

Thermal Energy Storage: A Review

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Abstract: In many parts of the world, direct solar radiation is considered to be one of the most prospective sources of energy. The scientists all over the world are in search of new and renewable energy sources. One of the options is to develop energy storage devices, which are as important as developing new sources of energy. The storage of energy in suitable forms, which can conventionally be converted into the required form, is a present day challenge to the technologists. Energy storage not only reduces the mismatch between supply and demand but also improves the performance and reliability of energy systems and plays an important role in conserving the energy. It leads to saving of premium fuels and makes the system more cost effective by reducing the wastage of energy and capital cost. Thermal energy storage with phase change materials (PCMs) offers a high thermal storage density with a moderate temperature variation, and has attracted growing attention due to its important role in achieving energy conservation in buildings with thermal comfort. This paper deals with literature review on thermal energy storage unit to select for best suitable PCM's and materials for the design of test bench of thermal energy storage unit.

Keywords: Phase change material (PCM), Thermal Energy Storage, Latent Heat of Thermal Energy Storage (LHTES), Thermochemical Energy Storage.

I. Introduction

There exist several TES (Thermal Energy Storage) technologies and applications. The selection of a TES technology for a specific application depends on many criteria, including the storage duration, cost, supply and utilization temperature requirements, and storage capacity. For many years, TES devices and systems have been utilized in building designs and integrated into solar power-generation, but the application of TES in the automobile industry did not start until the late 1970's. There are various potential applications of TES in the automotive industry. First, a TES device could be charged from an engine's waste heat during normal operation. In addition, TES devices could be utilized to provide heat during warm-up to reduce fuel consumption and emission. The drivers can avoid waiting for preheating and warming the engine. Moreover, TES devices have potential applications in hybrid and electric vehicles powered by batteries. Since the batteries operate poorly at low temperatures, the use of a TES device for rapid heating of the batteries could alleviate the degradation of battery performance in cold weather. Finally, a TES device could be used to enhance passenger comfort and aid in defrosting of windshields. In cold weather, it could take several minutes to provide significant warming in the passenger cabin before the internal combustion engine could spare enough heat. For electric vehicles, the situation would be even worse due to the lack of a high-temperature heat source. Since TES devices could produce heat directly without sharing with other compartments, they would be able to provide the thermal energy more efficiently and thereby greatly enhance the operation of vehicles during winter.

Thermal Energy Storage (TES) devices have attracted profound interest from researchers for their use in eliminating environmental problems and increasing the efficiency of energy consumption in general. TES devices store thermal energy (heat) in hot or cold materials for later use. It is an important technology in bridging the gap between the supply and demand of energy. Thus, TES devices allow the reutilization of stored energy to drive energy systems and prove to be extremely beneficial for renewable energy applications. They can also be used to mitigate the cold engine startup problem. As there are various potential applications of TES in the automotive industry. First, a TES device could be charged from an engine's waste heat during normal operation. In addition, TES devices could be utilized to provide heat during warm-up to reduce fuel consumption and emission. The drivers can avoid waiting for preheating and warming the engine.

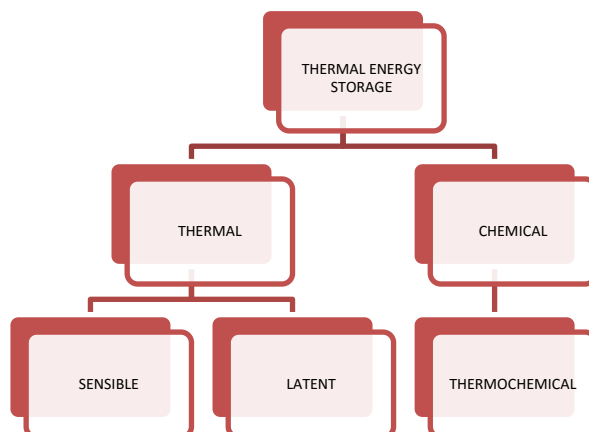


Figure 1:-Different types of thermal energy storage device

1.1. Sensible Heat Thermal Energy Storage

Sensible heat storage devices store thermal energy by heating or cooling the temperature of the storage material through heat transfer. Sensible heat TES devices take advantage of the heat capacity and the change in temperature of the material during the charging and discharging processes. The amount of energy stored in a sensible TES device depends on the mass and specific heat of the storage medium, and the temperature difference of the storage medium between its initial and final states.

