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## RESEARCH ARTICLE

# THERMAL ENERGY STORAGE SYSTEM USING PHASE CHANGE MATERIAL: A REVIEW

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**ABSTRACT**

Thermal energy storage (TES) is becoming a growing concern in modern technology and it has number of applications. Energy storage is essential whenever there is a mismatch between the supply and consumption of energy. Growing energy demands, lack of fossil fuels, and the continuous increase in the level of greenhouse gas emissions are the main driving forces to practice various sources of renewable energy. Due to irregular and unpredictable nature of solar energy; efficient, economical and reliable solar thermal energy storage devices and methods have to be developed. Among the different possibilities to store energy, systems using Phase Change Materials (PCM) can be preferred for its consistency in latent heat storage. The use of PCM is an effective way of storing thermal energy and has the advantages of having high storage density and the isothermal nature of the storage process. Due to this, the volume of material is reduces and so the cost of the system. But the PCM storage system has low thermal conductivity which leads to poor heat transfer so heat transfer enhancement techniques should be used. This paper summarise the selection of thermal energy storage systems using phase change material.

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## INTRODUCTION

Due to unpredictable and unstable nature of solar radiation, it becomes very difficult to satisfy the gap between supply and demand of electricity. The only solution to this problem is to have storage in the system which can satisfy the demand regardless of unavailability of radiation. In storage, the extra energy that is not required, is collected and used it during hours when sunlight is not ample to satisfy the demand. Thermal storage can also be used for process application where a waste heat can be stored in thermal storage and used when it is required. Table 1.1 shows the advantages of using thermal energy storage in solar thermal power plant.

### Thermal energy storage methods

There are many ways to store thermal energy. They can be divided into:

- Sensible heat storage
- Latent heat storage
- Thermochemical storage

### Sensible heat storage

In sensible heat storage, the thermal energy is stored due to increase in temperature of stored medium. The amount of energy stored depends on the specific heat, the change in temperature and mass of the material.

$$Q = \int_{T_1}^{T_2} mC_p dT$$

Sensible heat storage can be differentiated on the basis of storage media, *viz. (i)* liquids such as oil, water and molten salt, and (ii) solids such as rocks and metals.

### Latent heat storage

Latent heat storage system (LHS) uses the energy released or absorbed in the phase change region. When the material reaches the phase change temperature it absorbs or releases a huge amount of energy to carry out the phase change which is known as the latent heat of fusion or evaporation depending on the state and in this way the energy is stored. The materials used are known as phase change materials (PCM). They have very high energy density and hence they reduce the volume and hence the cost. Figure 2.2.1 explains the energy storage mechanism of a PCM. When a solid is heated, its temperature rises up to its melting temperature.

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**Table 1.1. Advantages of thermal energy storage in a solar thermal plant (F. Dinter and D. M. Gonzalez, 2014)**

| | | |
|---|---|---|
| (1) | Prevention of interruption due to intermittency of solar radiation | Compared to PV, power output of CSP with storage does not depend on the current solar radiation. So the power fed in grid can be kept constant despite of strong fluctuations in radiation. This becomes even more important in regions with strong fluctuations in weather |
| (2) | Shifting of power generation to peak periods and 24 hours per day of production | Since energy prices depend on its demand, TES enables a solar thermal plant to produce power during peak hours and increase the revenue. It can do this by avoiding power generation during low or negative energy prices |
| (3) | Regulation and frequency response | Regulation and frequency response is generally done by conventional fossil fired plants. CSP generation units can provide the same due to their inertia and response governors |
| (4) | Support for power quality | Power systems require reactive power for supporting and maintaining voltage levels. Other energy sources reduce the inertia of the system which can cause faster and larger frequency deviations due to sudden variation in generation and load. CSP with TES can provide quality power through reactive power support and inertia response. |
| (5) | Support to other renewable energy sources | Due to increasing penetration of wind and solar photovoltaic generation, there is an increase in variability of power supply. CSP with TES can help such sources by providing support to them. |
| (6) | Generation of power independent of weather condition and time | CSP without storage can produce power only during hours when solar radiation is available. |
| (7) | Improved economics | Due to more hours of power generation, revenues are more and hence the payback time is reduced |

