Phase Change Materials for Solar Cooking: A Review

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Abstract

Cooking with the help of solar energy using a solar cooker will provide colossal gap coverage for renewable energy. Solar can be classified mainly four types which can be stated as panel type cooker, box-type solar cooker, parabolic type solar cooker, and tube type cooker. The most widely used solar is the Box-type solar cookers and most modifications are done on the same. Solar cookers have a disadvantage due to the unavailability of solar energy in the evening and night time. However, this disadvantage can be removed by using thermal storage materials like Phase-change Material (PCM). Some developments have been done in different types of solar cookers in the last 25 years concerning different forms of glazing covers, booster mirrors, and cooking pots. In some recent advantages of solar cookers, thermal energy storage came into the picture. Various sensible and latent heat materials were used, which were placed in the form of encapsulation to the pot and storage tanks. This review covers various thermal storage materials, and a particular focus is on various types of PCM that can be used in solar cooking as thermal storage material [TSM]. Sensible TSM stores energy via increasing its temperature, while latent TSM stores energy via increasing its temperature as well as from its phase change. From the study, it was evident that organic thermal storage material is feasible. Fewer constraints come while using them, while eutectic PCM gives an advantage of including properties of both types of PCM i.e., organic and inorganic. PCM utilization is confined by its operating temperature range and storage container's material compatibility.

Keywords. Solar cooking, Thermal energy storage, Phase change materials, Sensible thermal energy storage, Latent thermal energy storage

1. INTRODUCTION

As per the Intergovernmental Panel on Climate Change (IPCC) report 2021, it is evident that quick and fast actions are required to correct the interventions and harms done to the planet. In the first part of the sixth test report, published in August and described as "code red for humanity," the IPCC showed that the world could hit 1.5 °C by early 2030 [1]. In COP26, India has set a target for meeting 50 percent of energy requirements from renewable energy (RE) by 2030 and achieving net-zero carbon by 2070. India, as a tropical country, has vast availability of solar energy. As the world's population increases, world energy demands and consumption are also increasing, which has led to a variety of environmental impacts that are impacting the environment in a very harsh manner. Most of the energy demand, nearly 80%, is fulfilled with the help of fossil fuels only [2].

The footprint of non-renewable resources has created health issues, environmental issues, and socio-economic issues, especially in underdeveloped regions of the world [3]. With the limited supply of fossil fuels, one must use renewable resources for demand fulfillment. However, the selection of renewable resources comes with some cons: the availability of the energy sources, irregularity of the energy sources, and the storing of the excess energy. To use the alternative and renewable energy source, one must think about storing the energy for future use or when the source is not available in its peak form. The solar energy from the sun can be collected and converted into electricity which can be said as conversion of high-grade energy to low-grade energy.

In developing countries, domestic energy is consumed for different daily needs like water heating, cooking applications, and lighting. This energy demand and consumption are different in different developing countries. In India, 36% of the total primary consumption and 90% of the rural households depend on biofuel for cooking purposes [4]. In underdeveloped or rural or agrarian areas, biofuels such as wood, agricultural wastes, and animal dung cakes are few of the primary energy sources utilized for cooking purposes, whereas, in developed or non-rural areas, kerosene and LPG are the primary sources of energy. The demand for firewood is fulfilled by cutting trees, which causes deforestation, leading to desertification and dung cakes polluting the environment. Also, the supply-demand chain of fuel for cooking and some other factors have given a continuously increasing price of the fuel, which implies a dire need to utilize different renewable energy resources effectively for the purpose of cooking. For India, it is a blessing that a large amount of solar radiation occurs good potential for solar cooker practical usage in India [5]. However, the issue of irregularity or limited availability of solar radiation is the primary reason for the underutilization of solar radiation-based cooking. The use of energy storage systems can improve this drawback. To counterbalance the consumption and production of energy, it is obligatory to reserve excess energy for the short term or the long term. In today's time, storing electrical energy is not economic, but on the counterpart, it is significantly low if the cost of storing thermal energy is considered. The power supply grid cannot transfer thermal energy, but excess electric energy can be exported to the grid connection. This gives an area of utilization of thermal storage. Thermal energy storage may complement the electric utility grid whenever it is in not working condition or is under stress. Batteries or phase change materials can be used to store energy [6]. However, as the energy storage capacity of a kilowatt-hour battery is currently limited and to enhance its capacity and usage, research is going on. It is a viable and practical option for phase change material as an alternative [7]. Phase change materials are of various types out of these which is to be used for solar cooking depends on their application temperature, their application process, and compatibility with the storage container's material.