The total amount of heat stored can be expressed as:

$$Q = \int_{T_i}^{T_f} m C_p dT$$

$$Q = m C_p (T_f - T_i)$$

Among all potential media for sensible heat storage, water has been the most promising candidate. Due to its high heat capacity ($\sim 4.2 \text{ kJ/kg} \cdot \text{K}$) and low cost, it is often used in storage devices over the temperature range of $20\text{-}70^\circ\text{C}$. Also, as a liquid storage medium with high convective heat transfer, water allows the storage device to have higher heat injection and extraction rates compared to other solid heat storage media. Due to their simplicity and low cost, sensible heat TES devices have been used in the automotive industry. Generally, they reserve a hot coolant in the storage phase and release the hot coolant into the engine circuit during the cold start. However, sensible heat storage devices are not great candidates for long-term or automobile applications because of the following drawbacks.

- Low energy storage density ($\sim 100 \text{ kJ/kg}$),
- Heavy insulation required to minimize heat loss to the ambient,
- Non-isothermal behavior during charging and releasing processes.

1.2. Thermochemical Energy Storage

Thermochemical energy storage devices use a reversible chemical reaction to store and release energy. It stores heat in the process of dissociation reaction and releases the energy in the exothermic step of a reversible chemical reaction. Thermochemical storage has not been developed commercially, but its advantages have drawn significant attention high energy storage density ($\sim 2 \text{ MJ/kg}$).

- No or low heat losses.
- Long-term storage period.
- Long distance transport possibility.
- Small storage volume.

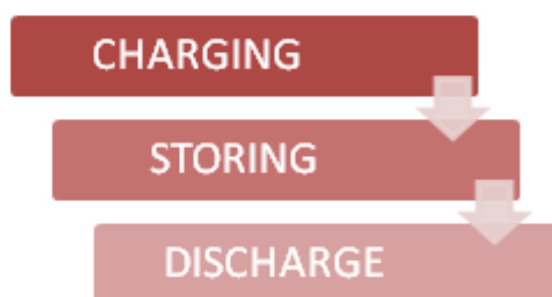


Figure 2:- Process of Thermochemical TES Cycle

1.3. Latent Heat Storage:-

In general, the latent heat storage is the most promising amongst different methods of thermal energy storage. In latent heat TES; energy is stored in the phase change materials (PCMs) through the change of a substance from one phase to another.

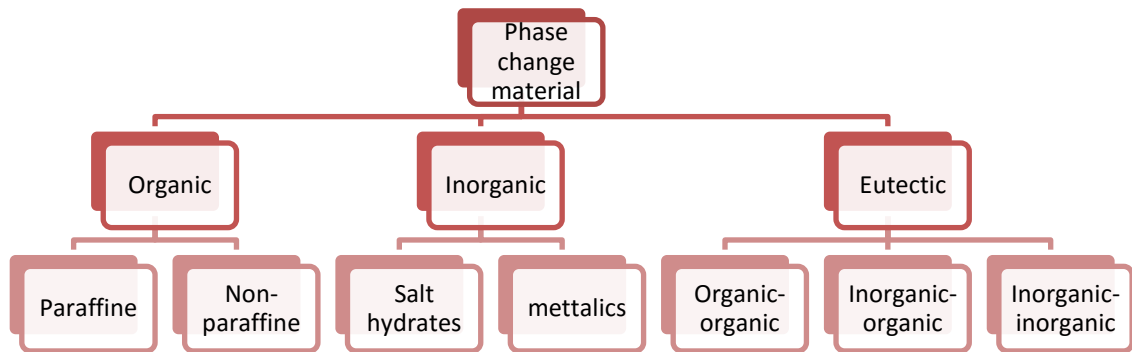


Figure 3:- List of most possible materials that may be used for latent heat storage.