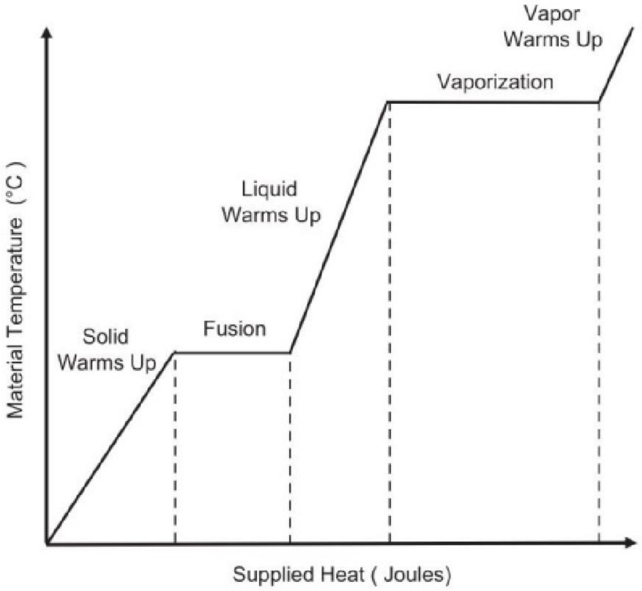


Fig.2.2.1. Temperature profile of a PCM with heat supply

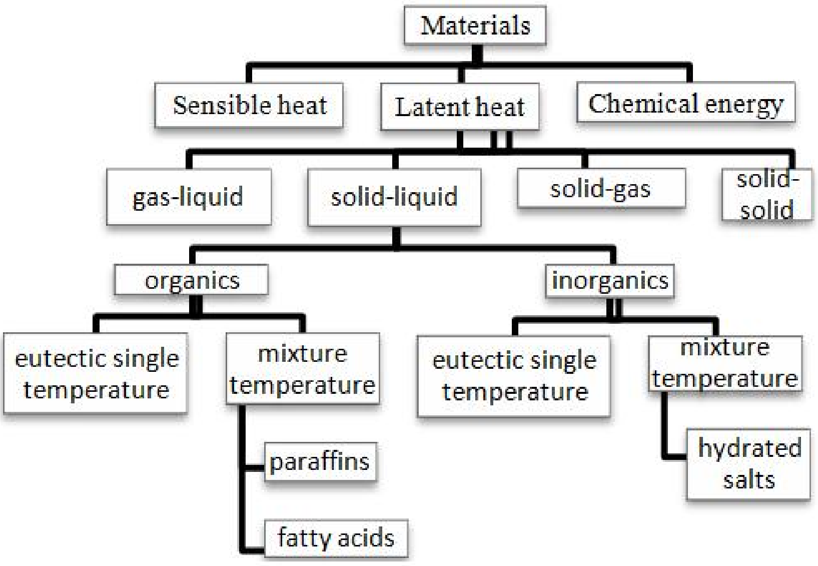


Fig.2.3.1. Classification of TES materials (Sharma et al., 2009)

After this point the temperature come to an end to increases and the phase change occurs. After the PCM has completely melted, the temperature rises again up till it reaches the boiling temperature. After this the temperature remains constant till everything is evaporated. In PCM application one can give and extract the energy within the phase change region and therefore without changing the temperature.

$$Q = \int_{T_1}^{T_m} mC_{p\_solid}dT + mL_m + \int_{T_m}^{T_f} mC_{p\_liquid}dT$$

- The 1st term represents the increase in sensible energy stored by the increase in temperature of material from initial temperature to melting temperature.
- The 2nd term represents the latent energy stored in the material by phase change.
- The 3rd term represents the sensible energy stored by increase in temperature.
- Most of the PCM suffer from a constraint of low thermal conductivity of around 0.2 and 0.5 W/mK for paraffin and inorganic salts respectively.

### Thermochemical heat storage

This is the most underdeveloped method of thermal energy storage. It contains the use of endothermic chemical reactions. When heat is supplied to an appropriate material, it is utilised in breaking the chemical bonds of the compound. Later all of this energy is recovered when the reaction takes place. This technology offers various advantages but it is in the early stages of development. The different types of PCMs are classified in figure 2.3.1.

