Cooling Mechanism for Pulsating Heat Load using PCM: A Review

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Abstract: *The overview of phase change materials (PCMs) and their properties are presented here with the review conducted over the years. The PCMs discussed here have very high latent heat of fusion, thereby storing large amount of thermal energy over a narrow temperature range. PCM's used in high power electronics and direct-energy weapons. High power electronics generate large pulses heat loads during operations. During heat pulse, the PCM absorb large amount of heat loads. Cooling media is used to dissipate the heat load with minimization of instantaneous heat load, reduces its physical size and power consumption. Latent heat storage can be achieved through liquid→solid, solid→liquid, solid→gas and liquid→gas phase changes. However, only solid→liquid and liquid→solid phase changes are practical for PCMs. Different PCM's are used as per their utility in different fields depending on temperature range, thermal conductivity and latent heat etc. which are explained here. PCM's used in fields such as mechanical, electrical and commercial area which is explained here.*

Keywords: ***Phase Change Material (PCM); Thermal Energy Storage (TES); Heat exchanger (HEx); Solar water heater (SWH).***

1. Introduction

A Phase Change Material (PCM) is a substance with a high heat of fusion which, melts and solidifies at certain temperatures, is capable of storing or releasing large amounts of energy. Unlike conventional storage materials, when PCM reach the temperature at which it changes phase (their melting point) it absorbs large amount of heat without rise in temperature.

When the ambient temperature in the space around the PCM material drops, the PCM solidifies, releasing its stored latent heat The thermal energy absorbed by a material when changing its phase at a constant temperature is called 'latent heat'. For practical applications, material that exhibit low volume changes is used, for example; solid-to-liquid and some special solid-to-solid phase change material.

The commonly used phase change materials for technical applications are:

a. Paraffin's (Organic)

b. Salt hydrates (Inorganic)

c. Organic-organic (Eutectic)

Latent heat storage offers a significant advantage if the application needs temperature cycles closely around the melting point.

In liquid or solid state the specific heat capacity is lower for most PCM materials compared to water.

PCM therefore absorbs and emits heat while maintaining a nearly constant temperature. Within the human comfort range of 20° to 30°C, latent thermal storage materials are very effective. They store 5 to 14 times more heat per unit volume than sensible storage materials such as water, masonry or rock. Latent heat storage is based on the absorption/desorption of energy when a storage material undergoes a phase change from solid to liquid, liquid to gas, or vice versa. Latent heat storage is particularly attractive since it provides a high energy storage density and has the capacity to store energy at a constant temperature or over a limited range of temperature variation which is the temperature that corresponds to the phase transition temperature of the material.

For instance, it takes 80 times much as energy to melt a given mass of water (ice) than to raise the same amount of water by 1oC.One of the potential and effective ways of storing thermal energy in buildings is the integration of brick with phase change materials (PCMs).

2. Literature Review

TES is a significant technology in systems involving renewable energies as well as other energy resources as it can make their operation more efficient, particularly by bridging the period between periods when energy is harvested and periods when it is needed.

That is, TES is helpful for balancing between the supply and demand of energy.

TES systems have the potential for increasing the effective use of thermal energy equipment and for facilitating large-scale fuel commutating. The selection of a TES system for a particular application depends on many factors, including storage duration, economics, supply and utilization temperature requirements, storage capacity, heat losses and available space. A complete TES process involves at least three steps: charging, storing and discharging.