As the temperature increases, the material transforms from solid to liquid phase and absorbs heat in the endothermic process. When temperature is reduced, the material undergoes phase change from liquid to solid and releases heat. Since PCM’s store energy in the form of latent heat of fusion, there is no significant temperature drop in the heat release process. The energy storage has to go through several phase transitions: solid-solid, solid-liquid, solid-gas and liquid-gas. In solid-solid transition, energy is stored by the crystalline transformation of the material. This transition contains much smaller latent heat and minor volume changes. As a result, solid-solid PCMs have the advantage of less strict container requirements that allow greater design flexibility. On the other hand, solid-liquid transformation plays an important role in the latent heat TES since it provides a high energy storage density and has much higher latent heat of fusion. In contrast to solid-solid and solid-liquid phase transitions, solid-gas and liquid-gas transitions have the advantage of higher latent heat of fusion, but their large volume change during the phase change process increases the difficulty and complexity of the storage system .

Overall, the amount of energy stored in latent heat TES devices depends on the heat of absorption or release during phase change, which can be calculated as:

$$Q = \int_{T_i}^{T_m} mC_p dT + m a_m \Delta h_m \tag{II}$$

Where *m* and *C_p* denote the mass and specific heat of the storage material, respectively, (*T_m - T_i*) is the temperature difference between the initial and the melting temperatures of the storage material, *a_m* is the extent of conversion, and *Δh_m* is the latent heat of fusion of the storage material. Compared to sensible heat TES, latent heat TES has benefits of higher heat storage density, small size of the system, reduced segregation of components, minor changes in structure during repeated phase transitions, and low cost . However, several drawbacks in latent TES such as poor heat transfer rate, short-term stability, high super-cooling effects, and low thermal conductivity, have prevented it from a wide commercial use.

II. Literature Review

Indian forces are working in very harsh environment in hot deserts at western border and cold deserts at high altitudes. Performance of man, equipment, and weapon system especially sensors and electronics, get adversely effected in harsh environment of desert, many times, leading to failure of critical equipments. Use of PCM can provide practical solutions to many of these problems. Defense Laboratory, Jodhpur (DLJ) has taken up a R&D program to develop PCM-based products to meet requirements of Armed Forces. Present paper describes status of science and technology of PCM along with materials and products developed at DLJ. PCM is very important topic for more innovations, because this material can be enhancing for more special applications. This material has wide range of applications and it can be increased by enhancing the PCM by adding some proper additives [3]. This paper presents modeling results of an innovative system for the temperature control in the interior compartment of a stationary automobile facing the solar energy from the sun. A very thin layer of PCM inside a pouch placed in the ceiling of the car in which the heating energy is absorbed and released with melting and solidification of phase change material. As a result the temperature of the car interior is maintained in the comfort condition [7]

Latent heat storage in a Phase Change Material (PCM) is very attractive because of its high storage density with small temperature swing. It has been demonstrated that, for the development of a latent heat storage system, the choice of the PCM plays an important role in addition to heat transfer mechanism in the PCM. The paper contains a list of about 250 PCMs and more than 220 references. Latent heat storage can be accomplished through solid-liquid, liquid-gas, solid-gas, and solid-solid phase transformations, but the only two of practical interest are the solid-liquid and solid-solid. Of the two practical systems, the solid-liquid system is the most studied and most commonly commercially available. Solid-solid systems show much promise, but are only recently being studied and most commonly commercially available. Solid-solid systems shows much promise, but are only recently being studied. Many phase change materials (PCMs) have been studied for practical use. This paper is a compilation of much of practical information on different PCMs and system developed based on latent heat storage technology [2].

This work investigates experimentally the performance of a thermal energy storage unit with phase change material encapsulated in cylinders. Air is the heat transfer fluid that flows across the tube banks to charge and discharge the storage system. The investigation analyses the storage system in terms of its storage capacity and the heat transfer rate to the phase change material. The aim of the analysis is to offer a solid ground for scaling up and implementation on solar residential domestic heating applications [6]. The use of a latent heat Eutectic aluminum silicon alloy, AlSi12, is an attractive phase change material because of its moderate melting temperature, high thermal conductivity, and high heat of fusion. A prototype thermal energy storage test rig has been built and tested as to better understand the behavior of latent heat thermal energy storage. A mathematical model was developed to predict the behavior of such a heat storage unit. The model was compared with the behavior of the test rig during discharge. The model proved to simulate the latent heat thermal energy storage with reasonable accuracy. It is recommended that more accurate material property data be obtained and that the thermal energy storage test rig be modified as to improve readings [5].

