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A Review on Thermal Energy Storage Unit for Solar Thermal Power Plant Application

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Abstract

In the present scenario of a huge energy demand, dependency on fossil fuels only, certainly creates crisis in future especially for developing country. Although renewable resources of energy like solar energy is being utilized on a broad scale now a days but the problem comes in law and economy i.e. social and acceptability. Main reasons of this kind of difficulties are low density of solar radiation on earth's surface and if it is available then fluctuating in nature with time of the day and the day of the year. To remove these kinds of difficulties solar energy storage unit must be introduced in solar thermal power application. In this paper, literatures on thermal energy storage unit with phase change material has been rigorously studied to select the best suitable PCMs and materials for the design of test bench of the thermal energy storage unit.

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Keywords: Storage Unit; Helical Coil Solar Cavity Receiver; PCMs

1. Introduction

In the present scenario when the demand is more than resources available, it's our necessity to develop an energy storage device to store energy at the time of availability and supply it whenever demand is more than available. Although Sensible heat storage is the most common method of thermal energy storage, but the recent research on advance material and system shows that density of stored energy is greater for latent heat storage than that of sensible heat storage[1-4]. Phase change material is generally used in latent heat storage system and this type of system has been widely used for heat pumps, solar engineering, and spacecraft thermal control applications [5].

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Tremendous increase in the price of fossil fuel and continuous upgrading in the level of greenhouse gas emissions are the main driving forces behind the effective utilization non conventional energy resources. The storage of energy in suitable forms, conveniently converted into the required form, is a present day challenge to the technologists. Solar energy storage unit has the following characteristics (a) To conserve energy (b) To improve the performance and reliability of energy systems and (c) to reduce the mismatch between supply and demand. Scientists in many parts of the world are in search of new and renewable energy resources and stated that direct solar radiation is a prospective renewable source of energy and the solar energy storage unit is the new source of energy. In other words solar energy storage unit can be called as the sub renewable sources of energy [6, 7].There are various kinds of phase change materials but paraffin has been widely used for latent heat thermal energy storage system because of their large latent heat and proper thermal characteristics such as no super cooling, low vapour pressure, good thermal and chemical stability and self nucleating behaviour [8-12].

Nomenclature

Q	Quantity of heat stored (J)
T_i	initial temperature
T_f	final temperature
T	temperature
T_m	melting temperature
m	mass of heat storage medium(kg)
C_p	specific heat (J/kg K)
C_{ap}	average specific heat between T_i and T_f
C_{sp}	average specific heat between T_i and T_m
C_{lp}	average specific heat between T_m and T_f
Δh_m	heat of fusion per unit mass(J/kg)
Δh_r	endothermic heat of reaction
a_r	fraction reacted
a_m	fraction melted

2. Energy storage methods

There are various forms of energies and their storage methods or mechanisms have been described below.Atul Sharma et al. [5] 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.

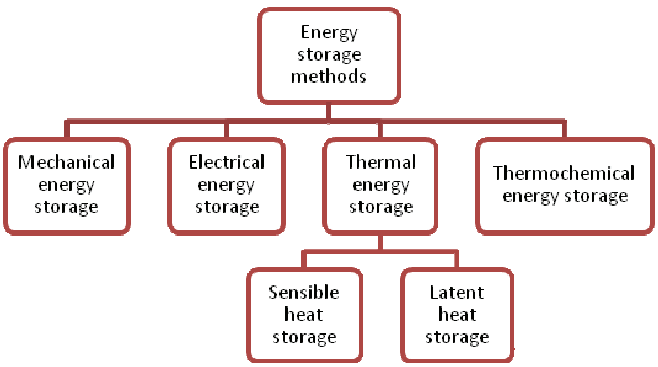

Figure 1 Different types of energy storage methods [5].

2.1. Mechanical energy storage

Mechanical energy storage systems include the storage due to gravitation as for example hydropower storage, storage due to pressure difference, compressed air energy storage and storage due to inertia, flywheels. Hydropower storage and compressed air energy storage can be used for large scale utility of energy while flywheels are more suitable for intermediate storage. Storage is carried out when off-peak power is available and the storage is discharged when power is needed because of insufficient supply from the base- load plant.

2.2. Electrical energy storage

Electrical energy is stored through batteries. When the battery is connected to the direct electric current then ionic reactions happens where the positive and negative ions are separated and hence chemical potentials are formed. At the time when the main supply disappears, this chemical energy is converted into electrical energy. The most common type of storage batteries is the lead acid and Ni–Cd. Potential applications of batteries are utilization of off-peak power, load leveling, and storage of electrical energy generated by wind turbine or photovoltaic plants.

