Chapter 3

An Overview on Phase Change Material Applications

3.1 Introduction

In the past, it would be suggested that the conventional energy sources are limited and it is required to minimize the use, save this energy as fossil fuels are limited. This kind of human thinking now day’s needs to change because the world scenario is changing. Moreover, everyday emission of toxic gases is increasing. Due to this research is required in the direction of global warming and to meet requirement of energy supply and demand. Such kind of motivation towards the energy conservation leads the development of country. India is one of the biggest among developing countries which requires paying key attention to present environmental and energy scenario.

Conventional heating and cooling technology are majorly working based on different types of refrigerants. Every system working overload condition or peak load and due to this energy consumption is high. Therefore, utilization of conventional energy would affect the environment. As environmental and energy supply and demand disputes deal with environmentally kind of systems and globally, there arises the urgent need of sustainable system.

Let’s discuss about global energy scenario for energy supply. As per the world energy consumption in 2016 total supply energy was 13500 Mtoe and it will probably reach up to 15000Mtoe up to 2020. Coal is one of the major utilized sources of conventional energy sources and its availability is up to 192 years as per current situation (WEB,2016.http://www.iea.org/bookshop/724-World_Energy_Balances_2016). It is fact that in the world the energy consumption rate is 5.5% more than previous year which is shown in figure 3.1 and figure 3.2. At the same time, it was observed that the pollution released into the environment grownup to the 32% from 2005 to 2015.
Looking towards the emission of CO₂ and CO into the environment, it was 31,258 million tonnes in the year of 2015 (Stephane de la Rue du et al., 2009a; Stephane de la Rue du et al., 2009c).


**Fig. 3.1 India year wise energy consumption in Million tons of oil equivalent**


**Fig. 3.2 Country wise energy consumption in Million tons of oil equivalent**


However, calculating the total energy consumption of India was 376 Mtoe in the year of 2011 and it was reached up to 882 Mtoe in the year of 2015, which is showing the energy consumption rate is growing day by day and Indian is on 3rd position in the
world for energy consumption. Figure 3.3 indicates India’s present energy installed capacity from Ministry of New and Renewable Energy. Total energy installed capacity of India is 170GW. India produces 811kwh electricity per year and 611kWh consumed per capita which is one fourth of the world. India is exploring the electricity production around 950GW by 2025. CO₂ emission rate is increased by 1.2% every year (Stephane de la Rue du et al., 2009a; Ernst et al., 2009).

As according to current scenario approximate 80% systems are running with conventional energy sources like coal, oil, gas and other fossil fuels. These fossil fuels were used since millions years ago. Now those sources are limited and hardly its stockpiles available up to 200 years more. Also, it is noticed that if the people may change their lifestyle pattern there can arise the energy supply shortage. Hence, the development of the country is quite difficult in future by use of conventional energy. Due to this reasons, alternative source of energy is required (Stephane de la Rue du et al., 2009a).

Fig. 3.3 Energy installation capacity in India
(MNRE. www.mnre.gov.in)

So finally, to avoid the shortage of energy and protect the conventional sources of energy, renewable sources play a key role to make changes in energy consumption, energy crisis, instability of fossil fuels, polluted climate effects. Though it is a fact that to find out such technology related to renewable sources, will give more output with less energy utilization, consistent and
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efficient technology and an eco-friendly system. Such system also operates at less energy use and removes the fossil fuel expenses (Aimee et al., 2008; Michael et al., 2008).

3.2 Energy consumption sector wise scenario

Development of the country’s economy mostly depends on the energy acts. The important and essential requirement of having reliable and affordable energy facilities are the major factor for country’s development. Current scenario of the maintenance in the different sectors of the energy produced for equipment’s is done by electricity, by use of gaseous fuels and liquid fuels. The figure 3.4 indicates the energy consuming sectors.

![Figure 3.4 Schematic representation of Major energy consumed sectors](image)

Fig. 3.4 Schematic representation of Major energy consumed sectors

It clearly shows that the industries are consuming around 32% of the overall energy consumption. Similarly, energy consumption in residential, commercial and agriculture sector is 52% of the overall energy consumption. In household application, major portion of energy consumption is air-conditioning and refrigeration.
3.3 Energy consumption in Building and its growth rate.

Looking at the energy consumption rate and limited source availability, the dream of the common people, researcher and government are to get the energy with minimum rate and limited consumption. As discussed in previous section mainly energy consumed in the residential sector is of mechanical cooling forms. The figure 3.5 shows the energy consumed in the household applications and commercial sectors (Stephane de la Rue du et al., 2009b).

Fig. 3.5 Graphical representation of the energy utilization in building sectors (Stephane de la Rue du et al., 2009b)

The energy consumed for cooling of the building by refrigeration system which works as mechanical cooling. This system consumes maximum energy among
the others as shown in figure 3.5. This demand for cooling of building and commercial sector will increase with growth of industries in the future. So, utilization of the energy conservation system is need of the current days for such application like heating and cooling of the building, hot water application etc. Figure 3.6 clearly shows the current and future demand of energy required for different sectors. Finally the annual growth rate of energy consumption by building sector is 1.7% for residential, 1.5% for commercial and 1.66% for total energy consumption (Stephane de la Rue du et al., 2009b).

![Graph showing the predictable rise in use of energy in various household applications](image)

**Fig. 3.6** Predictable rise in use of energy in various household applications (Stephane de la Rue du et al., 2009b).

### 3.4 Thermal Comfort

Thermal comfort is vital for climate control systems and beyond. Thermal comfort signifies that in an environment, a person having normal amount of clothes on feel neither cold nor warm. Thermal comfort is crucial for one’s well-being. It can only be obtained when air temperature, humidity and air movement are within the “comfort zone” range. According to ASHRAE Standard (ASHRAE, ANSI. Standard 55- 2010: “Thermal Environmental Conditions for Human Occupancy”), thermal
comfort is defined as that condition of mind which expresses satisfaction in that thermal condition. Also, British standard (British standard BS EN ISO 7730: Modern thermal environments) defines the thermal comfort as that condition of mind which expresses satisfaction with the thermal environment. The factors that influence on the thermal comfort of human beings are categorized as environmental and personal. The environmental factors involve air temperature, humidity, air speed and radiant temperature whilst personal factors are clothing, activity and conditions (Dincer and Rosen, 2002; Ahmad et al., 2013).

3.5 Methods used in Building for decreasing heat transmission

There are several ways to reduce the heat transmission in the building. During the change in climates, the thermal insulation material is most suitable in building element for moderate the heat flow into the building space. This material includes the foams, cotton, fiberglass etc. Moreover, this material acts as thermal resistance to the heat flow so effective cooling can be achieved. However, the demanded power for cooling of the building can be satisfied by the Natural Cooling Techniques. Also, such kind of techniques reduces the size and weight of the air conditioning equipment which is shown in figure 3.7.

![Various techniques for cooling of buildings.](image)

Fig. 3.7 Different types of cooling techniques for the buildings
3.5.1 Shading

Shading is the most common idea to prevent solar radiations. This shade is to be designed against the direction of radiation on the window. Schematic diagram 3.8 indicates the simple shade arrangement to protect the solar radiation in winter and summer seasons. In summer season horizontal projection with appropriate depth protect the radiation. While in the winter season east and west wall can be protected by a combination of horizontal and vertical louvers.

![Schematic diagram of shading arrangement in building](image)

**Fig. 3.8 Schematic diagram of shading arrangement in building**

3.5.2 Thermal Chimney

In this type of system windows or doors arrangements are on the lower side of the building. From this lower open side, the wind is coming and this air is to be removed from the inside hot air and exist from the top open window. The figure 3.9 shows the air circulating arrangement which is called thermal siphoning. Such kind of arrangement is most viable for major difference of inside and outside temperature.

3.5.3 Surface Shading

This kind of heat protection against the radiation has different arrangement than the others. This surface shading is provided on the internal part of the building or
sometimes it can be provided isolated on the building surface. Few walls of the building are highly textured and constructed under the shade, so affecting area by the radiation is less. Due to this textured wall is cooler that the flat surface. To improve the coefficient of the convective heat transferred, surface area can be increased. Such provision will lead to building cooling at night time. Figure 3.10 shows the surface shading arrangement.
Also, there is another type of shading arrangement by thoroughly covering inverted earthen port on the building surface. This arrangement is only possible on traditional buildings with flat and small area. Figure 3.11 indicates the earthen pots arrangements. This earthen port provides more surface area for radiation emission. At the same time heat flow is restricted by the insulating cover of still. This system is difficult to provide in a wide range due to its high maintenance and roof is rendered usable.

![Fig. 3.11 Arrangement of Roof surface shading with pots](image)

3.5.4 Ridge Vent

Ridge vent system is most effective top story ventilation system and it provides the continuous ventilation. This can also help to prevent the wind and bugs during the rain. This system is to be fitted on the new roof where easily installation is possible. Figure 3.12 showing rigid vent arrangement.

![Fig. 3.12 Rigid vent arrangement on Roof](image)
3.5.5 Roof Vent

This type of vent arrangement on the roof is most effective and inexpensive system and is shown in figure 3.13. This is installed on the roof at each end. The vent decreases the total accumulated heat and protects the emission radiation into the building. This roof vent will help to remove moisture from the room during the winter instead of cooling.

![Roof Vent](image)

Fig. 3.13 Building roof arrangement

3.5.6 Roof Spray

The sprayers are used for the exterior surface. This spray makes the roof wet. The imparted sensible heat on the roof surface plays important role to covert it into the latent heat. This latent heat of evaporation leads to the water being vaporized. This conversation of heat can cool the surface. Therefore, the temperature gradient is to be generated between outside and inside surfaces. Finally, cooling can be maintained. Also, this roof spray reduces the cooling load up to 25%. Temperature of the roof should be greater than the air due to threshold condition.

3.5.7 Earth Cooling Tubes

Earth Cooling Tubes have unique arrangement to get cooling. In this system pipe is to be fitted underground of the housing surface. The one end of the pipe is to be opened into the house and another end is to be opened to hot exterior air at outside the building. These pipes are buried at 3m to 4m under the land of house. The exterior hot air comes through the outside open hole of the pipe and gets cooling from
the deep cooled soil and provides the cooled air to another open end at the house.