### Classification of PCM

The materials used in latent heat application are known as phase change material (PCM). They may undergo the following transformations:

- Solid-solid (Ex. Cellulose diacetate)
- Solid-liquid (Ex. Paraffin)
- Liquid-gas (Ex. Water)

### Solid-solid PCM

Solid-solid PCM materials transform their crystalline structure at a particular temperature. The transformation energy is comparable to the best solid to liquid PCMs. They are very easy to handle and cost effective because the absence of liquid state eliminates the problem of leakage and need for encapsulation. Research is going on for developing steel alloy for such application (T. Nomura, et, al, 2010).

### Liquid-gas latent heat storage

The transformation from liquid to gaseous state requires the highest amount of energy. But due to enormous amount of change in volume, the economic and practical feasibility becomes very difficult. Also, not much information is available on the gaseous state of materials.

### Solid-liquid latent heat storage

The transition of materials from solid to liquid is studied and used widely in latent heat storage applications. Even though they have several times less latent heat compared to liquid-gas PCMs, they are acceptable as they do not present technical and economic difficulties of expansion. Normally their expansion is less than 10% of their original volume. There are many problems associated with the use of solid-liquid PCM such as the complexity of the container, phase segregation and subcooling. But, the biggest hurdle to its application is the low thermal conductivity. It restricts the extraction and storage of the energy in a limited time period and also leads to wastage of PCM material by remaining unused.

### Parameters for selection of PCM

Some points should be taken care while selecting a PCM for appropriate application (F. Agyenim, et, al, 2010), which are as follows:

- Melting temperature near our requirement
- High latent heat of fusion
- Low specific heat
- High thermal conductivity in solid state, so that the heat is diffused in lesser time
- Low thermal expansion coefficient so that design becomes easier and cheaper materials can be used for containing it
- Low or zero subcooling during freezing
- Non-poisonous, non-explosive and non-flammable
- Cheap and easily available

### PCM container

After the PCM has been selected, the factors to consider are:

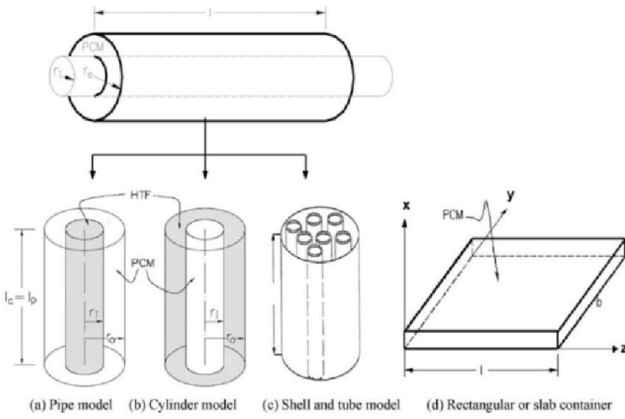
- Design of the PCM container
- The thermal and geometric parameters of the container required for a given amount of PCM

These factors have great role in influencing the parameters of heat transfer. PCMs are kept in long thin heat pipes (B. Horbaniuc, et, al 1999), cylindrical containers (E. Papanicolaou and V. Belessiotis2002), (F. Agyenim, et, al, 2009) or rectangular containers (P. D. Silva, et, al, 2002), (K.Ermis, A., et, al, 2007) as shown in figure 5.1. Rectangular and cylindrical containers are the most common shapes of container. Among them shell and tube system is the most commonly used one, which accounts for more than 70%.

The cylindrical PCM container can be used in the following ways:

- In the 1st configuration, the PCM is on the shell side and heat transfer fluid flows inside the tube(M. Esen, et, al, 1998)
- In the 2nd configuration, the PCM is in the tube and the HTF flows on the shell side. According to Esen et al.(M. Esen, et, al, 1998), the pipe model is better because it took less time to melt.
- The 3rd model is the shell and tube system. It is commonly used to improve heat transfer in PCMs. Agyenim

conducted experiments with horizontal shell and tube heat exchanger (4 tubes) and a pipe model (F. Agyenim, et al, 2010). Heat transfer in the shell and tube system was better. The reason for this was found to be multiple convective heat transfer.