2.3. 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 are shown in figure-2. [5]

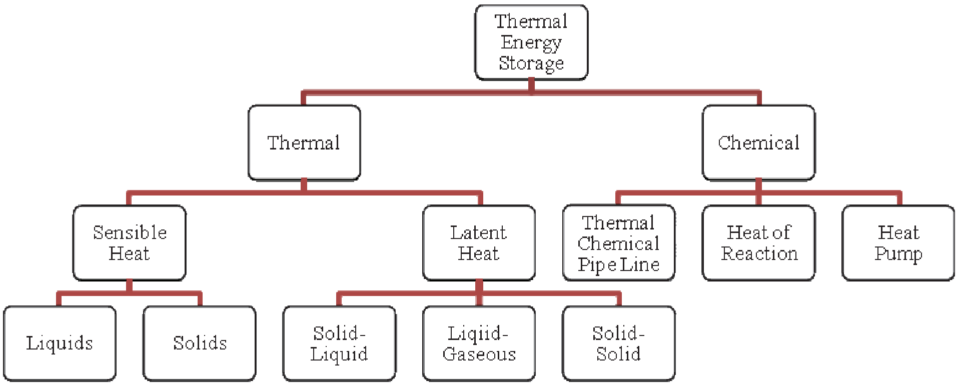

Figure 2.Different types of thermal storage of solar energy [5].

2.3.1. Sensible heat storage

In sensible heat storage (SHS), thermal energy is stored by raising the temperature of a solid or liquid. SHS system utilizes the heat capacity and the change in temperature of the material during the process of charging and discharging. The amount of heat stored depends on the specific heat of the medium, the temperature change and the amount of storage material.

$$Q = \int_{T_i}^{T_f} mC_p \, dT \quad (1)$$

$$= mC_{ap}(T_i - T_f) \quad (2)$$

Water appears to be the best SHS liquid available because it is inexpensive and has a high specific heat. However above 100°C, oils, molten salts and liquid metals, etc. are used. For air heating applications rock bed type storage materials are used [13].

2.3.2. Latent heat storage

In latent heat storage system charging and discharging phenomenon occur when the storage material undergoes phase change either from solid to liquid, liquid to gaseous or solid to solid. The storage capacity of latent heat storage system with a PCM medium is given by the following equations [13].

$$Q = \int_{T_i}^{T_m} m\,C_p\,dT + m a_m \Delta h_m + \int_{T_m}^{T_f} m C_p\,dT \quad (3)$$

$$Q = m[C_{sp}(T_m - T_i) + a_m \Delta h_m + C_{lp}(T_f - T_m)] \quad (4)$$

2.4. Thermo chemical energy storage

Sharma et al [5] said that charging and discharging phenomenon takes place during the breaking and reforming of molecular bonds in a complete reversible chemical reaction. In this case heat stored depends upon the amount of storage material, the endothermic heat of reaction, and the extent of conversion.

$$Q = a_r m \Delta h_r \quad (5)$$

Above discussed thermal energy storage technique, latent heat storage technique is one of the best suitable technique because of its high energy storage density and its characteristics to store heat at constant temperature called phase transition temperature of phase change material. Phase change can be in the following form: solid-solid, solid-liquid, solid-gas, and liquid-gas and vice versa.

Solid -Solid transition

- Change in crystalline structure
- Small change in volume
- smaller storage capacity than solid liquid transition
- Less containment required and greater design flexibility

Most preferable materials for solid-solid phase transition are organic solid solution of the followings whose characteristics, melting points and latent heats of fusion are tabulated below.

Solid–gas or liquid gas transition

- Higher latent heat of phase transition
- Larger volume changes on phase transition
- Larger containment required
- Impractical and complex system

Solid-liquid transition

- Intermediate latent heat of phase transition, volume change
- Most practical and economical system

3. Classification of phase change materials (PCMs)

The materials which are to used for thermal energy storage unit must have a high value of latent heat and thermal conductivity. They should have melting temperature lying in the practical range of operation, melt congruently with minimum subcooling and be chemically stable. It should be low in cost, nontoxic and noncorrosive. Materials that have been studied during the last 40 years are hydrated salts, paraffin waxes, fatty acids and eutectics of organic and non-organic compounds. Phase change materials should first be selected on the basis of their melting temperature and their applications. For air conditioning purposes, materials of melting temperature below 15^{o}C is to be selected, while materials that melts above 90^{o}C are used for absorption refrigeration system. All other materials that melt between these two temperatures can be applied in solar heating and for heat load leveling applications. These materials represent the class of materials that has been studied most [17].