3.5.8 Vegetation

This system is the most common and user-friendly approach. The creepers and the deciduous plants have capacity to evaporate approximately 1460kg of water. At the same time this evaporation effect on cooling of the surrounding area is 880MJ. This evaporation comes from the surface of leaf and its temperature is lower than the air temperature. Such kind of system is most suitable in summer days.

3.5.9 Wet Fiber Pads

In this wet fiber pads arrangement, the wetted pads are to be fitted on the windows instead of other material like glass. The constructions of the windows are in the directions of the strong wind. The coming hot air from the outside is humidifying during the contact with these wet pads. These wet fiber pads reduce the building appearance.

3.5.10 White Roof

This is also most common type of heat protecting methods. In this system, the light colors paint is to be painted on the wall surfaces. The nature of the light colors is high longwave emissivity. Similarly, white colour is most efficient due to its high reflecting and less absorbing capacity of radiations. Also it would be observed that the tiles and coating of SiO₂, LiF and MgO can improve the efficiency of daytime cooling into the building.

3.5.11 Movable Insulation Systems

The insulation system is to be constructed on the roofs of the building. This system has flexible or movable arrangement on the roofs. The insulating layer is generating a mass and minimize the heat (coming from the radiation) storage in the daytime. Similarly, in the night time thermal mass of the roof is open to allow the exposure by insulation layer. The main merit of such kind of system is that it can be reversed in winter seasons. The mass is protecting the sun
during the day time and is insulated at night time and finally, these reduce the heat losses.

### 3.5.12 Radiative Cooling

Few buildings have slop roofs toward the internal counter yard. Basically, parapet wall is used to prevent the air mixing on the roof. The hot air comes from the outside and cooled enters in to the lower level opening of the room through the counter yard. This method for cooling is normally not used in wide range. Figure 3.14 indicates air flow arrangements.

![Figure 3.14 Schematic view of Radiative cooling arrangement](image)

3.6 Energy storage system necessity and its methods.

In energy conservation system the renewable energy sources are utilized. Therefore, it is very important to check the availability of sources, nature of energy and demand. Observing the mismatch of this technical aspects of renewable sources encourage to integration of such system with energy storage system. Such integrated system with energy storage unit leads to implementation of effective energy conservative system. Among the all renewable sources the solar energy is most viable energy source because of its major availability worldwide, inexhaustible, cost free and many more. Solar energy has wide applications and its major factor is time dependent in nature. Therefore, the economics and commercial acceptance of solar thermal devices are more. Hence, such king of solar based system is to tie with the
thermal storage system will give the effective results for said applications and for end users.

The storage of the energy can fulfill the gap between the energy consumption and generation. This storage system can store the excess amount of energy which many times gets wasted. Such system can be designed for cooling and heating of the space. To design the energy storage system selection of the material, storage techniques are the major and technical parameters.

There are different forms of energy that are to be generated and can be made available. Hence there many types of energy storage systems are available which are mentioned in figure 3.15.

![Types of Energy Storage](image)

**Fig. 3.15 Classification of energy storage system**

### 3.6.1 Mechanical Energy Storage

As shown in above figure 3.15 mechanical energy storage system includes the compressed air storage, flywheel and hydro storage (pumped storage). Large scale energy requirement applications need high amount of energy storage which are possible in hydro storage and compressed air storage systems when used. On the other hand, flywheel energy storage system is used for intermediate storage. In this
storage system, storage of energy should be possible in off peak hours or power is available mostly in weekends or holidays. This storage can be used when the electricity is not available and it will be discharged. Due to limited storage and supply from the base load this storage system can be used for limited hours (Khartchenko and Kharchenko, 2013).

3.6.2 Electrical Energy Storage

Electrical energy storage systems are most common storage phenomenon. In this storage systems energy is stored in to the batteries and supplies. Battery gets charged when directly connected to the electrical sources. Also during discharge the stored chemical energy is transformed in to electrical energy. Electrical energy storage through batteries are widely used in load leveling, off-peak power and photovoltaic plants. Ni–Cd and lead acid batteries are the most common types for electrical storage (Baylin, 1979).

3.6.3 Thermal Energy storage (TES)

Thermal energy storage system is storing the thermal form of energy which can be utilized at the time of requirement. This system covers basically three major phases: thermal storing, thermal discharging and thermal charging (Cabeza et al., 2015). Thermal energy storage plays an important role for society because such system protects the environment and more efficient results are provided for heating and cooling of the building, space and industries. Hence, for energy conservation thermal energy storage system plays a key role. TES is an old developed system but somehow people were not aware of its technological development. Now days the government of India has also started awareness programs to utilize such systems. TES have also many applications for building heating and cooling applications, solar hot water applications. Such newly developed and impressive technology for heating and cooling of the building leads the market and society towards the modern technology.

Thermal energy storage systems have novel arrangements, so efficiency and effectiveness of the energy conservation system will improve. This amalgamation of
large system can sustain the world against the limited sources. There are significant benefits to use thermal energy storage systems among the others like reduced energy costs, consumption, initial and maintenance costs, equipment size. Also this system improves indoor air quality, effective and efficient utilization of equipment and increase flexibility of operation (Dincer and Rosen, 2002).

3.7 Types of Thermal Energy Storage

Thermal energy storage has two main types: 1. Thermal energy storage by latent and sensible heat storage, 2. Thermochemical storage systems are shown in figure 3.16. Among these three thermochemical energy storage system has potential to provide efficient results but the materials which are used for storage are too expensive, its development techniques and massive work is difficult (Pintaldi et al., 2015). However, such system can be used in energy production sectors. On the other hand, a huge development is done in thermal energy storage technologies based on sensible and latent storage techniques. These two techniques are most permissible and are high potential thermal storage systems. Now looking to the scenario of sensible...
energy storage systems, they are simple and cheap because its storage medium (water) is easily available (Hesaraki et al., 2015). Likewise, in the latent heat storage systems are most convenient and viable. Latent storage systems have ability to store high amount of energy and due to its compact design, this system provides higher overall efficiency and low heat losses. In comparison with sensible storage system, latent storage system can store 6 to 15 times more heat per volume (Sharma et al., 2009).

### 3.7.1 Sensible Heat Storage (SHS)

Thermal energy can be stored by sensible heat storage system and is common and well-developed technology. In this system energy is stored either by heating or cooling of a solid or liquid. During the process changes in material phase is not possible. The numerous materials are available for such system. Basically, few most common materials are pebble beds, water, solid, organics, metal salt and hydrocarbon oil. Among these all, water is most preferable material because water has high specific heat and density, cheap and easily available and it is abundant. However, the other materials are used above the 1000°C. Sometimes rock bed type storage system is used for air heating applications. The most important factors for amount of thermal heat storage capacity are material specific heat, quality of material and the temperature changes. A container, storage medium and input/output ports are the main components of Sensible heat storage system. The main function of the container is to avoid the thermal losses and preserve the storage material (Sharma and Sagara, 2005).

The amount of SHS capacity is to be defined by

\[
Q = \int_{T_1}^{T_2} m \ C_p \ dT = m \ C_p \ (T_2 - T_1) \tag{3.1}
\]
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The equation 3.1 clearly justifies that the quantity of thermal energy stored by sensible heat depends upon the temperature changes, mass and specific heat of the material. The graph of heat stored against the temperature is shown in figure 3.17. Also in table 3.1 the various sensible heat storage materials with its properties are shown.

Table 3.1 Different properties of sensible heat storage materials

<table>
<thead>
<tr>
<th>Material</th>
<th>Type of fluid</th>
<th>Temperature Range (°C)</th>
<th>Specific Heat (J/KgK)</th>
<th>Density (kg/m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Concrete</td>
<td>-</td>
<td>19.90</td>
<td>800</td>
<td>1901-2301</td>
</tr>
<tr>
<td>Brick</td>
<td>-</td>
<td>21</td>
<td>880</td>
<td>1498</td>
</tr>
<tr>
<td>Butanol</td>
<td>Liquid Organic</td>
<td>&lt; 118</td>
<td>2450</td>
<td>804</td>
</tr>
<tr>
<td>Isotunaol</td>
<td>Liquid Organic</td>
<td>&lt; 100</td>
<td>2998</td>
<td>806</td>
</tr>
<tr>
<td>Propanol</td>
<td>Liquid Organic</td>
<td>&lt; 97</td>
<td>2520</td>
<td>801</td>
</tr>
</tbody>
</table>
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<table>
<thead>
<tr>
<th>Material</th>
<th>Type</th>
<th>Temperature Range</th>
<th>Specific Heat Capacity</th>
<th>Latent Heat Capacity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Octane</td>
<td>Liquid Organic</td>
<td>&lt; 126</td>
<td>2423</td>
<td>705</td>
</tr>
<tr>
<td>Engine oil</td>
<td>Oil</td>
<td>&lt; 160</td>
<td>1880</td>
<td>889</td>
</tr>
<tr>
<td>Water</td>
<td>-</td>
<td>0-100</td>
<td>4120</td>
<td>1012</td>
</tr>
<tr>
<td>Calorie HT43</td>
<td>Oil</td>
<td>12-260</td>
<td>210</td>
<td>845</td>
</tr>
<tr>
<td>Isopentanol</td>
<td>Liquid Organic</td>
<td>&lt; 148</td>
<td>2100</td>
<td>830</td>
</tr>
<tr>
<td>Ethanol</td>
<td>Liquid Organic</td>
<td>&lt; 78</td>
<td>2420</td>
<td>778</td>
</tr>
<tr>
<td>Rock</td>
<td>-</td>
<td>20</td>
<td>889</td>
<td>2565</td>
</tr>
</tbody>
</table>

In sensible heat storage system, energy exchange is easily possible and this is the main advantage of such system. On the other side this system has very low heat storage capacity per unit volume. Also, this system should not provide energy at constant temperature. So, this system has a major limitation of energy storage and supply at constant temperature.