2. ENERGY STORAGE SYSTEMS

There are several types of energy storage systems. However, their utilization depends mainly on the application for which it will be used and its environment, including the equipment and working principles used. Figure 1 describes different energy storage systems based on their working principles.

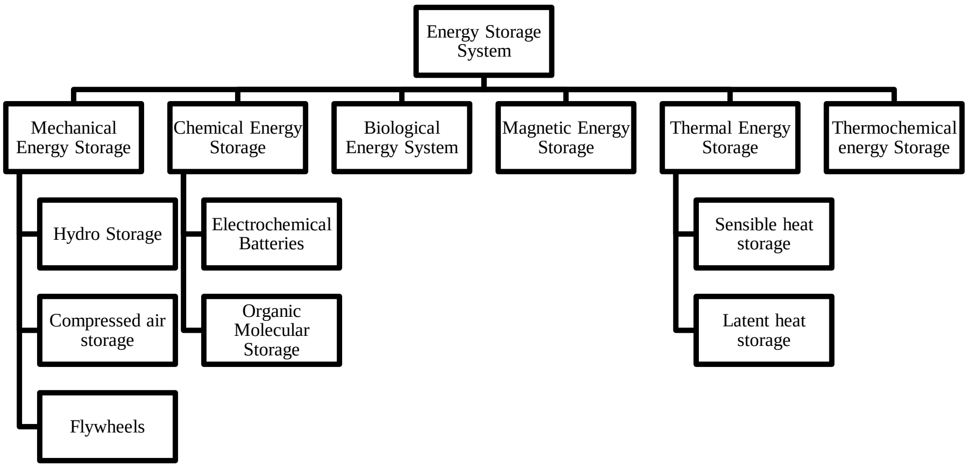

Figure 1. Types of Energy Storage Systems [8]

As mentioned earlier, thermal energy storage (TES) gives the highest efficiency of all the systems. TES systems can lessen the consumption of fossil fuels which will restrict CO_2 emissions. Utilization of the solar energy and excess energy generated during the daytime and stored for an extended or short period. This stored energy can be used to achieve an efficient system. One of the TES subcategories is PCM, a desired and valuable material because it stores a high energy density at a steady temperature.

3. CLASSIFICATION OF PCM

PCM is a viable option for solar heat storage due to its large energy storage capacity and property like a rapid supply of a large amount of heat to the application area. PCM's energy storage has many advantages over sound systems due to its low weight and volume. Energy is stored at a stable temperature which dissipates over time in which phase changes, and energy lost to the environment are smaller than in traditional arrangements.

3.1 Working Principle

As the temperature reaches a critical temperature, as the phase changes from solid phase to liquid phase, in this transition the chemical bonds of the PCM breaks down. The phase conversion process from solid to liquid is endothermic and PCM absorbs energy in the form of heat energy. When one keeps PCM in the area of storage, the PCM starts to melt when it detects the temperature change of critical value. The temperature then remains constant till the time the melting process is completely finished. The stored heat during PCM phase transition is called Latent heat. Latent heat retention can be defined via a high degree of energy density. When the temperature starts decreasing, the stored energy is again transferred to the critical area of interest with the help of sensible heat and latent heat from the exothermic process of solidification, which can be viewed in Figure 2. Figure 3 shows various types of heating, i.e., sensible and latent heating.