3.1 Organic phase change materials

Organic PCMs are further described as paraffins and non paraffins. The main interest with organic materials is that they involve long term cyclic chemical and thermal stability without phase segregation and consequent crystallize with little or even no supercooling. Finally, they are non corrosive which is an important feature as listed previously. Subgroups of organic materials include paraffin and non-paraffin organics. Paraffin consists of a mixture of *n*-alkanes CH_3-(CH_2)-CH_3 into which the crystallization of the (CH_3) - chain is responsible for a large amount of energy absorption. The latent heat of fusion of paraffin varies from nearly 170 kJ/kg to 270 kJ/kg between 5^{o}C to 80^{o}C which makes them suitable for building and solar applications. Non-paraffin organic materials are the most common of the PCMs and they involved varying properties. Buddhi and Swaney [19] have conducted an extensive survey of esters, fatty-acids, alcohols and glycols suitable for energy storage. These materials generally have a high heat of fusion but low thermal conductivity, inflammability, toxicity, and instability at high temperatures. Although fatty acids are somewhat better than other non paraffin organics, they are even more expensive than paraffins [20].The development of a latent heat thermal energy storage system involves the understanding of three essential subjects: phase change materials, containers materials and heat exchangers [5].

3.2. Inorganic phase change materials

Inorganic compounds include salts hydrate, salts, metals, and alloys. The first were investigated because of their low cost which is determinant in most projects. Moreover, inorganic PCMs permit high density storage because they have high volumetric latent heat storage capacity and their conductivity may be twice as high as that of organic materials. The authors [21] used salt hydrates but experienced supercooling, phase segregation, and a lack of thermal stability. Moreover, it is reported that some are corrosive. Supercooling and phase segregation could be prevented [22] in some cases but then the economics may suffer. Metallic PCMs are low melting point metals such as Galium and metal eutectics. These have not yet been investigated thoroughly because of their weight. However, when volume is a major issue, they could be considered as they have high latent heat of fusion and very high conductivities compared to other PCMs.

3.3 Eutectics

A eutectic is a minimum-melting composition of two or more components, each of which melts and freezes congruently forming a mixture of the component crystals during solidification [23]. A large number of eutectics of inorganic and organic compounds have been reported [24, 25]. Eutectics are generally better than straight inorganic PCMs with respect to segregation [20].

4. Composite phase change materials

Vasishta D. Bhatt et al. [26] 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. [27] present the composite PCMs, epoxy resin paraffin wax with melting point 27^{o}C as a new energy storage system. Ahmet Sari et al.[28] 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 [29].

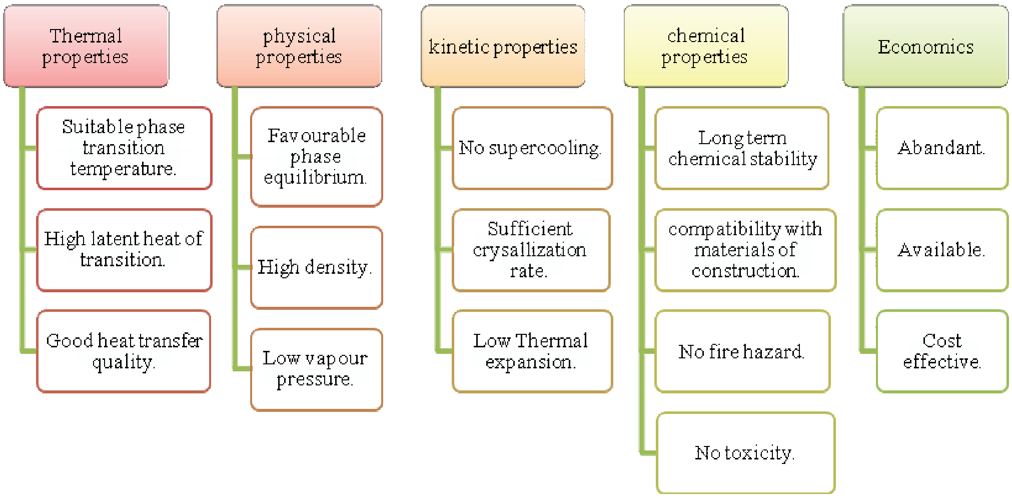

Figure 3.Desirable properties of PCMs

5. Development of latent heat storage system

Latent heat storage material stores thermal energy while undergoing a phase transformation. Developments of these storage systems include selection of material of desirable properties, material of containment and compatibility between these two. Initially latent heat storage material behaves like a conventional storage material but once the phase transition temperature reached, it acts as a latent heat storage material. Latent heat thermal energy storage system stores 5-14 times more heat than sensible heat thermal energy storage material as mentioned above in ref [5]. After the selection of latent heat storage material, there must be a concept to develop heat exchanger which takes the stored heat away from phase change material and send it to the helical coil solar cavity receiver present at the focus of parabolic trough concentrator under consideration.