#### 3.7.2 Latent Heat Storage

In contrast of the sensible heat, the latent heat storage system depends on the energy release or absorption during the phase change of storage material. In this storage system latent heat of the storage material is to be used for storage. This LHS system is most viable and important for energy conservation system because of their high storage capacity, high density. Also, this system act as isothermal behavior during its phase change process. Fusion and vaporization are the types of latent heat. When the material changes its phase from solid to liquid or vice versa, the released amount of heat is known as latent heat of fusion. Similarly, the material changes its phase from liquid to vapor or vice versa, the absorbed heat is known as latent heat of vaporization. However, the vaporization of latent heat type storage system is not suitable because of large change in volume when material phases changes.
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The amount of thermal energy stored in form of latent heat in a material is calculated by

$$ Q = \int_{T_i}^{T_m} m \cdot c_p \cdot dT + m \cdot a_m \cdot \Delta h_m + \int_{T_i}^{T_f} m \cdot c_p \cdot (T_f - T_i) $$ .................................. 3.2

$$ Q = m[c_{sp}(T_m - T_i) + a_m \cdot \Delta h_m + c_{ip}(T_f - T_m)] $$ ................................................. 3.3

From the equation 3.2 the stored thermal energy as latent heat is dependent on the value of latent heat of the used material and its mass.

![Diagram showing latent heat storage against temperature](image)

Fig. 3.18 Latent heat storage against temperature

Schematic diagram 3.18 shows the latent heat storage against temperature. However, any latent heat storage system includes main three essential features: a) Phase change material with melting temperature range b) suitable heat exchange surface (heat exchanger) c) suitable container material with phase change material (Abhat, 1983).
The recent trend is to develop such system to protect the limited energy sources and make non-polluted environment. Therefore, many researchers are taking much interest to develop the thermal energy storage systems for different applications.

3.7.3 Thermochemical energy storage

In this energy storage system thermal energy is used for chemical reaction (certain endothermic chemical reaction) and the product of the reaction is stored. By exothermic reaction the stored energy is released. However such kind of system is not used as it is more expensive and is not viable for domestic and commercial purpose (Sharma and Sagara, 2005). In thermochemical storage system the discharging and charging steps are shown in figure 3.19

![Fig. 3.19 Thermochemical energy storage](image)

Finally, from the all above techniques the most appropriate and efficient technique for thermal storage is latent heat thermal storage system. This system has ability to provide the constant temperature and high energy storage density corresponding to changes in the material phases. Such system has great potential to achieve the numerous applications of subzero to very high temperatures. Moreover, the thermal energy system is one kind of heat exchanger in which heat can be transferred through phase change materials. The process of this system basically
follows the thermodynamic cycle. In thermodynamic cycle there are two phases, one is charging and other is discharging which is also known as melting and solidification respectively.

Based on the above phenomenon several studies have been performed for heating and cooling applications using the latent heat thermal storage system with Phase change material. In these studies, the performances are majorly depending on the PCMs characteristics, system design, selection of material etc. The storage energy from the alternating source like sun and after carrying out many processes based on technology and geophysics are the relevant problems of phase change heat transfer (H Abedin and A Rosen, 2011).

Sensible heat storage systems are very simple in design compared to the others storage systems like latent heat and thermochemical. But this system has major demerits of non-isothermal behavior (charging and discharging process of PCMs) and the storage capacity per unit volume is low. On the other side, latent heat storage systems have major advantages of having isothermal behavior and high storage capacity in small volume. Additionally, LHS system provides the constant temperature.

3.8 Phase change material as heat storage devices, characteristics and its selection

Today’s environment pollution shows that the continuous toxic gases are released nonstop to the higher-level layers and in high amount. This scenario causes the higher cost of the fuel and other conventional energy sources. Such situation motivates the researchers to develop renewable sources operated system. For that solar energy and its amalgamation with thermal energy storage is the vital solution. In thermal energy storage latent heat with phase change material is effective and efficient system as mentioned in the above portions (Naumann and Emons, 1989; Buddhi et al., 1987).
In Industries, residential and commercial applications require the electricity during day and night time. The energy consumption by the mentioned sectors is varies significantly during the summer and winter seasons. This variation in energy is because of the major domestic applications of heating and cooling (air conditioning) of the space.

Observing the global scenario, energy storage plays the key role for utilization and the conservation of energy. The phase change material application for the heating and cooling of the building was found since 1940s. But the execution and the research sources were limited at that time so effective system was not developed. Moreover phase change material has unique features of energy storage capacity than the conventional material (Buddhi et al., 1987).

Phase changes are possible with respect to changes in the temperature. If the ambient temperature rise, the phase changes from solid to liquid (if Solid-liquid PCMs). During this period of changes in the phase absorption of heat occurs. This process makes the environment cool and material gets solidified.

Several types of materials are invented, and among them few has characteristics of change in its phase according to the different temperature. Every material has its own properties to change its phase during change in temperature. Furthermore, latent heat and thermal conductivity are different for different materials. It is found that the main demerit of the phase change material is their low thermal conductivity. Due to this reason heat transfer rate goes down. As described in previous section selected PCMs have suitable temperature range for particular application. In reality, there is no standard material to be utilized for PCM systems because each material has its own merits and demerits.

Moreover, phase change materials are used for thermal energy storage purpose so more attention is required due to large capacity of storage. Metallic alloys, inorganic salts undergo reversible phase transformation, organic paraffin are the significant parameters of phase change materials. Such system can be used for building or space heating because of its isothermal behavior during process. In an
efficient system, latent heat storage is desirable when the temperature changes are small. This only happens because of phase change enthalpy, high storage density etc.

Selection of Phase change materials is an important part to developing efficient thermal storage systems. The basic criteria to select the phase change material are nontoxic, suitable melting point, no chemical reaction etc. Figure 3.20 indicate the fundamental of phase change material.

![Diagram of Phase change material working concept]

Fig. 3.20 Phase change material working concept

Generally Organic PCMs have low melting points and Inorganic PCMs have high melting point. Organic PCMs are less corrosive than that of inorganic due less proportion of water content. Following are the desirable characteristics and properties for any PCM system that should be satisfied (Abhat, 1983; Buddhi D, 1994.).

3.8.1 Thermo physical Properties

This characteristic includes high thermal conductivity in both liquid and solid phases, high density, no sub cooling during freezing, Phase change temperature fitted to the application, Low volume change during the phase change, Low density
variation during phase change, High latent heat of fusion per unit mass, and high value of specific heat to give additional benefits of sensible heat storage

3.8.2 Chemical Properties

Chemical properties are important due to their chemical reaction with different material and atmospheric condition. Among all such properties, non-corrosive, Non-flammable, no phase separation or chemical decomposition, Chemical stability after many cycles of operation, no degradation after many cycles of operation and non-toxic are to be considered during selection.

As discussed in above section selection of PCMs are vital factor for the thermal storage system. Also, it is observed that the cost and availability of material should be Abundant and Cheap.

3.8.3 Kinetic Properties

These properties of the phase change material play important role because it prevents the super cooling of liquid phase, heat recovery from the storage system is high because of high rate of crystal growth. Super cooling has been creating the problems in PCM enlargement. This would be found in salt hydrate type material.

3.8.4 Economic Properties

This property of the PCMs highly affects the society. The low cost and large-scale availabilities gives attention for using such kind of systems for energy conservation.

Thermal energy storage system by using phase change martial helps to prevent high temperature and improve thermal protection of the buildings. This phenomenon was developed and demonstrated for effective performance (Abhat, 1983).

The main aim was to utilize the phase change material for high latent heat of fusion. This process prevents the building against the heat, by absorbing the heat from the building by melting process (Sharma and Sagara, 2005). The author focused more
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on the appeal of the PCM. This system was used in heating and cooling of the building space, solar water heating, green house, waste heat recovery system and solar cooking. Ravikumar and Shrinivasan 2008 (Ravikumar and Srinivasan, 2008) stated the cooling capacity of PCM based system in the building. This novel technique delivered cool air without energy requirement. As discussed above the PCM has low thermal conductivity, so the system will act as self-insulators. Few studies were carried out for cooling application of PCM with electronic equipment and thermostators. Apart from this study the maintenance of the PCM system was low and maintained comfortable temperature inside the building.

However, in the building the electricity consumption was more due to consumption of more power by active cooling equipment. This lead toward the improvement in thermal energy storage which was observed (Xiao et al., 2009). Hence, the design of the thermal energy storage played important role for achieving required energy efficiency for thermal comfort, planning and implementation. Yuning Liu and chao chen 2006 (Liu et al., 2006) developed the latent heat storage system on wall. They observed efficient performance and improvement in the storage capacity. Therefore, it is now days beneficial to develop such efficient and effective system of thermal energy storage by using latent heat storage principle. These types of technologies are developed under certain level in industries, residential and commercial sectors.

3.9 Classification of Phase Change Material

The classification of phase change material in four states which can be defined as solid to liquid, solid to solid, gas to liquid and gas to solid. From the review solid-liquid phase change materials are used practically for heating and cooling applications because other changes in material phases have limitations (Sun et al., 2016; Anisur et al., 2013). The numerous phase change materials are available in the market based on their melting point.
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Basically, there are three types of phase change materials which includes; 1. Organic Materials 2. Inorganic Materials and 3. Eutectic Materials. The figure 3.21 shows their classification. The brief description of the each classification is mentioned in below section (Cao et al., 2015; Zhou et al., 2012).

In general, it is observed that there is no material which will satisfy the all criteria for thermal storage. The volumetric latent heat storage ability of inorganic compound is double than the organic compounds. Hence, the design of thermal energy storage depends on the thermal and chemical behavior. The brief discussion of its subgroup is mention in further portion (Sharma et al., 2009).

3.9.1 Organic Phase change materials.

In this phase change material, hydrogen and carbon molecules are used. Organic materials have no super cooling and are non-corrosive, have extra latent heat capacity, stable chemical and physical properties. Organic phase change material includes the many types such as materials of n alkanes, esters and fatty acids which are famous for latent heat storage (Kenisarin, 2014). In pure organic phase change
material few limitations are there for it practical use like low thermal conductivity, high variation in volume and sometime leakage of liquid is possible during the changes in phase (Fang et al., 2014; Mehrali et al., 2014). These types of PCM are classified in to paraffin and non-paraffin types. Majority of Phase change materials (PCMs) are characterized by their capability to freeze and melt under the different temperature condition. Organic materials have a congruent melting characteristic that means they freeze and melt continuously without phase isolation.

- **Paraffin type organic phase change materials.**

Paraffin is saturated hydrocarbons from \( C_nH_{2n+2} \) groups. It has very similar properties in which C5 and C15 paraffin are in liquid state and others are in wax solid state. From its crystalline structure CH\(_3\), chain drained a high amount of latent heat. With increase in the chain length of CH\(_3\) corresponding latent heat of fusion and melting temperature increases. The wide temperature ranges are available in paraffin so it is used as thermal energy storage material (Peng et al., 2004). However, the cost and selection process of material plays important role but this material is most efficient for latent heat thermal storage system. The major benefit of this material is chemically non-reactive and stable at below 500°C (Sarı et al., 2014). Because of this benefit it has low vapor pressure and high energy density on melting. The paraffin wax contains the straight chain hydrocarbons and it has low melting temperature in the range of 23°C. So paraffin wax is most effective PCM for domestic applications (Lachheb et al., 2014; Kamali, 2014). Figure 3.22 showing the paraffin wax material.