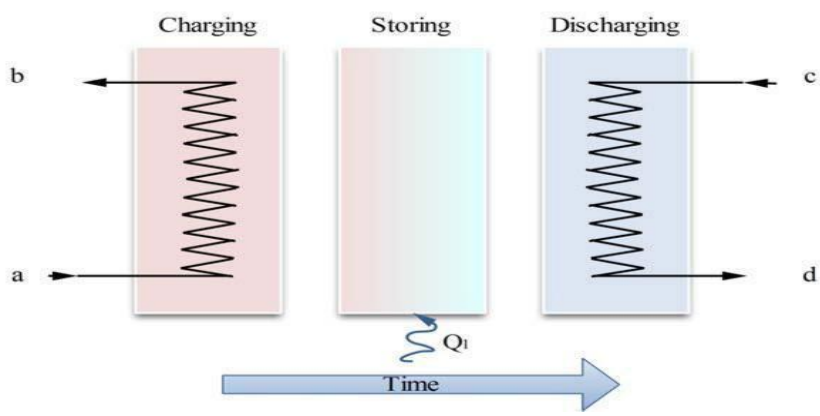

Fig 2.1: The three processes in a general TES system

2.1 TES System classified according to its temperature and thermal storage:

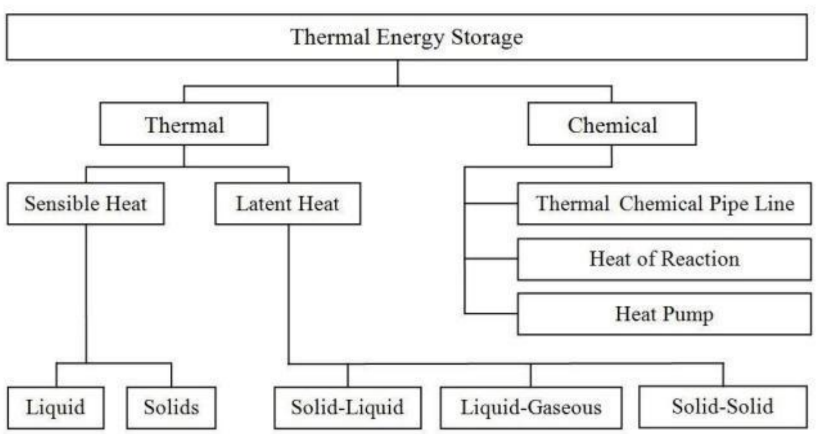

Fig 2.2: Thermal Energy Storage Type
(www.typesofTES.net)

In sensible heat storage systems (SHSS), thermal energy is stored by raising the temperature of a solid or liquid media.

Such as metal which phase do not change at certain temperature (Only temperature change). In Latent heat storage is one of the most efficient ways of storing thermal energy. In latent TES systems, energy is stored during the phase change (e.g. melting, evaporating and crystallization). Unlike the sensible heat storage method, the latent heat storage method provides much higher storage density, with a smaller temperature difference between storing and releasing heat.

In Thermo-chemical TES systems use an endothermic chemical reaction, where the energy associated with a reversible reaction is required for the dissociation of the chemicals.

The amount of energy stored is given by the relation:

$Q = \int m\, Cp\, dT = m\, Cp\, (Tf - Ti)$ (Sensible heat storage)

$Q = m\, [\int Cp,s\, dT + k + \int Cp,l\, dT]$ (Latent heat storage)

$Q = arm\, \Delta hr$ (Thermo-chemical heat storage)

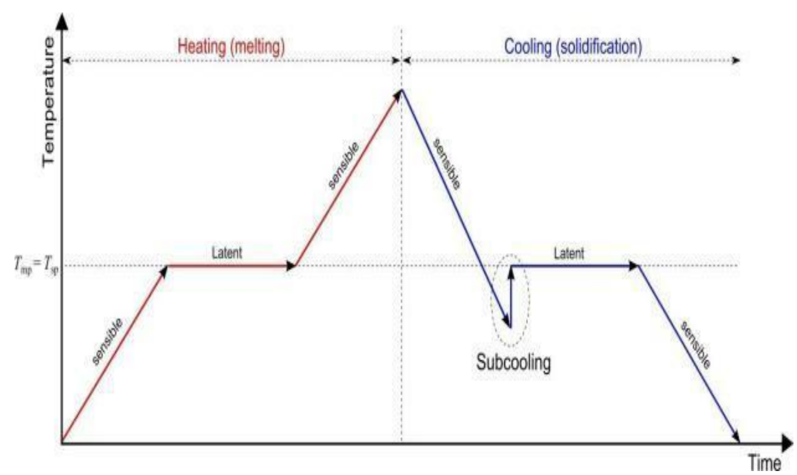

Fig 2.3: Graph b/w Temp. & Time (www.pcmproperties.com)

