacity of the box type solar cooker using PCM as medium showed very beneficial for energy conservation. The food cooked in solar cooker can be kept hot for 3–4 h with the help of PCM medium. The same application can be used as a part of solar water-heating systems, solar air heating systems, solar green house, space heating and cooling application for buildings, off-peak electricity storage systems, waste heat recovery systems.

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