![Fig. 3.22 Paraffin wax material](image)
• **Non-paraffin type phase change organic material**

The non-paraffin organic phase change material has very different types of properties. In comparisons with paraffin it has own variables, but all other properties are same. Non paraffin have sub group of fatty acids and non-paraffin organic (Buddhi D, 1994.; Abhat et al., 1981). Figure 3.23 shows the fatty acid. Non-paraffin organic phase change materials have various properties. The review states that it includes alcohols, glycols are used for thermal energy storage. Hence these materials are high flammable. However, the fatty acid is suitable compared to paraffin because it has high latent heat of fusion and no super cooling during freezing. Fatty acid chemical structure is defined by CH₃(CH₂)nCOOH. But major disadvantage of this material is its high cost and mild corrosiveness (Sari, 2004).

![Fatty acid materials](image_url)

**Fig. 3.23 Fatty acid materials**

The merits of the non-paraffin are chemical stability, recyclable nature, compatibility and its pattern that it gets solidified without super cooling. The materials are not in wide range application for thermal heat storage system because of its low thermal conductivity, less volumetric latent heat storage, require more heat flux for process, high cost and flammability (Sharma et al., 2009).
3.9.2 Inorganic Phase change materials.

In comparison to organic material, inorganic material has higher heat of fusion per unit mass. Also, such materials are available at lower cost and usually flammable. Moreover, these materials have low thermal stability, decomposition and supercoiling demerits. The demerits of this inorganic material make the limitations on its use (Baetens et al., 2010; Tyagi and Buddhi, 2007; Fauzi et al., 2014). This phase change material are further classified as by salt hydrates and metallic (Ferrer et al., 2015).

- Salt hydrates type inorganic materials

Salt hydrates contain the water and salt. This combination of water and salt create the crystalline matrix after getting solidified. Salt hydrates are available in different types of melting temperature ranges between 15°C to 117°C. Salt hydrates have unique characteristics of latent heat thermal storage, so it is used in PCMs. Due to segregation in hydrates and dehydrates salts reduces its volume for thermal energy storage. In thermal energy storage, metallic containers are used for storage purpose but corrosion occurs due to salt hydrates.

Phase transformation from solid to liquid in salt hydrates is basically due to dehydration of salt. So, this procedure of melting or freezing acts as thermodynamic cycle. The hydrate crystals breakup in to water and lower hydrates during the melting point (Iten and Liu, 2014, Tatsidjodoung et al., 2013).

Moreover, the salt hydrates suffer from the poor nucleating characteristics. For this reason, super cooling is to be started before starting of crystallization process. This can be avoided by using the nucleating agent which initiates crystals formation. Finally salt hydrates have significant group of phase change materials which are used for latent heat thermal storage system. The most attractive and important properties of this materials are high thermal conductivity, small volume changes, not corrosive, high latent heat storage (algae, 1978.).
• Metallic type of inorganic Materials.

Likewise, metal eutectics and low melting metals are the part of metallic. Metallic materials as a PCM survey are limited due to its high melting temperature and heavy weight. However, such materials are used where weight is not a major parameter and only focuses on the volume. Also, these materials have low specific heat and High heat of fusion per unit volume. Hence it is creating the unusual engineering problems. In comparisons with other phase change material, dissimilarity is found in their high thermal conductivity. This material has unique properties like low latent heat of fusion per unit weight and high latent heat per unit volume.

3.9.3 Eutectics

The eutectics comprise of at least two segments where each of them melts and stops consistently framing a blend of a segment of that precious stone amidst crystallization process. For the most part, eutectics liquefy and solidify without isolation. Amid dissolving process, both parts melt in the meantime without probability of partition.

Finally, it would be concluded that organic materials are not super cool and are chemically stable, also they are non-acidic. Their latent heat of fusion is very high. Inorganic compounds are corrosive and are not easily available. They also undergo super cooling and their decomposition rate is very high. Most of inorganic materials are hydrated salt.

As discussed in previous section, organic materials are selected as they materials are cheaper in cost, are more corrosion resistance, are easily available and have low thermal conductivity. So, it is better to select the organic material than inorganic. Table 3.2 is showing the various types of phase change material and its properties. Also in table 3.3 the comparison of phase change material is mentioned.
<table>
<thead>
<tr>
<th>Name</th>
<th>Melting Point (°C)</th>
<th>Density (Kg/m³)</th>
<th>Thermal Conductivity (W/mK)</th>
<th>Latent Heat (kJ/Kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>n-Dotricontane</td>
<td>69</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>n-Hentriacontane</td>
<td>-</td>
<td>930S , 830L</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>n-Nonacosane</td>
<td>63</td>
<td>-</td>
<td>-</td>
<td>240</td>
</tr>
<tr>
<td>n-Octadecane</td>
<td>29.1</td>
<td>868S , 765L</td>
<td>0.30S, 0.169L</td>
<td>246</td>
</tr>
<tr>
<td>n-Dodecane</td>
<td>-13</td>
<td>750</td>
<td>0.21 S</td>
<td>-</td>
</tr>
<tr>
<td>n-Heptadecane</td>
<td>25</td>
<td>778</td>
<td>-</td>
<td>215</td>
</tr>
<tr>
<td>n-Octacosane</td>
<td>60</td>
<td>900S , 725 L</td>
<td>-</td>
<td>255</td>
</tr>
<tr>
<td>n-Nonadecane</td>
<td>32</td>
<td>769L 935S</td>
<td>0.21S</td>
<td>226</td>
</tr>
<tr>
<td>n-Tetradecane</td>
<td>5.1-6.1</td>
<td>771</td>
<td>--</td>
<td>235</td>
</tr>
<tr>
<td>n-Hexacosane</td>
<td>55</td>
<td>645</td>
<td>0.22S</td>
<td>265</td>
</tr>
<tr>
<td>n-Docosane</td>
<td>42</td>
<td>-</td>
<td>-</td>
<td>250</td>
</tr>
<tr>
<td>n-Pentadecane</td>
<td>12</td>
<td>786</td>
<td>0.18</td>
<td>206</td>
</tr>
<tr>
<td>Compound</td>
<td>Value 1</td>
<td>Value 2</td>
<td>Value 3</td>
<td>Value 4</td>
</tr>
<tr>
<td>---------------------</td>
<td>---------</td>
<td>---------</td>
<td>----------</td>
<td>----------------</td>
</tr>
<tr>
<td>n-Tetracosane</td>
<td>50</td>
<td>-</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>n-Hexadecane</td>
<td>17.9</td>
<td>756</td>
<td>0.20 S</td>
<td></td>
</tr>
<tr>
<td>Paraffin Wax</td>
<td>31.9</td>
<td>775S, 756L</td>
<td>0.454S, 0.268L</td>
<td></td>
</tr>
<tr>
<td>n-Heptacosane</td>
<td>58</td>
<td>669</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>n-Tricontane</td>
<td>64</td>
<td>-</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>n-Eicosane</td>
<td>38</td>
<td>-</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>n-Heneicosane</td>
<td>43</td>
<td>-</td>
<td>--</td>
<td></td>
</tr>
<tr>
<td>n-Tricosane</td>
<td>76</td>
<td>-</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>n-Tritriconcane</td>
<td>70</td>
<td>-</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>n-Tridecane</td>
<td>-6.5</td>
<td>786</td>
<td>--</td>
<td></td>
</tr>
<tr>
<td>n-Pentacosane</td>
<td>53</td>
<td>-</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>Type</td>
<td>Organic material</td>
<td>Inorganic material</td>
<td>Eutectics</td>
<td></td>
</tr>
<tr>
<td>--------------</td>
<td>------------------</td>
<td>--------------------</td>
<td>-----------</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Paraffin</td>
<td>Non paraffin</td>
<td>Salt hydrates</td>
<td>Metallic</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(fatty acids)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Latent heat</td>
<td>189.8–261.2 kJ/kg</td>
<td>129.8–249.9 kJ/kg</td>
<td>99.9–199.8 kJ/kg</td>
<td>24.9–90.1 kJ/kg</td>
</tr>
<tr>
<td>Melting point</td>
<td>11.9 to 70.8 °C</td>
<td>7.9–188.2 °C</td>
<td>10.9–119.8 °C</td>
<td>29.8–96.1 °C</td>
</tr>
<tr>
<td>Cost</td>
<td>Genuinely costly</td>
<td>A few times more costly than paraffin</td>
<td>Reasonable cost</td>
<td>Expensive</td>
</tr>
<tr>
<td>Attributes</td>
<td>As number of carbon content increase, latent heat and melting point increase.</td>
<td>Range of melting point and latent heat of fusion is huge.</td>
<td>Wide interests for study</td>
<td>Due to practical restrictions and high density cost, not largely considered.</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Defects</td>
<td>Poor conductivity</td>
<td>It should not open to extremely high temperature, because of</td>
<td>Super-cooling Corrosive Salts settle down at base and diminish</td>
<td>Per 1 kg of weight, heat of mixture and specific heat is low.</td>
</tr>
<tr>
<td></td>
<td>Melting point is not sharp.</td>
<td>Great</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Combustibility partly dynamic
Volume change corrosive
is Substantial Flammable because of
nature, high density.
flames or
oxidizing
agents.

**Advantage**
No separation Precisely High Per unit & super phase availability Per unit
freezing. conversion volume, & super

Chemically freezing. & super

steady. phase

conversion

High latent

heat

Appropriate

thermal

Conductivity

With all metal

containers, Small size

compatibility is variation

great. Appropriate

density

Harmless and

non-reactive

---

3.10 Methods of Encapsulation available

All the above properties will completely satisfy when they are packed in containers with some reagents. This packing of PCM is also known as encapsulation.

Salt hydrates, fatty acids and esters, and different paraffin’s are most commonly used PCMs. In recent study ionic liquids were also used as PCMs. Organic
solutions are free of water they can be easily exposed to air so all the salt based
PCM solutions should be properly encapsulated.