2.2 PCM materials can be divided in three groups as reported at below:

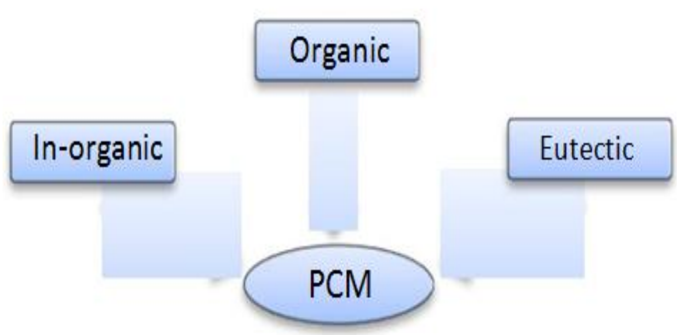

Fig 2.4: Classification of PCM

Organic PCMs have a number of characteristics which are non-corrosive, they have a high latent heat per unit weight, they are recyclable, they melt congruently and they exhibit little or no super cooling i.e. they do not need to be cooled below their freezing point to initiate crystallization.

Organic materials are divided into two groups:

a. Paraffin

b. Non-paraffin

Inorganic materials used as PCM are divided

into salt hydrate, metallic's and cover a wide temperature range. Compared to organic PCM, inorganic materials usually have similar melting enthalpies per unit mass, but higher ones per unit volume due to their high density.

a. Salt Hydrates

b. Salt

c. Metallic

A eutectic is a mixture of two or more constituents, which solidify simultaneously out of the liquid at a minimum freezing point, also called eutectic point. At the eutectic point, the liquid reacts to a solid that is composed of two or more solid phases with different composition; however, the overall composition is still the same as in the liquid. Therefore, eutectics nearly always freeze without segregation because they freeze to an intimate mixture crystal. The most common eutectic PCMs are Triethylolethane + water + urea, Triethylolethane + urea, $Mg(NO3)3.6H2O$ + $NH4NO3$, $Mg(NO3)3.6H2O$ + $MgCl2.6H2O$, and $Mg(NO3)2.6H2O$ + $MgBr2.6H2O$.[12]

Table 2.1: PCM Advantage and dis-advantage

	Organic (Paraffins)	**Inorganic (Salt Hydrates)**
Advantages	Non-corrosive; Chemically and thermally stable; No or little sub-cooling.	High melting enthalpy; High density.
Disadvantages	Lower melting enthalpy; Lower density; Low thermal conductivity; Flammable.	Sub-cooling; Corrosive Phase separation; Phase segregation, lack of thermal Stability; Cycling stability.

To improve the efficiency of the charging and discharging processes of a PCM-TES system, the most relevant parameter to be studied is thermal conductivity of the material:

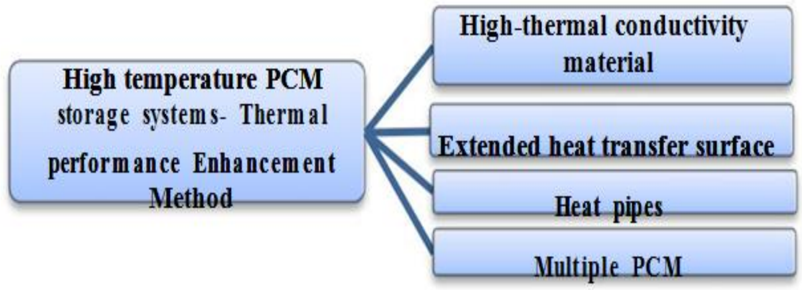

Fig2.5: Thermal Performance Enhancement Method

Hence, the heat transfer coefficient is dominated by the thermal conductivity of the solid PCM. However,--most PCM usually provide low thermal conductivity around 0.5W/(m·K), which results in poor heat transfer between the HTF and the storage material. Thermal-composites are a term given to combinations of phase change materials (PCMs) and other (usually solid) structures. In order to increase the thermal-conductivity of PCM, several heat transfer enhancement techniques have been studied incorporating high thermal conductivity enhancers into PCM and porous heat transfer media, extending heat transfer surfaces by fins and capsules, using intermediate heat transfer medium or heat pipes and employing multiple PCMs.