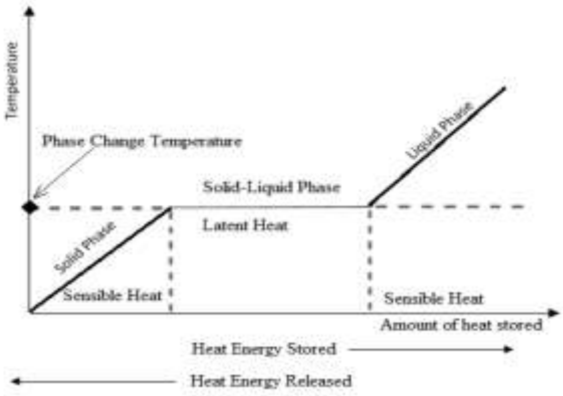

Figure 2. The Phase Transition of PCM [9]

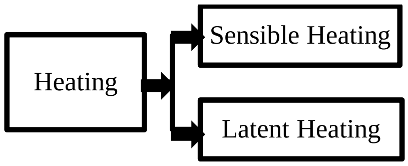

Figure 3. Classification of PCM based on heating

3.2 Sensible Heat Storage Materials:

Materials which are utilized in order to store heat by change in its temperature only are sensible heat storage devices. The widely used suitable heat-retaining materials are water, oil, and salt dissolved in alcohol. A list of solid and liquid thermal fluids used to maintain reasonable temperatures and their properties is shown in Table 1**.**

Table 1. Sensible heat storage materials with their properties [10]

S. No.	**Medium**	**Density (ρ) (kg/m^3)**	**Specific Heat Capacity (C) (J/kg K)**	**Heat Capacity $\rho \times C \times 10^{-6}$(J/m^3 K)**
1.	Calcium Chloride	2510	670	1.68
2.	Cast Iron	7900	837	6.61
3.	Clay	1458	879	1.28
4.	Aluminium	2707	896	2.43
5.	Steel, Limestone	2500	900	2.25
6.	Ethylene glycol	1116	2382	2.66
7.	Ethanol	790	2400	1.89
8.	Isobutanol	808	3000	2.42
9.	Lithium	510	4190	2.14
10.	Water	1000	4190	4.19

Water is an excellent choice for requirements in which a low temperature below 100 ℃ is required. Oil is used for medium temperatures applications varying from 100 ℃ to 300 ℃. Soluble and inorganic salts are of use when installing large temperatures that require temperatures ranging over 250 ℃. Advantages of using melted salt are very high stability of the cost of the material, high density, high temperature, non-combustion, and low vapor pressure. Solids-liquids and solids-liquid mixtures can be utilized in sensible storage devices in the TES of solar cookers. Fuels that can be used as sensible liquids are Coconut oil and Engine oil. To maintain a reasonable temperature in high temperatures, such as energy production via solar power plants, a non-eutectic salt solution consists of 60 % by weight sodium nitrate ($NaNO_3$) and 40 % by weight potassium nitrate (KNO_3) is used. This composite is known as "sun salt" in layman's language. The resulting non-eutectic mixture possesses a melting point of 240 ℃ & maximum melting point temperature of about 550 ℃. Solid materials are stone, brick, brick/mortar, concrete, concrete, earth / dry and wet soil, metal, wood and concrete board. Very often solid materials show lower storage capacity than water. The use of rocks is acceptable on the basis of the per-unit cost of storage media of stored energy [11].

3.3 Latent Heat Storage Materials:

When a PCM for solar cookers is finalized, the operating temperature should be similar to PCM's critical temperature. The volumetric latent heat should be high to lessen the PCM's physical space/size required. Property such as high thermal conductivity would enhance in storing and dissipating power of PCM. Various types of materials are shown in table 2 with their properties.

Table 2. Latent heat storage materials with their properties.[10]

S.no.	PCM	Melting Point (℃)	Latent heat of fusion (kJ/kg)
1.	Stearic acid	55.8	160
2.	Acetamide	82	263
3.	$Mg(NO_3)_2.6H_2O$	89	134
4.	Paraffin	100	140
5.	$MgCl_2.6H_2O$	118	167
6.	Erythritol	118	339
7.	D-Mannitol	169	326.8
8.	Nitrate salts (KNO_3-$NaNO_3$)	220	146

PCM can also be classified based on its chemical structure, i.e., Organic, Inorganic, and eutectic, as mentioned in figure 4. Organic PCM includes Non-Paraffin and paraffin, and Inorganic PCM includes salt and metallic hydrates. Eutectic PCM includes inorganic-inorganic, organic-inorganic, and organic-organic, depending on what PCM types are being mixed.