PCMs have been used since late 19th century as a medium for thermal storage. They have been also used as refrigerated transport for rail and road applications and so they are very well known. Encapsulation must be done because PCMs changes phase between solid-liquid in thermal cycling.

Initially macro-encapsulation of PCMs failed due to less thermal conductivity of PCMs. The heat transfer was not much effective as the material was solidifying at the edges of containers (Pasupathy et al., 2008).

But the micro-encapsulation was a success. It was applied into construction materials, such as concrete. It was easy and economic with sufficient heat transfer. Portable heat storage system was possible with micro-encapsulation (Pasupathy et al., 2008). In this method PCM were placed in a protective coating. System was also known as phase change slurry (PCS). Figure 3.24 shown the micro-encapsulation.

![Wall with Micro Encapsulated](image)

**Fig. 3.24 Micro-encapsulation**

Another method developed was Molecular-encapsulation by Dupont de Nemours which allowed a very high concentration of PCM within a polymer compound. With the invention of this method drilling and cutting through the material without any leakage was possible (Pasupathy et al., 2008). Molecular encapsulation is sown in figure 3.25
As PCMs give best efficiency in small containers, so they are generally divided into cells. The material of packing should be a good conductor of heat. Also, it should be strong enough to accept changes to storage material’s volume as phase changes. Materials should not dry out. The packaging must be corrosion and leakage resistance. Stainless steel, polypropylene and polyolefin are common packaging materials which have chemical compatibility with room temperature.

The heating and cooling of the building sectors are the wide application. To improve the efficiency of thermal energy storage system, techniques such as passive and active technologies should be preferred (Gil et al., 2010). The passive based thermal storage energy system is defined so as to provide cooling and heating by using any alternative sources and connections of mechanically operated equipment. Finally, these joining passive technologies provide the thermal comfort (Parameshwaran et al., 2012). However, such systems are more comfort with shading effect using blinds, thermal mass, ventilated facades, free cooling and solar heating techniques (De Gracia et al., 2011; Castell et al., 2010).
Similarly, active technologies are used in the building for thermal energy storage purpose to maintain the high degree control. This system can control the indoor room conditions and heat energy storage in proper way. The active technologies are used in the domestic hot water applications, shifting of peak load, free cooling (Agyenim and Hewitt, 2010).

The following section covers the active and passive technologies for thermal energy storage existing and explores the brief discussion on building sectors.

3.11 Passive technologies

The purpose of selection of passive technology is to deliver the thermal comfort with minimum use of the heating ventilation and air conditioning systems. Because of the this conventional energy source consumes the much power (Soares et al., 2013). The passive sensible storage technologies are most comfort with the high thermal mass storage in the building sectors. Also, this innovative technology increases the thermal comfort or stability inside the building. Among the several materials alveolar bricks, stone or concrete or rammed are preferably used more. Some other ideas are also used for energy storage in building through sensible passive technologies like solar water walls, trombe wall (Llovera et al., 2011). The problem arises during the massive portion of solar water wall and it would be replaced by the containers of water forming on the wall.

The phase change materials are integrated with passive technology for thermal storage, play key role in the field of building cooling and heating. The phase change material can be stored in building by the different ways like encapsulation, construction materials, shape-stabilization and microencapsulation (Memon, 2014) In encapsulation there were leakages observed because of new layer constructed on the wall. Also, such problems were found in material added for shape stabilization. So finally it was found that the wall board are the best option for the installation of PCM by Passive technology (Lee et al., 2015).
3.12 Active technology

The thermal energy storage system is the versatile and attractive resolution of the old and new building. Such system resolved many domestic applications and provided free cooling by preserving the renewable sources (Sun et al., 2013). Here in active system can be installed in the building floor, walls, ceiling, photovoltaic system or ventilation and used as liquid or air collector for storage or transfer energy. The most significant advantages of active system is to provide free cooling by storing the night time low temperature and release of this cold air in the day time or when it is required (Waqas and Din, 2013). In the phase change material construction small gap between cold source and the building comfort should be provided because of high energy density during the changes in the phase. In this type of technology solidification of the PCM is poor in changes in climates. Temperature drop is limited below the PCM solidification range. This barrier can be resolved by the improving thermal conductivity (Saelens et al., 2011).

Moreover this active technologies efficiency of storage can be improved by the providing the air collector to the building storage unit (Fraisse et al., 2006; De Gracia et al., 2013). These active technologies are not limited to use of renewable sources in buildings for such applications but it is also emphasized on the existing technologies performance improvement and efficiency enhancement. Corresponding to this shifting of the peak load in to the off-peak load; can be achieved by the thermal energy storage system with heat pump. Also heat pump is functioning as energy savings for heat recovery system and outdoor unit defrosting system. This combination of active system is much promising technology for demand and supply of power (Arteconi et al., 2013). The active technologies are beneficial for both cooling and heating application by using low-cost electricity tariff and deliver the free cooling or save the energy at very low cost (Moreno et al., 2014).

Moreover, the active system technologies can be incorporated with the smart control unit for building applications and it can improve design, performance and architectural concept which is shown in figure 3.26 for cooling of the building room.
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Fig. 3.26 Active thermal energy storage system for cooling of building

3.13 A systematic review of thermal energy storage system for different applications.

In the energy conservation field thermal energy storage by phase change material is the most favorable and efficient technology. In this energy storage field several researchers are still working for the multiple practical applications. But the most important is for efficiency of the system which is depending upon its material selection (Ravikumar and Srinivasan, 2012). However, PCM based thermal energy storage has great potential to satisfy the heating and cooling application of the different energy sectors. Moreover, such systems have high initial cost compared to
the conventional energy sources like fossil fuels. Looking on the other side impact on environment is limited and has more energy sources sustainability.

Abhat and lane studied (1983) thermal energy storage system of phase change material. This system is economical and efficient. Their observation concluded that the PCM would be the best for low thermal applications using solar radiation. Also, they suggested that the passive system for thermal energy storage was appropriate because of its more power or energy storage and it can be stored for stable thermal energy with temperature changes.

Naumann and emons (1989) carried out the studies on salt hydrates phase change material and their investigation proved that salt hydrates based system were not feasible at high temperature. This type of material systems has own limitations of flammability, high thermal conductivity etc. However, latent heat of thermal storage system setup can be used for the low temperature applications and storage of high rate of energy.

Zalba et al. (2003) came up with the awareness program on the energy conservation technologies. They were more focused on the thermal energy storage and its applications. Moreover, they justified the technologies of thermal energy storage with the phase change material and concluded that latent heat of storage would be the best. Finally, study concluded the latent heat thermal energy storage would be the virtue of providing high heat transfer and thermal energy storage.

Sari et al. (2008) performed the three main practical namely eutectic combination with phase change material (gypsum board), thermal energy stored by means of different calorimetry techniques and comparing phase change gypsum board with uncomplicated structure ring. From all three performances, results stated that the phase change gypsum board had good efficiency for shifting peak load, warming and chilling of the equipment. Practically they defined that the phase change material gypsum board had thermal stability after 900 thermal cycles.
Sharma et al. (2009) reviewed that the phase change materials was vital source of thermal energy storage through latent heat. Also, they suggested numerous applications for more studies. Jegadheeswaran and pohekar (Nagano et al., 2003) proved that the latent heat of thermal energy storage system was efficient in solar thermal application but its performance was restricted up to some level due to its limitations of thermal conductivity.

Therefore, looking the phase change material possessions, the performances can be improved by proper calculation of melting and freezing time period, and heat transfer rate. The important factors for selection of phase change material and its characteristics discussed in the above section, all aspects of the different applications of the thermal energy storage using phase change material are discussed in following sections.

3.13.1 Air conditioning and refrigeration

Nowadays air conditioning and refrigeration are the common need of the human being. To satisfy their need of cooling air and chilled water such technologies is used. Thermal energy technology is widely used for this purpose. Air conditioning systems are available in the building and commercial sectors which consumes maximum power or electricity. To meet the day time comfort cooling can be achieved by Traditional air conditioning. Similarly, chillers satisfy the electrical demand of few hours per year, due to this day by day efficiency is going to be low. Therefore, such system needs an option for improving the efficiency and consuming the low power. Thermal energy storage can meet the demand of required energy for cooling. The system with thermal energy storage and chillers plays important role. In which during off peak hours when electricity requirement is low, at that time additional cooling of chiller can be stored by thermal storage system of PCM and this storage energy would fulfill the energy requirement in day time. This storage system will improve the chiller efficiency up to 40% to 60%. Thus, low cost of electricity is generated, save the electricity and cooling can be effectively managed. Figure 3.27 indicate the
cool thermal storage tank which is integrated with chiller system. The unique system can meet the 12 story building with 93000 m² cooling demand at day time.

![Thermal storage tank](image)

**Fig. 3.27 Thermal storage tank for cooling installed in Chennai India**

Nagano et al. (2003) developed the system which absorbed cooling from the air conditioning system and supplied it to the located area. This absorption was done by the spongy based floor and via pipe or vent. These systems have drawback of wet floor. The floor was wet during morning when air-conditioning system was on because it got cooled at night. Likewise, inadequate though this it was very difficult to maintain the low temperature because thermal energy storage capacity of building mass was insufficient. To avoid this major problem, incorporate the air-conditioning systems with latent heat thermal energy storage system.

The refrigeration systems are most probably used in the industries for very low temperature applications of production cycles. Furthermore, the backup system or the stand by facility is kept in to the industries to maintain production cost, time and losses. Therefore, to reduce such problems thermal energy storage is vital and flexible solution. TES systems are able to provide peak demand without intermediate generating capacity. Also, sometimes online software can be used to generate the design conditions for better efficiency.
Furthermore, they have taken a floor size 0.5m² for experiments. As phase change material granulated foamed glass beads and mixture of paraffin. The thickness of packed bed of PCM was 3 cm under the floor with multiple holes. Practically change in the room temperature and total stored energy was calculated. The results provide the cooling load was bare by the granulated phase change material.

So, the PCM based technology is new innovation and development. Ostermana et al. (2012) resolved the heat transfer problem from flowing fluid and wall side packed with PCM. The melting and solidification of the Phase change material was not at correct time therefore appropriate design of heat exchange and operation procedures done properly. The required quantity of thermal storage was kept properly without bothering the capacity of storage. The research results projected that the 3 and 30 kg/m² based material was required for respective applications.