Storage system using phase change materials (PCMs) 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. PCMs have been widely used in latent heat thermal storage systems for heat pumps, solar engineering, and spacecraft thermal control applications. The uses of PCMs that melt and solidify at a wide range of temperatures, making them attractive in a number of applications, this paper also summarizes the investigation and analysis of the available thermal energy storage systems incorporating PCMs for use in different applications [1] Polyethylene glycol/silicon dioxide composite, a kind of form-stable phase change material. The composites can be made into mortar which is able to adhere to the surface of building structure and absorb the fire heat. This aims to study the effect of the composites on the fire resistance of building structure [4].

2.1. Energy storage methods

There are various forms of energies and their storage methods or mechanisms have been described below. Atul Sharma et al. [1] describes in their review paper on, thermal energy storage with phase change materials and Applications, about different type of energy storage methods and their mechanisms. In this paper main emphasis is given to the latent heat storage method to store solar thermal energy.

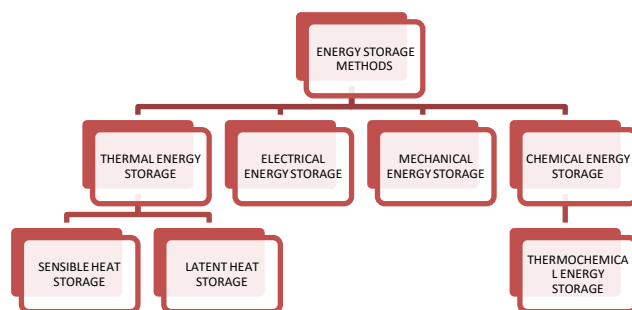


Figure 4:- Different types of energy storage device

2.2. Thermal energy storage:-

Thermal energy can be stored as a change in internal energy of a material as sensible heat, latent heat or thermochemical or combination of these. Sensible heat storage is due to temperature change of material while latent heat storage is due to the phase transformation either it is solid-liquid, liquid-gas or solid-solid. Different types of Thermal energy storage of solar energy is shown in figure-4 [1].