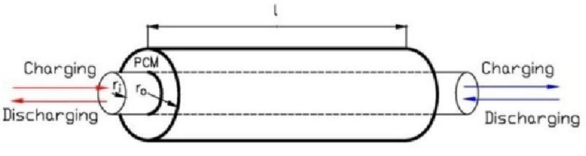
(a) Pipe model (b) Cylinder model (c) Shell and tube model (d) Rectangular or slab container

**Fig.5.1. Commonly used PCM containers**
**(F. Agyenim, et al., 2010)**

### Comparison of counter-current and parallel heat transfer fluid (HTF) flow directions

In a cylindrical assembly, the HTF can flow in two directions during charging and discharging of the PCM, viz. (a) hot and cold streams are entered from same direction, and (b) hot and cold streams are entered from opposite direction. Gong and Mujumdar (Z.X. Gong and A. S. Mujumdar 1997) conducted numerical simulations to find the effect of the parallel and counter-current flow modes. They found that parallel flow increases the energy charge/discharge rate by 5% more than counter-current flow.

(a) Parallel HTF flow



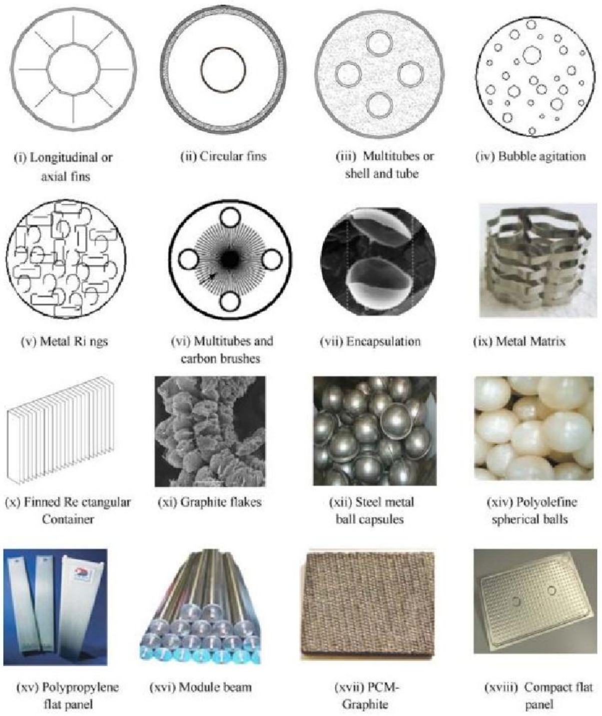
(b)Counter-current HTF flow

**Fig.6.1: Comparison of parallel and counter flow**
**(F. Agyenim et al., 2010)**

### Heat transfer enhancement techniques

Most of the PCM suffers from low thermal conductivity which leads to very poor heat transfer coefficient. In order to overcome this problem, heat transfer enhancement techniques are used as shown in figure 7.1, such as,

- Finned tubes
- Bubble agitation
- Insertion of a metal matrix in the PCM
- PCM dispersed with high conductivity particles
- Micro-encapsulation of the PCM
- Shell and tube



(i) Longitudinal or axial fins (ii) Circular fins (iii) Multitubes or shell and tube (iv) Bubble agitation (v) Metal Ri ngs (vi) Multitubes and carbon brushes (vii) Encapsulation (ix) Metal Matrix (x) Finned Re ctangular Container (xi) Graphite flakes (xii) Steel metal ball capsules (xiv) Polyolefine spherical balls (xv) Polypropylene flat panel (xvi) Module beam (xvii) PCM-Graphite (xviii) Compact flat panel

**Fig.7.1: Common heat transfer enhancement technique**
**(F. Agyenim et al. 2010)**

It should be noted that different researchers used different experimental setups and different materials of PCM and container. Also, researchers used different parameters to assess the heat transfer enhancement in the PCMs. (Velraj*et, al,* 1999)evaluated the performance by calculating the effective thermal conductivity. Horbaniuc et al, evaluated the performance of fins in terms of time taken for complete solidification. (Choi and Kim J. C., et, al, 1992) used the ratio of overall heat transfer coefficient in the finned and unfinned tube systems.