Mosaffaa et al. (2012) discussed and provided the numerical results of shell and tube finned and cylindrical shell and rectangular type heat storage equipment. This numerical analysis was done in equal volume and heat transfer external area. The melting and solidification of the phase change material was more found in shell and tube finned compared to cylindrical shell and rectangular type. Also, this study was focused on the variations in heat flux and temperature under the air inlet and flow rate condition for effective thermal storage.

Joseph stalin (2013) did the novel experiment of phase change material installed on ceiling fan for cooling application. They strongly proven that the latent heat was stored and it can be used at latter time. This latent heat was stored because of the changes in phase of material. Now this set up bounces cooled air from the fan during changes in solid phase to liquid. Finally, the outcome of this was to cool the room by absorbing the heat and solidification and thus reduced the room temperature. The air conditioner running and initial cost is high compared to such set up system. Disparate the conventional cooling system such idea is beneficial for low cost and free cooling. Moreover, this fan with PCMs will work in absence of the electricity.
Parmeshwaran and Kalaiselvam (2014) did the research on the PCM entrenched with the silver nanoparticles. This concept actually worked and gave the high heat transfer during charging and discharging process. Results stated that the 48% of saving of electricity by the PCM based air conditioning system compare to conventional air conditioning system. Also, they suggested that PCM storage system combined with latent heat storage system will improve the efficiency.

3.13.2 Textiles

Gokhan Erkan (2004) studied the applications of phase change material in the field of textile industries. PCM have outstanding performance in the garment industries. The cloths like suit, shirt are the products of textile industries. The internal property prevents the products against fatal consequences. The changes are in phases of material based on the normal human body temperature. These exclusive and fascinating features are useful for textile industries for selling of all type of season cloths.

The basic fundamental behind the PCM based garment material is that they store the heat generated from human body and it gets released based on requirement. Such material changes it phases continuously. However, it mostly depends on the atmospheric temperature and physical doings of human. These continuous changes define as dynamic nature. Mondal (2008) had done experimental analysis of the manmade fiber. By adding the PCM in to the fiber the temperature control was possible.

Wiesława bendkowska and henryk wrzosek (2009) inspected the non-woven phase change material thermo regulation properties. Acrylic-butadiene copolymer was coated by Microencapsulated n-alkanes. Screen printing method is used for same. Nonwoven have micro phase change materials and its performance was carried out in which innovative devices were utilized as dynamic heat source. The experiment and the performance were carried out on the thermal properties and thermal energy storage by nonwovens under steady state condition.
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The outcome of this search was that of the temperature regulating factor and its value provide the latent heat in nonwoven fabric per unit area.

3.13.3 Solar water heating system

In the global solar energy is the biggest alternative energy source which will be used more in future. Only one major limitation as described in above section is solar energy is time dependent energy. Thus, solar systems are needed to store the energy for night time use. The storage limitation of the solar energy is fulfilled by phase change material. The following section is the brief dissection of phase change material based solar water heating system and also combination of PCM with latent heat storage system.

From the last two decade water heating by the solar energy is the most common technology which is simple to maintain, fabricate and inexpensive (Tanishita, 1970; Richards SJ, 1967.). Prakesh et al. (1985) performed the research on the constructed solar water heater. This solar water heater has phase change material layers at the bottom most side. PCM gets the heat from the heated water during the day time. The water is heated by solar radiation from the sun and transfer the heat to PCM. During this process PCM stores energy (latent heat) and melts. Similarly, when sunshine hours are finished, the hot water is withdrawn and cold water is allowed to flow inside the PCM system. During this process water gets energy from the stored thermal energy in PCM. At the same time PCM changes its phases (liquid to solid) because energy is released from it. The results proven that this kind of system is not much effective because of poor heat transfer rate between water and PCMs. Bansal and Buddhi (1992) hypothetically calculated the performance of the cylindrical storage system with flat plate collector. The major focus was on the discharging and charging mode of set up. Stearic acid was used as phase change material. The paraffin wax p-116 was used for the calculation of the fluid temperature and interface moving boundary. Solar energy can be stored by sensible heat and latent heat. The comparative study of these two types of technique has been done. Such system maintains the hot water by solar heated for night time.
Chaurasia (Chaurasia, 2000). Aimed to this aspects and basically two same type of storage units were used. In this storage unit was different storage phase change material is used. The system unit is mostly heat exchanger with aluminium tubes and general industrial tank. Total 17.5 kg Paraffin wax and simple water was used in storage unit. The solar collectors with same absorbing capacity were used to charge the both units during day time. The performance of this study indicated that the latent heat storage system had good efficiency to store the heat compared to the sensible heat storage. Furthermore vessels were used for the latent heat storage with different size and water tank were used for sensible heat storage with different group (Ghoneim, 1989). These storage vessels have number of pipes in which the PCM was filled and in the vessels heat transferred fluid was circulated as shown in the schematic diagram (Figure) 3.28.

**Fig. 3.28 The phase change material storage in cylindrical shell**

The research was carried out on calcium chloride tetrahydrate calcium chloride hexahydrate, two grade thermal storage system. This system was developed for 30-20 °C and 60-30 °C temperature respectively. The study observed the storage capacity and maximum use of solar energy during the changes in cycle. Such system provided hot water for domestic applications.
Kamiz Kaygusuz (Kaygusuz, 1995) did the theoretical and experimental analysis to check the performance of the solar water heating system with phase change material. The phase change material was CaCl\textsubscript{2} \_6H\textsubscript{2}O. Also, they did the comparisons of this system with rock and water based storage system as shown in figure 3.29. It would be noticed that the storage capacity encases 1500 kg PCM. This was happened during the day time when solar radiation was available. Moreover, the working media for phase change material was in tubes of the vessels and heat transfer fluid water was flowing in vessels.

![Figure 3.29 Compression of the phase change material, water and rock based system performance](image)

Rabin et al. (1995) studied the water heating application by solar collector with phase change material. The phase change material was salt hydrates for this study. This study focused on temperature effects during charging and discharging and thermal performance of the salt hydrate based PCM system.

Sharma et al. (2003) developed the novel box type solar collector for the hot water application during day and night time. Also, this set up examined the latent heat storage capacity. This novel design performed with very
good results of hot water temperature. The paraffin wax was used as phase change material for this study.

Mettawee and Assassa (Mettawee and Assassa, 2006) developed the solar collector based latent heat storage system in which compact PCM was used to improve its thermal efficiency. The design and the function of the solar collector or absorber plate in such a manner so that it can perform both the functions like storage of PCM and absorb the solar energy.

The storage of the solar energy was in phase change material (paraffin wax). This energy will discharge during the cold water passes through pipes. They had taken a 1 m² effective area of collector and the total volume was considered 0.2 m² per each sector. Checking the feasibility of such system is the most important for the said application so authors carried out the experiment on compact solar collector for hot water. The systematic and time to time readings were taken of solar radiation, solar intensity, temperature changes, charging and discharging process. The water mass flow rate was 8 to 21.7 kg/h was decided for each sector. The outcome of this study was if the molten layer thickness increases its effect on heat transfer coefficient, it sharply improved from its average value. Likewise, water mass flow rate increased as the heat gain was increased.

Cabeza et al. designed and developed the solar model for testing the actual behavior in physical situations (Cabeza et al., 2006). Such test setup worked with the constant with electrical heater or solar system. The experiments include the few cylinders on the top of water tank and as a phase change material Graphite (90% sodium acetate trihydrate and 10% graphite) was used. The conclusion of this study was that phase change material was the most feasible technology for storage of hot water for longer period. This can be achieved without applying extra energy.

Suat et al. (Canbazoğlu et al., 2005) did the study and performance on sodium thiosulfate Pentahydrate as phase change material combined with conventional water heating system (open loop passive). This experiment has been carried out in the month of November. Also, this set up was extended for better performance and
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included the solar thermal energy storage unit. Finally, the performance was checked and compared with the conventional solar water heating system.

Moreover, the researcher did another study on the same framework but with changes in phase change material. They used salt hydrates phase change materials and did the studies. Calcium chloride hexahydrate, zinc nitrate hexahydrate, sodium sulfate decahydrate and disodium hydrogen phosphate dodecahydrate were used as salt hydrates material. Also, such experiments were done by using its thermo physical properties and meteorological data. Results concluded that the hot water storage capacity, total mass of water, heat transfer rate were 2 to 3.5 times more than the conventional water heating system with minimum efforts technically and economically. Enhancement of this setup with salts hydrates were found most effective in solar thermal energy storage in comparison of other combination of such setup.

3.13.4 Solar air heating systems

Morrison, Abdel Khalik and Jurinak (Morrison and Abdel-Khalik, 1978; Jurinak and Abdel-Khalik, 1979) introduced and experimentally tested performed on the air based solar heating system with phase change material storage unit. They were two types test one was melting temperature and latent heat effect of phase change material on the air based solar thermal system performances and the other was to develop the experimental unit for phase change storage system. The results of the number of test performed concluded that the melting temperature was the important factor compared to latent heat for PCM selection. Correspondingly the major remark was observed that the storage of sodium sulfate decahydrate required space one fourth and one half of the pebble bed and water tank storage unit respectively.

Ghoneim and Klein (Ghoneim and Klein, 1989) carried out the statistical analysis for water and air based heating system. They considered the major parameter for their study was phase change material and its latent heat storage. Paraffin and Sodium sulphate decahydrate were used for phase change material and found that they have similarity in their performances. Jurinak and Adbel Khalik (Jurinak and Abdel-Khalik, 1979) Enibe (Enibe, 2002) did the extensive
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literature survey to develop the solar based air heating system which was operated by the natural conventional process. The novel concept of his research was that he designed and developed the phase change material storage unit that was attached with natural convective system of solar air heater. The test was performed under the natural environment and no-load condition at the day time. The results of ambient temperature were varied between 18 - 39 °C at the same time irradiation was in the range of 4.8 – 18.9 MJ m². Also, the remarkable efficiency of the system was approximately about 49.9 % and the peak temperature was around 15 K. Such systems are applicable in the medical plants, dryer rooms etc. moreover they don’t require the direct sunlight.