PCM

- Organic
- Paraffins
- Non-Paraffins
- Inorganic
- Salt hydrates
- Mettalics
- Eutectic
- Organic-Organic
- Organic-Inorganic
- Inorganic-Inorganic

Figure 4. PCM classification based on chemical structure

Organic PCMs are hydrocarbons, primarily paraffin (C_2 H_{2n+n}), lipids, and sugar alcohols. Organic PCM freezes without showing significant supercoiling. They have a property to melt congruently. Organic PCMs are generally compatible with commonly used construction materials. They are chemically stable, which gives an advantage for usage, and are non-reactive. Organic PCMs generally show a phase change temperature range of -5 ℃ to 190 ℃. Organic PCM is behind due to its low thermal conductivity for solid structure, resulting in a high heat transfer rate during the phase conversion from liquid to solid. Its volumetric latent heat storage capacity is low compared to some inorganic PCMs.

Inorganic PCMs are generally Salt Hydrates ($M_xN_yH_2O$) type structures. The main advantage of using an inorganic PCM is its high volumetric latent heat storage capacity. Inorganic PCMs exhibit sharp melting points as well as high thermal conductivity. Most inorganic PCMs are readily available, and that too at low cost. Inorganic PCMs go through phase separation upon repeated process, which causes a considerable loss in latent heat enthalpy. Inorganic PCMs generally exhibit a phase change temperature range of -50 ℃ to 175 ℃. Water or oxygen in its chemical structure can cause corrosion to most metals of construction. There can be an issue with supercoiling in solid-liquid phase change, which should be considered in the design phase of the container only where PCM will be stored.

The eutectic mixture combines more than one type of PCM, which can be any organic or inorganic. It has a sharp melting point, High volumetric storage density. The issue with the eutectic mixture is that very little data is available, so using a eutectic mixture will require an experimental approach to some extent [12]. In many binary eutectics, different types of fatty acids may be incorporated into almost any melting point of TES systems according to climate requirements. Eutectic mixture PCMs generally have a phase change temperature range between -5 ℃ to 225 ℃, and this will depend on combining two mixed materials. Thermal properties and thermal reliability of pure or eutectic PCM should be examined for thermal cycling health tests to confirm the duration of the utilization of the TES system.

4. PCM PROPERTIES

PCM properties play an essential role in selecting PCM for solar cooking. Table 3 shows different properties of PCM Materials that are required if used as TES in solar cooking.

Table 3. PCM properties

S.NO.	PROPERTIES TYPE	PROPERTIES

1.	Thermophysical properties	• Melting temperatures lies in a fixed range. • Per unit volume high latent heat of fusion. • High specific heat so to have additional usable sensible storage. • High thermal conductivity in both phases, i.e., liquid and solid. • Small volume variation during transition and slight vapor pressure for working temperatures. • Befitting melting and freezing of PCM for a material storage capacity with both melting and freezing process. • Phase changing temperature conformable to use. • To minimize heat storage size, latent energy should be high. • Possess high enthalpy. • Fixed and mentioned transition temperature. • Density should be high during transition. • Small volume variation during phase transitions. • It should have high thermal conductivity.
2.	Kinetic properties	• High nucleation rate in order to elude supercooling in the liquid phase. • Crystal growth rate should be high that enables the system to fulfill the requirements of heat recovery from the material. • Undercooling crystallization rate should be pretty sufficient during the freezing process.
3.	Chemical properties	• Chemical stability throughout the working temperature. • Complete reversible for melting and freezing cycles. • No or minimum degradation even after a huge number of the working cycle. • Non-corrosive behaviour with the storage fabrication material. • Non-noxious, non-corrosive, non-combustible, and non-detonative material. • High chemical stability.
4.	Material characteristics	• The unit size should be small. • Desired low vapor pressure.
5.	Economic characteristics	• Cheap and large availability

5. PCM SELECTION CRITERIA FOR A BASIC SOLAR COOKER

When selecting PCM for a solar cooker, its properties and requirement both should be kept in mind. Some criteria are mentioned below:

- It should have critical temperatures within the required operating temperature (installation in solar cooker 60 ℃-120 ℃).