Table2.2: Heat exchanger (HEX) can be classified according to performance:

Double pipe HEX	Shell and tube HEX	Flat plate type HEX
	Advantages	
Suited to high pressure applications.	Suited to high temperature and pressure applications.	Simple &compact size.
Standardization, Simple maintenance & servicing.	Less expensive compared to others.	Less maintenance cost.
Flexible and units can be added and removed as required.	Easy to control and operatable.	Easy installation.
Easy in Construction.		Negligible heat loss.
Can be used at low heat transfer area.		Capacity can be increased by introducing plates in pairs.
Cheap		Overall weight of set is less.
	Disadvantages	
Leakage corner.		Not compatible for higher temperature and pressure above 200 and 20 bars.

Maintenance is time consuming. Occupy more floor space compared to others.	Maintenance cost is more. Required large space.	Initial cost is high. Careful dismantling and dismantling to be done.
	Application	
Used for refrigeration process in appliance like refrigerators, domestic heating system and car radiators.	Used as regular heat exchanger for distillation column, chemical equipment stream cooling and heating purpose, used internally in reboilers and evaporators.	Used in oil cooling system in automobiles, steam condensation, Swimming water cooling system, refrigeration system.

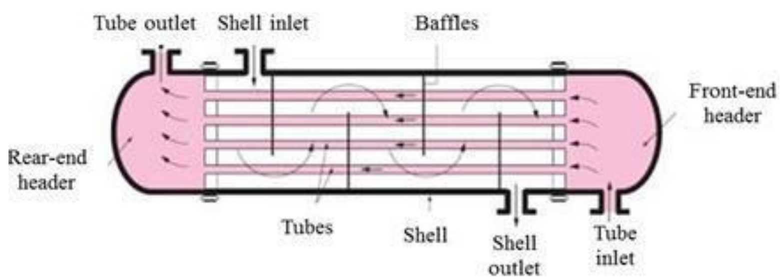

Fig. 2.6: Double Pipe Heat Exchanger (www.HEXtypes.com)

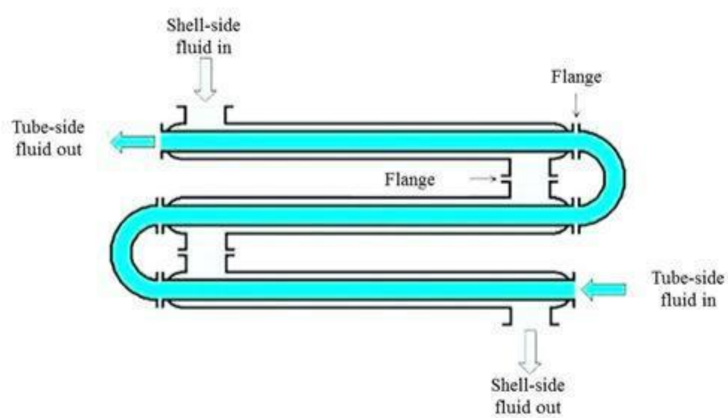

Fig. 2.7: Shell and Tube Heat Exchanger (HEXtypes.com)

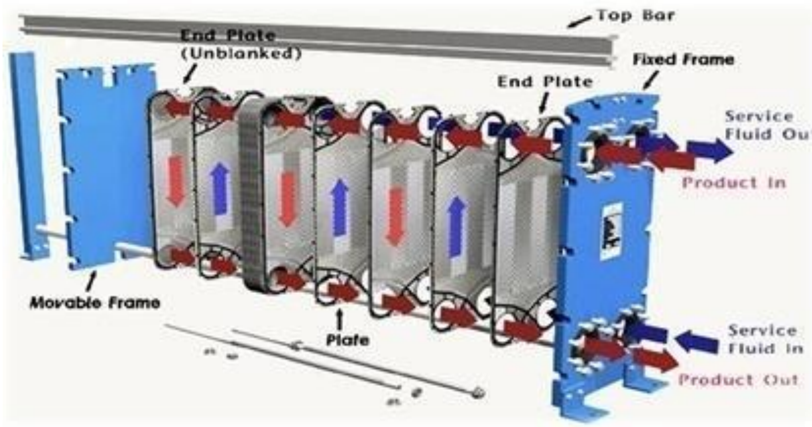

Fig. 2.8: Flat Plate Heat Exchanger
(HEXtypes.com)