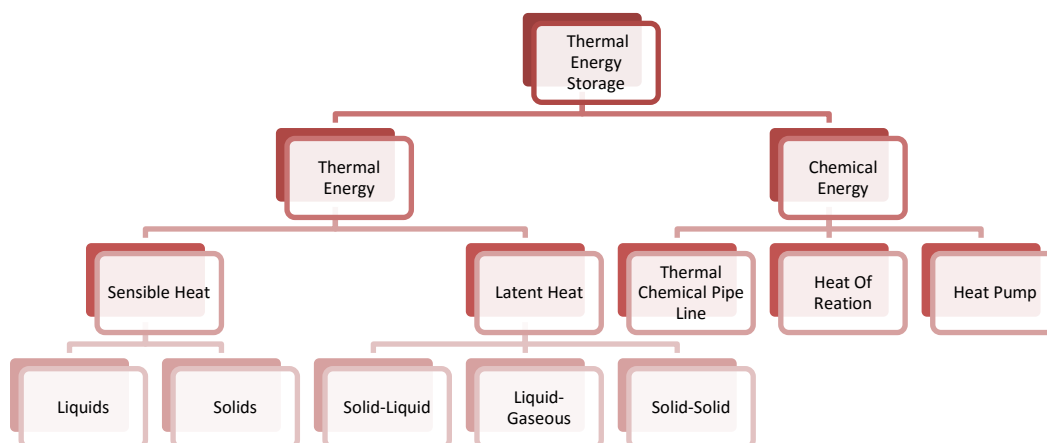


Figure 5:- Different types of thermal storage of solar energy

2.3. Composite phase change materials

Bhatt et al. [11] presents nine most suitable PCMs for thermal energy storage device. They studied rigorously about sixty PCMs and select most suitable PCMs based on the properties like thermal conductivity, heat of fusion, density and melting point. For the enhancement of storage capacity and different properties of phase change materials for the suitability of thermal energy storage device. Moussa Aadmi et al. [12] present th composite PCMs, epoxy resin paraffin wax with melting point 27°C as a new energy storage system. Ahmet Sari et al.[13] determines the thermal properties of blends of Polyvinyl alcohol(PVA)-stearic acid(SA) and Polyvinyl chloride(PVC)-stearic acid(SA) as form stable phase change material for thermal energy storage. In the blend, SA has a function of storing latent heat of fusion during its solid-liquid phase change where as the polymer(PVC or PVA) acts as a supporting material to prevent melted SA leakage because of its structural strength. A variety of polymer matrices are available with a large range of chemical and mechanical properties [4].

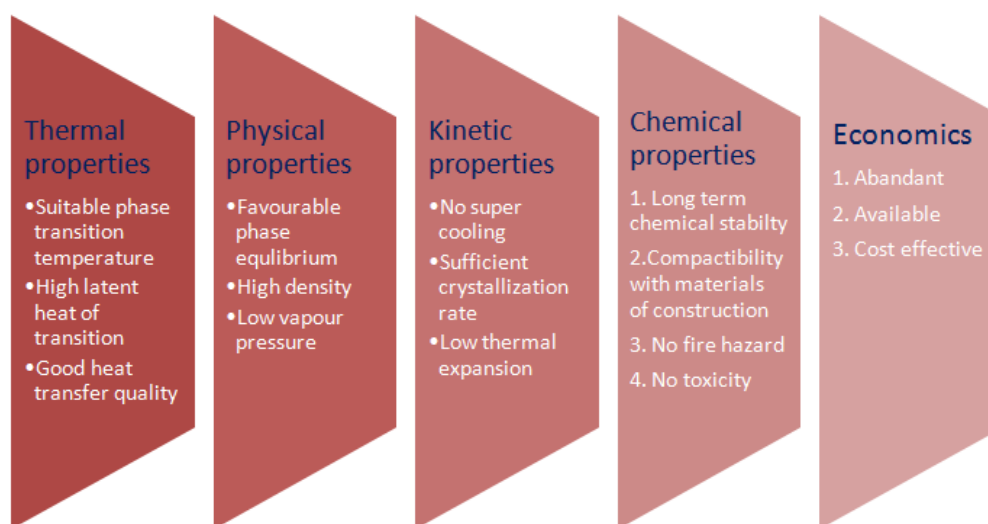


Figure 6:-Desirable properties of PCMs

2.4. Research Gaps in Literature Review & Future Research Directions

The literatures reviewed still have a wide range of gaps which are to be addressed in the upcoming years with focused dedication so as to enhance the concept of Thermal Energy Storage Unit in order to bridge a gap between the present and past research and also connect a ladder from present to future research.

Authors hereby proposed some important directions in Thermal Energy Storage Unit research:

- Material durability tests should be carried out to assure the long-term thermal cycling performance of the TES device. Before commercialization of the product, the latent heat TES has to show reliability and durability closely matching the average lifespan of a vehicle.
- To further improve the performance of the latent heat TES device, compared to increasing the cooling water flow rate which would require a larger pump and greater power, this method could be more cost-effective.

- After rigorous review on phase change material, a conclusion must be drawn that future best suitable PCMs are composite PCMs which have the enhanced properties in comparison to any single phase PCM.
- For selecting best suitable composite PCMs, a test bench may be designed to test various composite PCMs one by one and performance curve can be drawn to select best suitable PCM for high temperature thermal energy storage application.

III. Conclusions

The following conclusions are drawn from the present study:

1. The primary application of the latent heat TES devices is to store waste heat from an automobile engine during its operation and to provide the stored energy to warm up the engine components in cold weather and at start.
2. Composite PCMs are the materials that have the enhanced properties like thermal conductivity, heat of fusion, density and melting point in comparison to single PCM like paraffin wax etc. So, if serious attention will be given to composite phase change materials then a better and most efficient thermal energy storage unit can be designed.
3. Latent heat thermal energy storage system stores 5-14 times more heat than sensible heat thermal energy storage material.
4. Selection of phase change material and its compatibility with the containment where PCM encapsulated is the main issue to design most efficient thermal energy storage unit.

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