- It should acquire a high latent heat of fusion per unit mass in order to lessen the amount of PCM required.
- For maximum benefit, PCM must have a high specific temperature to maximize sensible heat retention.
- PCM materials must have high thermal conductivity to reduce charging and discharge duration.
- It should possess small volumetric expansion as well as small shrinking coefficients for phase changes.
- It must have little or no cooling during solidification.
- It must be chemically stable and non-corrosive for the containers used for storage.
- In addition, it should be non-toxic, inflammable, or non-explosive.
- PCM should be readily available at a low cost to improve cost optimization and mass production.

6. Problems with Latent Heat Materials

The selection of latent thermal materials is based primarily on properties such as thermo-physical, which are the melting point, latent heat of fusion, specific heat, and thermal conductivity. However, the critical parameters limiting latent heat storage use are the number of repeatable processes without change in material properties and the valuable life of PCM-container setup. So the problem which has limited application of LHS (Latent Heat storage) is the requirement that it must last for a long time [13].

7. Problems with usage of PCM Material in Solar Cooker

PCMs, come with some disadvantages, which get highlighted when used in the solar cooker. Some common issues with PCM usage are as follows:

1. It increases the weight of the solar cooker as a whole setup which reduces its portability as using PCM increase weight of solar cooker by 10kg [14].
2. It increases the cost of a solar cooker setup.
3. Removing or refilling PCM from its storage tank is a heavy and challenging task.
4. The heat trapped inside the box increases due to the presence of PCM, which gives a condition like handling pots with gloves is a must condition.
5. The stability and lifecycle of some TES are very less for practical applications [15].

8. Applications

Substantial efforts have been made to develop a latent energy thermal system in solar systems, where heat must be stored in the daytime for nighttime usage. Many PCMs possess a low thermal conductivity which lowers the rate of heat transfer, making them infeasible for their applications. Therefore, PCM should be integrated in such a way as to limit a significant decrease in heat transfer rates that happens along the phase transition processes. PCM usually consists of small flat containers, such as plate-type heat exchangers [12]. The significant enhancement of rate of heat transfer was achieved via inserting PCM into small plastic parts to form a complete bed storage unit. Direct heat transfer by phase transition using hydrated salt provides significantly high temperatures. Storing thermal energy is essential for efficient solar energy in a building. PCM storage provides an extra edge for solar cooking purposes also. Solar ponds are one of examples for solar energy storage which

happens naturally. Photosynthesis is a natural process in which solar energy is converted to other form of energy.
Similar to other applications, PCM will gain and store energy in day/sunshine time and store it, which can be used in night/off-sunshine time. Especially for solar cooking, latent heat comes forward as a better option for TES. PCM placement within the solar cooker setup is also a topic worth noting. The outer cover for the vessel can be co-cylindered [16], and PCM can be filled in that space which will act as the single-layer transmission of energy from PCM to food in the solar cooking vessel. Another area where PCM Materials can be stored will be the base of the solar cooker, where the solar cooking vessels are placed. However, there will be a two-layer energy transmission from PCM to food in the solar cooking vessel in this format. This drawback can be removed by providing holes of the same size as the vessel based on the cost of size and placing the solar cooking vessel.

9. CONCLUSION

This review paper can be concluded via the following points:

- Thermal storage materials are a viable option for better utilization of solar energy as it provide easy, convenient and practical application of energy storage.
- Organic, inorganic, and eutectic, all types are usable TES materials to utilize solar energy in the solar cooker. So, for a particular applications many options are there depending on type of application one can choose from them.
- Most salts are usable in the hydrated form, limiting the type of material used for storage tanks for TES.
- Organic PCMs generally have a low melting point, but it is short-range to cook food.
- The number of thermal cycles are higher when low or medium temperature range PCM are used compared to high temperature range PCM.
- Sunflower oil and many more edible oils also acts as a valuable material for TES.
- Stearic acid and paraffin wax are commonly used due to their easy availability and economically viable options.
- A sound approach is a must condition in area of solar cooking to promote its usage and affordability.

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