2.3 Shell and tube type heat exchanger

a. The simple design of shell and tube heat exchanger makes it an ideal for a wide variety of application.

b. To be able to transfer heat well, the tube material should have good thermal conductivity.

c. The tube material also should be compatible with both the shell and tube side fluids for long periods under the operating conditions (temperature, pressure, PH etc.) to Minimize deterioration such as corrosion.

d. All of these requirements call for careful selection of strong, thermally, conductive, corrosion-resistance, high quality tube material.

2.4 Cooling of Helmet:

A helmet cooling system eliminating the requirement of the power supply uses phase change material (PCM) to absorb all the heat generated from the head at a relatively constant temperature to provide cooling of the head. Thus, the interior is maintained at a certain cooled temperature which is close to the melting temperature of the PCM and creates a thermally comfort environment to the head without requiring electrical power supply. The PCM is enclosed in a pouch and placed between the head and the helmet. When the head skin temperature is above the melting temperature of the PCM, the PCM begins to melt as it absorbs the heat from the head.

The basic components of the PCM-cooled helmet are illustrated in Fig. 2.9. The key component of the helmet cooling system is the PCM pouch, The PCM is enclosed in the pouch, A flexible heat collector made of copper provides a good thermal path for conducting heat transfer from the wearer head to the PCM pouch, the heat collector is attached to a vinyl cushion which is filled with a water based solution (gel). The vinyl cushion provides a comfortable interior for the helmet.

The problem of overcooling on the head does not occur as the head skin temperature is maintained at a temperature which is near to the melting temperature of PCM. The choice of PCM material is important to achieve appropriate cooling on the head. When the head temperature is above 30 °C (designed temperature to be maintained), the PCM begins to melt to provide a cooling effect on the head. When the skin temperature is below 30 °C, the PCM pouch provides a warming effect.

Several PCM, such as the organic-based paraffin-based PCM, salt hydrates, certain metallic alloys, and ‘‘dry’’ PCM can be used. Each has its own strength and weakness for the application. The paraffin PCM is relatively inexpensive and widely available. Paraffin has higher heat storage capacity per unit volume.

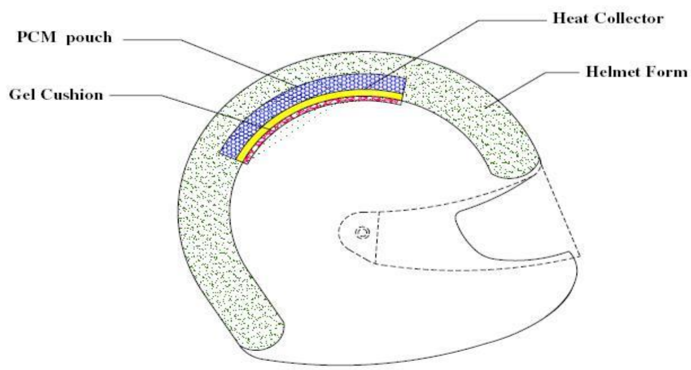

Fig 2.9: Cooling of Helmet

The cooling unit is able to provide comfort cooling up to 2 h when the PCM is completely melted. The stored heat from the PCM pouch would then have to be discharged by immersing in water for about 15 min to solidify the PCM before re-use.

2.5 Transportation:

A huge percentage of our food is transported by road with refrigerated vehicles now common place. Controlling the temperature of food packages during transport is needed with the rise of online shopping. During transport, food requires cold temperatures to maintain freshness. A major issue is the undesired warming of food when packages are exposed to warm temperatures on airport tarmacs and temporary unrefrigerated storage during air transportation.

Fig. 2.10: Cooling Of Dairy Product (www.pcmproducts.com)

PCM technology offers both mechanical-refrigeration-free and back-up cooling options. To solve this problem, phase change materials (PCMs) can maintain package-temperature by changing their phase from liquid to solid or vice versa, to absorb or release latent heat. Although this technology is still not fully commercially viable yet, it has good potential.