Zhou et al. (2007) mathematically developed the thermal energy storage system with hybrid system for heating purpose. The thermal energy was stored by shape-stabilized phase-change material in this concept. For this numerically developed model, passive solar house was taken for direct gain solar energy. In this house shape-stabilized phase-change material was installed on the ceiling and inner walls linings. To get the hot air in the winter season cold time period was selected for experiment. The simulation was done by verified and developed enthalpy model which was unsteady. Supplementary heat was when the load is required comparatively high to maintain minimum temperature 18 °C. This extra heat was required at the mid night time or during insufficient heat at day time. Concluding this analysis, the outcome of it was amazing improvement of shape-stabilized phase-change material by providing thermal storage. Such combined system improved the thermal comfort in indoor and save 47% conventional energy. In winter time it will save 12 % of total energy consumed. Such applications of high electricity required like power plan, tariff policy used for day and night time can be satisfied by hybrid heating system.

3.13.5 Solar green house

As discussed in the previous sections the phase change materials have wide range of applications among them one is for solar operated green houses. The solar
based phase change material storage system is to be used for the drying and curing of the plant and process of greenhouse (Hung K, et.al 1975.). Kern and Aldrich (1979.) had performed on study 36 m² area of greenhouse which was made of tedlar coated fiber glass. He used 1650 kg CaCl₂.6H₂O in aerosol cans. The weight of each aerosol can was 0.74 kg. The study emphasized on the energy storage capacity inside and outside of the selected area of green house. They selected two types of room one was outside and other inside the green house. These stores were used for the phase change material cans. The arrangement of this cans was in such a manner to provide the 22.86 mm gap between each other. The process of thermal energy storage inside the green house was started during the day time. The material absorbed the heat from inside the green house and at night time airflow was reversed. The arrangement of such system is shown in figure 3.30

Huang and Toksoy (1983) developed the latent heat storage design. In this experiment constructions different pile structure and inner part (air baffling) of the greenhouse ere combined with latent heat storage system. The performance was presented that the latent heat storage system has batter storage efficiency compared to water and rock storage. The Viable cylindrical storage rods were considered as the storage element. Also, such study relates the cross baffled and ring baffled storage unit performance for energy storage. The results found that the
ring baffled storage unit has better performance than cross baffled unit. Another study was carried out in France in 500m² area using phase change storage system. The solar generated heat in the greenhouse was transmitted to the underground flat heat exchanger. This hot air was recycled by the phase change material of the flat plate heat exchanger. The solar greenhouse performance with PCM storage system was better than the traditional greenhouse. The use of propane gas in greenhouse is to be found 20% only if phase change storage system was used for same temperature. Special arrangement of stands or rack should be designed in green house for latent heat storage which was should be is in direct contact of solar radiation (Hhyum – Kasp Song, 1988.).

Looking in to the depth of greenhouse systems, circulating hot air inside the system does the reaction with phase change material and charging and discharging was done. As discussed, the stored energy was used at night time to maintain the desired temperature. Here the phase change material was Na₂SO₄.10H₂O. Furthermore, studies were performed on Na₂SO₄.10H₂O by adding various additives to enhance the phase change material properties for storage. Also, few additives prevent degradation and separation in phase change material during the heating. These experiments were done in Japan. The effect of phase change material with latent heat was found on 40 to 60 %, rest was not efficient for energy storage and discharge.

Takakura and Nishina (1980)did the experimental setup on conventional greenhouse. On this conventional greenhouse they had attached the phase change material storage system and performed the test. The line diagram of general storage in greenhouse is shown in the figure 3.31. As phase change material for this experiment were CaCl₂.6H₂O and polyethylene glycol. This set up was designed for 7.2 m² area. The test was applied and both the systems were compared. The phase change material with green house system act with proper efficiency. Such system can maintain the 8°C temperature inside the green house when outside
temperature goes down to -6°C and its total efficiency was 58% with solar collector attachment.

![Schematic diagram of the phase change material storage in greenhouse]

Fig. 3.31 Schematic diagram of the phase change material storage in greenhouse

The further study about the greenhouse system was to be controlled by computer oriented program. Such program established the easy controlled and accurate results. Such system was developed by Baille and Boulard (Baille A, 1987.).

Boulard et al. (1990) did studies on the greenhouse with 176m² area which was made of polycarbonate-cover. The greenhouse has forced ventilation and maintains the 21°C temperature inside. The temperature was to be set by regulator for day and night time in the month of February and March. It would be set 12°C and 14°C in the month of February and 22°C and 26°C in the month of March. The energy stored in greenhouse during day time was 0.260 kW h/m². Similarly, in night time energy stored was 0.360 kW h/m². The air velocity of the greenhouse was 1 m/s. the outside air temperature in February and March was 3.8°C and 6.8°C. Correspondingly inside air temperature was 10.8°C and 13.5°C at same time periods. Through this phenomenon overall performance of efficiency was 30% and heating load can be achieved up to 40%. The schematic view and cross section of the energy storage system is shown in figure 3.32.
Ozturk (Öztürk, 2005) developed the greenhouse system for 180 m² area. This system was of thermal energy storage system by phase change material. Here they have used the paraffin wax as a PCM. The latent heat storage unit, flat plate solar air collectors, data acquisition unit, heat transfer unit, experimental greenhouse was used in the experimental set up. The performance analysis states that the average thermal energy and exergy stored in the unit was 109.3 W and 78.9 W respectively. They also found the exergy and energy efficiency of the system was 4.3% and 40.5% respectively.

3.13.6 Telecom Shelters, Automobiles Transportation of Temperature Sensitive Materials and solar cooker.

Telecom shelter is the newest sector for phase change material and it was found that the PCMs are very useful for this area. Telecom sectors include the Base Transceiver Station, small insulated houses for mobile communication etc. the battery and Base Transceiver Station are the temperature sensitive. This telecom shelters are most commonly used for undeveloped area where it will be installed. Usually air conditions and other things are running by electricity power. Sometimes it would be connected with generator when power is not available. To avoid such problems in
power cuts period or power saving PCM material storage system would be the great and effective solution.

In automobile industries, concept of PCM is novel. Automobile industries have many difficulties during starting the engines at low temperature, fuel consumption and inefficient combustion during warm-up etc. all these problems can be satisfied by the preheating of engine but by conventional method pre-heating is expensive and limited source. The innovative idea can fulfill the requirement and provide economical solution. The engine out-let waste heat management is required. The phase change material can store this waste heat. The phase change material is to be store at the tail pipe of the automobile or vehicle to get the waste heat.

The transportation of preservative food, explosives chemicals, ignition transformers, pharmaceutical items which are temperature sensitive required the air conditioning or refrigeration truck. These vehicles are to be operated by the design or petrol. It consumed many litters in a day and pollutes the environment. In market phase change material for cooling and heating applications are already found for example ice box, transport box.

The wide use of solar energy is in the field of cooking the food. Solar cooker is the most appropriate equipment to prepare the food but its major limitation is it will not be used at evening hours. Therefore, solar cooker with phase change material can satisfy the demand. Few studies were done in this area by Domanski et al. (1995) in which they have used the magnesium nitrate hexahydrate as phase change material. Buddhi and Sahoo (1997) worked on the box type solar cooler. They used stearic acid as heat storage material below the absorbing plate.

3.14 Building applications

The building or room or space is the daily requirement of the society. Maintain the comfortable temperature in the room there are several conventional ideas that are like thick wall construction, providing conventional cooling equipment in
summer and winter time period. Also, sometimes light weight building is one of the options but in such building their thermal mass is very low and high fluctuation in the temperature. These demerits consumed more cooling and heating power demand. To resolve such kind where high energy is consumed for heating and cooling of the building sector, energy storage system is to be introduced. Thermal energy storage by phase change material is the most appropriate solution as discussed in above applications. Similarly, here also PCM based thermal energy storage system plays important role. Such storage systems installed in building sector is advantageous to maintain the heating and cooling for long period, less maintenance and energy conservative system.

The phase change materials have been used as thermal energy storage for building since 1990. The suitable and efficient phase change material should be installed in wallboards, on the floor (below the tiles), trombe wall, ceiling and any other suitable places of the buildings. Forthcoming portion of the literature survey includes the various studies, test performances, design and developed model or experiment setups for building cooling and heating applications by thermal energy storage by phase change material. The phase change material works with basically two types of supportive system one support is by solar energy and other is by conventional manmade support for its working process. Also, such extensive review includes the vital source of alternative solar energy with this storage system. This is to get comfort temperature during day and night time in cold and hot days. On the other side the energy produced is not only thing that matter but the amount of energy with respect to its demand and supply, time and cost are also the major factor to be considered in the development. Principally there are several ways to install phase change materials in the buildings but the following three are the most common and efficient of cooling and heating of the such sector a) Special storage unit (heat and cold) for phase change materials b) installed in building walls C) other components (other than wall) like floor, ceiling etc.
Now a day the government of India has approved the research and development in the field of off peak load utilization. The schematic diagram 3.33 is shown the difference between the conventional and latent heat storage off peak power system.

**Fig. 3.33 The cooling component and line diagram for use of off peak power**

Moreover, the latent heat thermal storage system to be installed in building for energy conservation is discussed below. Phase change material is a latent thermal energy storage material and it can be installed in a wall board, under the floor for heating technology, ceiling board, trombe wall and shutter. The following section (table3.4) includes the different studies of phase change material applications.
### Table 3.4 summary of various studies using phase change material