### Extended surfaces

Most of the people use fins in PCM as it is simple to manufacture as well as they are cheap. The best improvement in heat transfer was reported by Velraj et al. where the thermal conductivity was improved by 10 times (Velraj *et, al,* 1999). It was observed that there is no degradation of the material after testing more than 400 h with $NaNO_3$ as PCM (W.D. Steinmann, D. Laing, and R. Tamme2009). Both, aluminium and graphite sheets did not get corroded due to the contact with the galvanized steel of the pipes. Steel fins occupy more volume than graphite fins for same heat transfer. The cost of steel fins is significantly higher because of this. Mostly encapsulation is used in low temperature materials. It is costly to encapsulate PCM with melting temperatures above 200 $^0$C. The initial volume of PCM should not be more than 80% of the capsule volume while using a rigid capsule. By doing this, it is ensured that capsule can withstand the pressure exerted.(R. Steinmann and Tamme2003)

### Multiple PCM method

Multiple PCM technique contains more than one PCM having different melting temperatures in the LHS unit. The heat transfer rate is decided by the difference in the temperature of the HTF and the PCM melting point(S. Jegadheeswaran and S. D. Pohekar2009). If a single PCM is used, heat transfer becomes poor because temperature difference decreases in the flow direction of the HTF. In order to keep a constant temperature difference during the melting process, multiple PCMs should be used in decreasing order by their melting points. This leads to a nearly constant heat flow to the PCM. When HTF is flowed in reverse direction during discharge, the PCMs remain in the increasing order of their melting points, and almost constant heat flow happens from the PCM to the HTF. Figure 7.2.1 shows how we can use multiple PCMs in a shell and tube configuration.

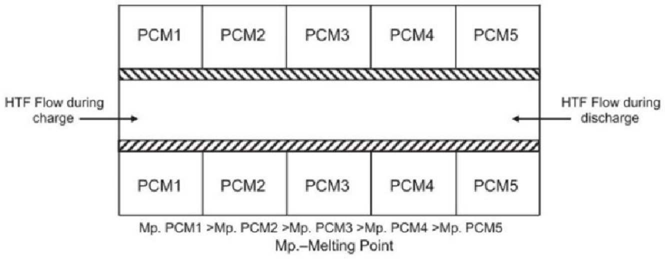


**Fig.7.2.1. LHS system with multiple PCM (Seeniraj et al., 2002)**

Farid and Kanzawa (Faridand and Kanzawa1989) used 3 PCMs with different melting points in cylindrical capsules. Air was used as HTF. A 10% increase in heat transfer rate was obtained during charging and discharging. Michels and Pitz-Paal (Michels and Pitz-paal2007) experimented with 3 PCMs on shell side and synthetic oil in the inner tube. Most of the PCM melted during the experiment. It is necessary to choose right combination of PCMs. For this we require an appropriate difference between the melting points and proper amounts of PCM. Fang and Chen (M. Fang and G. Chen, 2007) performed a numerical study in a shell and tube module to examine the effect of different combinations of PCM. The results showed that it is best to have more melting point difference between the PCMs. It is best to use multiple PCM along with extended surfaces for even better enhancement (Seeniraj et al., 2002). Hence more studies are needed to investigate and find a combination of PCM with even better performance along with extended surfaces.

### Melting process in the PCM

In order to work with PCM, it is very important to understand the process of melting. (Zhang and Bejan1989) together with (Sari and Kaygusuz 2003), (Agyenim et al. 2010) and (Hirata and Nishida 1989) described the melting process in following stages:

- Sensible heating at starting increases the temperature of solid PCM. Pure conduction heat transfer occurs during this
- After some time a second conduction regime is formed in which heat is purely transferred by conduction from the heated wall to the PCM. Solid-liquid interface is formed when melting had just begun
- As the thickness of the melt layer increases transition from conduction to natural convection starts. At the interface, there exists equilibrium between solid body and a pool of its own liquid
- A convection regime is formed when most of the solid has been melted and the liquid core temperature distribution depends on height.

### Conclusion

From the literature survey, it is observed that very few experimental studies are done on thermal enhancement techniques with phase change material (PCM). Mostly paraffin is used as PCM for low temperature application (<100 ˚C). Hence there is need to do more research in PCM storage with thermal enhancement in the temperature range of 150º C to 200º C.Things that should be taken care while designing a storage system with PCM are as follows:

- Choose PCM of good thermal conductivity and high latent heat of fusion
- Shell and tube type container is preferable
- If PCM is to be used, use of heat transfer enhancement technique is must. Out of all the options, extended surface is easy to implement.
- Parallel heat transfer fluid (HTF) flow direction is better compared to counter one.

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