Table 2.3: Show the Compression transportation facility b/w with and without using PCM (www.pcmproduct.net):

Parameters	Without PCM	With PCM
Cost of truck and the insulated container	8.5 Lakhs	8.5 Lakhs
Cost of the refrigeration equipment included	Nil	3.75 Lakhs

PCM and charging unit for PCM based truck		
Cost of the refrigeration unit for conventional truck	2.50 Lakhs	Nil
Total capital cost	11 Lakhs	12 Lakhs
Diesel consumption for the vehicle	4 liters per hour	2.50 liters per hour
Cost of electricity	Nil	Rs. 6 per unit(10 unit per day)
Total running cost	10 Lakh per annum	6.5 Lakh per annum
Investment in capital cost of PCM based refer over conventional truck	1.25 Lakhs (one time cost)	
Saving per annum using PCM system	3.5 Lakh per annum	

2.6 TES with PCM for improving energy performance of building:

Some south and oil-exporting countries have also recognized the importance of reducing the energy consumption of buildings to balance the energy domestic market and exportation.

As stated by Soares et al. some of the most promising passive latent heat TES systems for buildings (for some climates and certain typologies of buildings) are those related with harnessing solar thermal energy for heating during winter and those optimized to reduce overheating during summer.

These systems can integrate a vertical stack of rectangular cavities filled with PCMs in their configuration, which is the case of the exterior PCM-shutter proposed by Soares et al. There are three different ways to use PCMs for heating and cooling of- -buildings such as PCMs in building walls, PCMs in building components other than walls i.e. in ceilings and floors, PCMs in separate heat or cold stores. The first two are passive systems, where the heat or cold stored is automatically released. When indoor or outdoor temperatures rise or fall beyond the melting point. The third one is active system, where the stored heat or cold is contained thermally separated from the building by insulation. Therefore, the heat or cold is used only on demand and not automatically.

In building applications, only PCMs that have a phase transition close to human comfort temperature (20– 28ºC) can be used. Some Commercial PCMs have been also developed for building application. Material type such that commercial paraffin waxes to be used as PCMs in passive TES applications for buildings have typically low thermal conductivity (~ 0.2 W m-1 K-1).

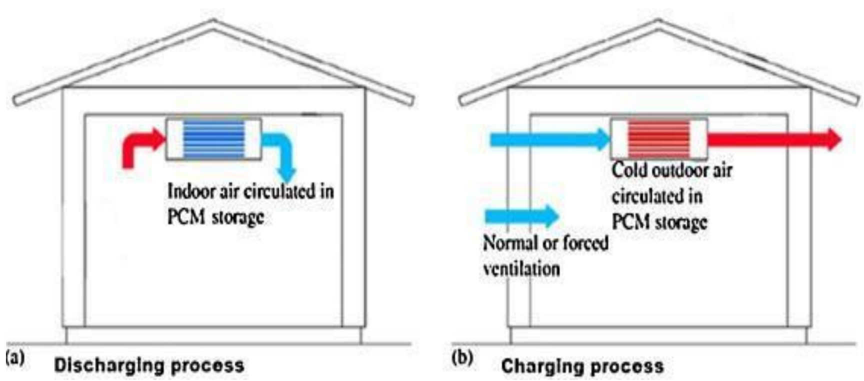

Fig 2.11: Cooling Building (www.pcmapplications.com)

This TES system was designed to take advantage of solar thermal energy for winter night time indoor heating in Coimbra, Portugal (Mediterranean climate).