6. Research Gaps in Literature Review & Future Research Directions

Despite profound contributions by research scholars and academicians of national and international repute on the topic of Thermal Energy Storage Unit. 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:

- It will take time to reach phase transition temperature for latent heat storage system. But up to the phase transition temperature fig-6; it is sensible heat storage system. Therefore, a system must be designed which will work as both sensible and latent heat storage unit, called multi functional storage unit. This system is applicable for both water heating as well as steam generating purposes.
- After rigorous review on phase change material, a conclusion must be drawn that future best suitable PCMs are composites 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.
- Vasishta D. Bhatt et al. [26] 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 but emphasis should also be laid down on the basis of properties like kinetic, chemical and economic.

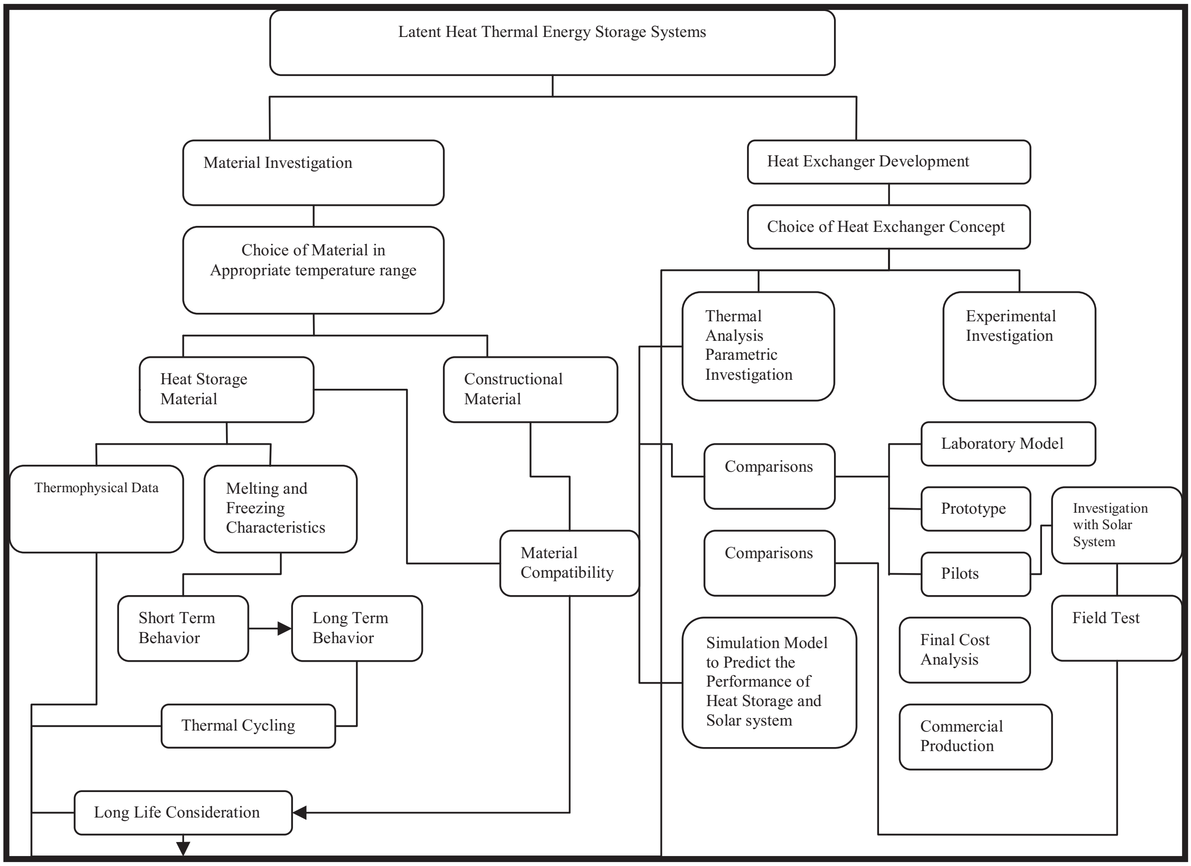

Figure-4 Flow chart for the development of latent heat thermal energy storage unit under different stage [5].

Conclusion

Thermal energy storage unit is integrated with solar thermal power plant so as to supply continuous power even at night or in the situation when the cloud covering is occur in the sky. In this paper, various types of storage unit are described but main emphasis is given to thermal energy storage unit with the help of phase change material. Different kinds of PCMs and their properties have been described in this paper but a special and the most recent type of PCMs called composite PCMs has also been described. 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. Latent heat thermal energy storage system stores 5-14 times more heat than sensible heat thermal energy storage material. By considering as a whole we come to the conclusion that latent heat thermal energy storage is more economical and their robust design may lead to store as much energy to supply continuously to the helical coil solar cavity receiver system of parabolic trough concentrator. There are large numbers of phase materials but few of them are utilized in accordance with the applications. For air conditioning purposes, materials of melting temperature below 15^{o}C is to be selected, while materials that melts above 90^{o}C are used for absorption refrigeration system. All other materials that melt between these two temperatures can be applied in solar heating and for heat load leveling applications. 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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