During the night, the system is to be closed to minimize the heat losses through the window and to allow it's discharging (releasing the stored energy indoors). Afterwards, the right-side and the left-side shutters can be switched to solve both the summer and the winter challenges. To improve the heat transfer through the PCM bulk, the small TES unit was made of aluminum and provided with some horizontal fins connecting the heated/cooled vertical walls, thus forming a vertical stack of rectangular cavities. The magnitude of the cost savings is more during the summer months whereas the percentage difference in cost savings is more during winter month. A maximum percentage cost savings of about 30% (October) was - observed at the residential utility rate, and 28% (November) was observed at the business utility rate. This suggests that the currently employed Bio-PCM with melting point of 29 °C works most efficiently in the transition between summer and winter season during which less intense isolation and ambient temperatures were observed. March was found to have the least cost savings of around 10% for both the residential and business utility rate. Thermal storage can be part of the building structure, even for light weight buildings, by the addition of PCMs to gypsum board, plaster, concrete, or other building materials. When determining the effects of the inlet velocity on melting time, it was found out that it takes approximately half an hour more if we reduce velocity for 2 m/s. Melting time also increases with modified geometry. If melting temperature is decreased, then naturally melting time decreases as well, since the temperature difference increases.

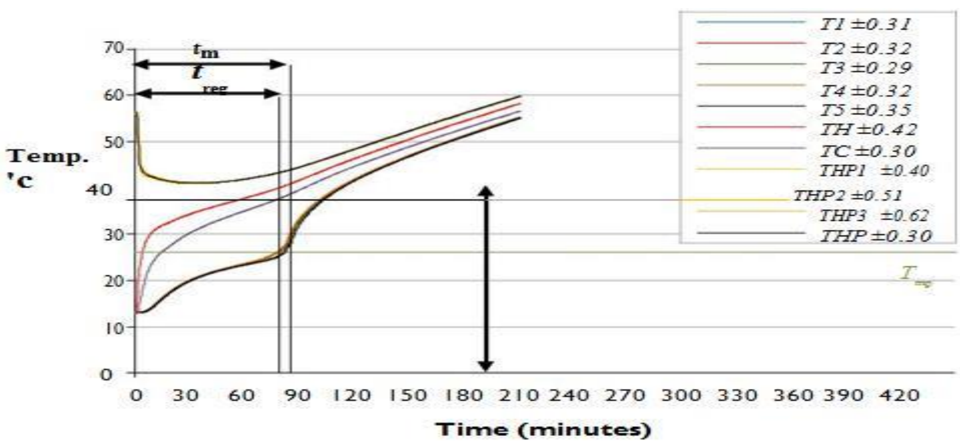

Fig 2.12: Charging phase temperature and time graph (www.BCPusingpcm.com).

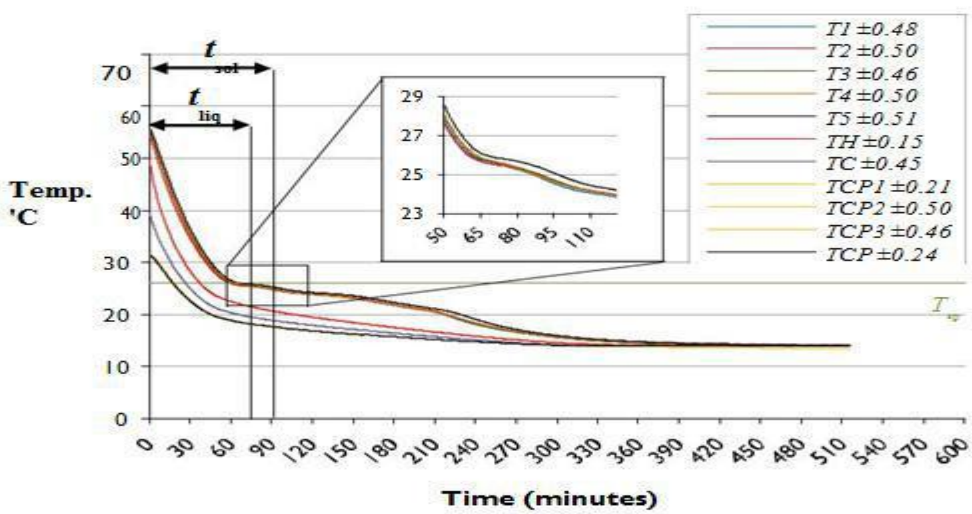

Fig 2.13: Discharging Phase Temperature and Time Graph (www.BCPusingpcm.com)

Changing melting temperature range from 24-25°C to 20-24°C, it reduces melting time for one hour. The use of PCM in solar water heater helps to reduce cooling rate of water, thus it enhance the maximum utilization of solar energy and hence improves efficiency of system. In this research with use of PCM efficiency of solar water heater increase from 31.25% to 44.63% and also heat storage capacity increase from 3260.4 kJ to 4656.5 kJ.

3. Conclusions

I have presented the information about the types of the PCM and Kind of refrigerant used. Related to my study I learned more about the theory of heat transfer and its practical application in the real world. There is still a lot to learn and to improve. Herein the PCM used is ice. Heat Exchanger of shell and tube type is best suitable for this purpose. Phase Change Material has the wide area of application as an engineering point of view.

Use of PCM can lead to save the energy and proper distribution of the load on the resources such as Demand Side Management etc. Air Cooling and heating with the help of PCM can help to the air conditioning for human comfort. Cooling of Electronics equipments with the help of PCM saves the energy to cool the equipments. PCM can be use for the lot of engineering applications for conservation of energy. The use of PCM in solar water heater helps to reduce cooling rate of water, thus it enhance the maximum utilization of solar energy and hence improves efficiency of system. In this research with use of PCM efficiency of solar water heater increase from 31.25% to 44.63% and also heat storage capacity increase from 3260.4 kJ to 4656.5 kJ.

I learned about cooling helmet in which the problem of overcooling on the head does not occur as the head skin temperature is maintained at a temperature which is near to the melting temperature of PCM. The choice of PCM material is important to achieve appropriate cooling on the head. When the head temperature is above 30 °C (designed temperature to be maintained), the PCM begins to melt to provide a cooling effect on the head. When the skin temperature is below 30 °C, the PCM pouch provides a warming effect. The principal contender of such type of cyclic cooling technology is the Thermal Energy Storage (TES), in the form of Latent Heat of Fusion, in the Phase Change Materials (PCMs). In this Paper, I learned wide area PCM used and their properties.

We discussed types of PCM at different areas with different temperature and thermal conductivity.

A literature review on different passive TES systems for buildings and solar water heater are provided.

References

1) Demirbas M.F., Thermal Energy Storage and Phase Change Materials: An Overview, Energy Sources, Part B, 2006.

2) Review of passive PCM latent heat thermal energy storage systems towards mechanical system' energy efficiency" by Soares et al.

3) Karthikeyan S., Muthu Saravanan S., Prashanth R., Energy conservation through phase change material based thermal energy storage system-a project report, Anna University Chennai, 2006.

4) Zalba B., Marın J.M., Cabeza L.F., Mehling H., and Review on thermal energy storage with phase change: materials, heat transfer analysis and applications, Applied Thermal Engineering 23, 2003.

5) Heinz A., Streicher W., Application of phase change materials and classification PCM for thermal energy storage, Available at: http://talon.stockton.edu. /eyos/ energy_studies /content/docs/FINAL_PAPERS/8B-4.pdf, (accessed 10/05/2012).

6) Gawron K., Schöder J., “Properties of some salt and salt hydrates for latent heat storage”, Energy Research, 1977, Vol.1. 351-363.

7) Wang W. [et al.] Enhanced thermal conductivity and thermal performance of form-stable composite phase change materials by using β-Aluminum nitride. [Journal] // Applied Energy. - 2008.

8) "A computational model of a PCM heat exchanger in a vapour compression system with a large pulsed heat load.by Greg Troszak & Xudong Tang, Proceedings of the ASME 2012 Summer Heat transfer Conference HT 2012.

9) Demand Side Management Through Efficient Thermal, Waqar A. Qureshi, Student Member, IEEE, Nirmal-Kumar C. Nair, Member, IEEE, Mohammed M. Farid, Non-member.

10) Solar Water Heating System with Phase Change Materials Available from: https:// www.researchgate.net /publication/265111061_Solar_Water_Heating_System_ with_Phase_Change_Materials.

11) Samira Haghshenaskashani, "HadiPasdarshahri, Simulation of Thermal Storage Phase Change Material in Buildings", World Academy of Science Technology. Department of Materials Science & Engineering,