<table>
<thead>
<tr>
<th>Author(s)</th>
<th>Type of phase change material</th>
<th>Used phase PCM</th>
<th>Meltin g point (°C)</th>
<th>climate and location</th>
<th>Methodology used in study</th>
<th>Applicable type of software</th>
<th>type of Capsulation of PCM used in study</th>
<th>Location of PCM in building</th>
<th>Factors to be considered for examination.</th>
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<td>Eutectic Palmitic and capric Acid</td>
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<td>changes in temperature</td>
<td>Mathematical and experiment based study.</td>
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<td>Macro-encapsulation</td>
<td>Used in Building Wall-board</td>
<td>Maintain the inside temperature and shifting of peak hour loads</td>
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<td>Evola et al.,(2014)</td>
<td>Organic Paraffin</td>
<td>23.9</td>
<td>Check in hot climate of Italy and Catania</td>
<td>Graphically energy analysis</td>
<td>Energy Plus 7.0</td>
<td>Macro-encapsulation</td>
<td>Used in Building Wall-board</td>
<td>Identify the variation in temperature with ventilated cavity.</td>
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<table>
<thead>
<tr>
<th>Author(s)</th>
<th>Material Type</th>
<th>Temperature Range</th>
<th>Study Type</th>
<th>Software Used</th>
<th>Location</th>
<th>Phase Change Effects</th>
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<td>Jin et al., (2014)</td>
<td>Inorganic Salt hydrate</td>
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<td>Change in experimental temperature</td>
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<td>Macro-encapsulation</td>
<td>Used in building wall</td>
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<td>Diarce et al., (2014)</td>
<td>Eutectic RT35 from Rubitherm GmbH</td>
<td>26-28</td>
<td>Spain</td>
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<table>
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<th>Temperature Range</th>
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<th>Simulation Tool</th>
<th>Encapsulation Type</th>
<th>Material Use</th>
<th>Notes</th>
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<td>NA</td>
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<td>Fatty acids / glycerides</td>
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<table>
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<th>Encapsulation</th>
<th>Application</th>
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<td>Seasonal changes in temperature</td>
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<td>Used on building ceiling and floor</td>
<td>Phase change material mean temperature with PCM amount and time for installation</td>
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<th>Study Type</th>
<th>Integrated into</th>
<th>Uses in Building</th>
<th>Remarks</th>
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<td>Mathematical experiment</td>
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<td>Amount of energy storage and</td>
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(2015) country based study. wall delivered and also check the solidification of the phase change material for cooling applications.
3.14.1 The survey of phase change material in building wall board

The use of phase change material encapsulation in wallboards is the most common and suitable technique. This technique is relatively cheap and economical. The benefit of the latent heat storage should be principally applied with any type of building material. The process of the phase change material installation on the wallboard through the plaster of the building wall. These can be done by two methods one is by mixing liquid PCM with manufacturing martial and pasted on hole spaces and in another idea, is adding PCM in wet stage of plaster boards. This process of phase change material incorporating with wall board is practically tested and demonstrated. Stovall and Tomlinson (1995), focused on the thermal comfort on the lightweight buildings. To enhance the comfort level of such building storage in wallboard is the better idea. The researcher has done various forecasting studies previously (Kedl and Stovall, 1989; Feldman et al., 1989; Neeper, 1989). They used direct immersing or macro capsules process. Such process has so many disadvantages to store the thermal energy. They faced lots of problem in charging and discharging passes of the energy storage material. To pay the attention on its drawbacks phase change material based energy storage system was not popular in the market. However, to overcome such problems and improve the utilization of PCMs in building wall boards microencapsulate is the key solution or technology (Drake, 1987). Schossig et al. (2005) had developed the microencapsulate system through the support of German government and its product are available in the market which reduced the total 42% of electricity consumption.

3.14.2 The systematic evaluation under the floor for heating technology

The energy building has floor and using it for the heating and cooling application is an innovative idea. The test were done by Athienities and Chen (Athienitis and Chen, 2000) presented the heating from under the floor and developed heat transmission system. They did the studies majorly for the effect of the stored material under the floor which includes the effect on cover layer, effect of solar radiation on the floor and its temperature distribution. Also, this performance includes the energy consumption study. For study card
board (wooden) floor area were taken and installed the gypsum–concrete mixture phase change material as thermal storage. They collected the practical reading from outside area of the room floor (uncovered floor) where sunlight was directly imparted on it. The results proven that the temperature was 8°C higher than the shaded area. Than after they did the experiment on the partially covered with carpet and result was found 15°C lower than uncovered floor readings. They conclude that the 30% or more than that energy could be saved for heating of the room by using phase change material based thermal energy storage. Also, they tried to improve the thickness of PCMs from 6.5mm to 10mm but did not get much difference. To improve its efficiency or energy saving and maintain very good thermal control advance control algorithms are needed.

Another most viable technique for heating compared to conventional heating system is radiant heating. The major merits of this system are it saves the working and living space if covered with building structure. The floor heating system was integrated with the thermal mass and it could be used during off peak hours. Therefore, peak load power is to be shifted to night time and save the electricity of high cost in peak hours (Bakos, 2000). The dense concrete structure provides the maximum fluctuations in the building indoor temperature. Incorporating the phase change material for latent heat storage could store large amount of energy in small area. Also, this amalgamation effects on the thermal comfort of the building. Such system consists the wooden floor, air layer, PCM plats polystyrene insulation, electric heating system, electric heaters and is shown in figure 3.34. The main function of the electric heater is to melt the phase change material by using low cost electricity at night time and store the heat. The phase change material layers were solidified during day time and draw the stored heat. At that time electric heater was switch off. China is the biggest developing country in which electricity rates are different for day and night time. In a night time it would be 1/3 or 1/5 of the day time tariff plan is applied. Thus, the significant solution is that to shift the peak load hours to off peak hours. It is more beneficial to the power plants buildings. Lin et al. (2004) developed the cooling system using latent heat storage in the building. He has done experiment in 0.5 m² area.
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Paraffin mixed with foamed glass beads was used as phase change material. The thickness of the phase change material was 3 cm. The small holes were imparted on the pack bed of phase change material and spreader under the floor. The experimental results were conducted on the setup and it was noticed that the granulated pack bed stored energy save 18.23% of total consumed energy. So, such kind of energy storage can help for the small rooms of limited area.

![Diagram](image)

**Fig. 3.34 Phase change material plates with under floor electric heating system**

3.14.3 PCM shutter

The use of phase change material in the shutter is hardly available for application but it can be used for small area. The phase change material is to be stored in the shutter of the window. This window was opened during the day time and absorbs the heat and PCM stored that energy. In night time PCM stored in closed window and provide the heating in the building by window shutter. The design and development of such technology was in turkey (H. M. S. P., April 18–20, 2004). Its major limitation is that more area of storage was required and less efficient than other technology.
Another study was done by the Qian Wang and Zhao on phase change material installed on window. The design of the window provided the air gap, phase change material melting temperature and its tackiness should be proper to maintain to everyday changes in the climate conditions. The air gap played key role in this system. In summer duration hot air comes from the outside through the window. The phase change material transferred the coolness to the hot air. This hot air gains the cool energy and provided comfort level in the room.

### 3.14.4 Ceiling boards

Every building has a ceiling in their structure. It is the significant part of the building roof. The cooling and heating application can be fulfilled by utilizing the ceiling boards. Bruno (2002.) had designed the system for cooling application in which phase change material can store the energy in off peak period and supply that stored energy during its requirements. Also, study was performed for the air-conditioning system control by using phase change material for ceiling. The most important factor for phase change material is melting point and it was in the range of 20–30 °C for this study. This selection of the melting point is because it is most convenient for room temperature. To maintain isothermal conditions in the chicken brood latent heat solar roof system was used in the village. Basically, experiment was divided in to two parts one was yard portion and another connecting portion was brooder. They have used the 2 semi-circular tanks for this performance, in which 42 kg paraffin wax was filled as phase change material was filled. The tanks upper and lower portion was made of glass and both glasses were air tight. Another material polyurethane insulator was located between glass roof and paraffin tanks. This setup maintain the temperature 22 °C to 30 °C. (Benard et al.; 1981).

Also, the ceiling is for the heating of the space by installing the phase change material. The performance was done by the Guthertz and Schiler (Guthertz and Schiler, 1991). The arrangement of the charging of the PCM material was by solar energy. The sun radiations were entered the house and reached up to the ceiling by the reflection technique. The significant merit of ceiling thermal heat storage system was that they allowed using
large area for material storage. Also, such system does not require the large volume for storage. As the results shows such systems can save 17 to 36 % of the heat loss and that is the great potential of the system. Turnpenny et al. (2000) made the system for coolness in the space by latent heat storage system. The phase change materials are in the heat pipe. The PCM gets the charging at night time from the cooled air and discharge the cooling air in a day time. Kodo and Ibamoto (Kodo T, 2002.October 1–2,) worked on office building for the energy saving of air conditioning system. This conventional system is to be attached with the phase change material storage system on ceiling board. The ceiling board phase change material system efficiency was improved by adding micro-capsulate material in rock wool. Its melting point should be enhanced (25 °C) and matches with room temperature. Here to avoid using the rock wood ceiling board. Special air flow unit is to be designed for proper amount of cooled air flow to the ceiling board phase change material. The cool air from the night time is to be consumed by this unit and stored as thermal energy. Similarly, this storage energy gets used at day time and air flow unit discharges the cool air in to the room. Also for this system working in day time, this air flow unit absorbs the warm air of room the room and supply to ceiling board that is then cooled by the thermal storage unit and returned to the room. Thus, the thermal load can be reduced. Normally cooling time of the system starts from 7:00 a.m. to 1:00 p.m. The peak hours start by 1p.m. to end of service time. From 4:00 a.m.to 7:00 a.m. is the time for thermal energy storage for this study. Therefore, the energy saving should be possible and get low cost of electricity. So finally, this study concluded with thermal energy storage benefits in comparison of conventional energy system. The benefits are 1. Phase change material based ceiling board system has cool air poon with high density resulting in efficient thermal storage system. 2. All type of phase change materials can be installed on the ceiling board without any indolent of the beam. 3. Phase change material melting point and the ceiling board surface temperature should be closer so radiant field and the indoor thermal environment can be improved.
3.14.5 A systematic study of phase change material in Trombe wall in building

Many authors have studied and proposed the phase change material with thermal energy storage system in building floors, ceiling, and wall for changes in temperature or to get comfort temperature. Now here brief study of the thermal energy storage system with Trombe wall which has unique and novel idea of heat storage. Basically, a Trombe wall is nothing but the glass external layers. The Trombe wall can also be made of masonry. That masonry work can be replaced by the phase change material. Numerically and experimentally this phase change material based Trombe wall has been tested (Swet, 1980; Ghoneim et al., 1991). As compare to Trombe walls or water walls, phase change material storage unit required smaller space for storage. This system has lighter weight. The most common material hydrocarbons and salt hydrates are used. However sometimes metallic additives were added in to the above materials for improving the efficiency and increase the overall conductivity. Therefore, it was widely used in retrofit type building applications.

Furthermore the research has been conducted for phase change material based latent heat storage system active ness with Trombe wall. This research was based on passive heating system for building. Primary the experiment employed on the concrete based Trombe wall having 30 cm and 10 cm thickness and measured the transient temperature. This simple concert wall was compared with another same concert wall made of phase change material with 20% paraffin wax added in it. Castellon et al. (Eiamworawutthikul C. http://intraweb.stockton.edu/eyos/energy_studies/content/docs/FINAL_PA-PERS/14B-1.pdf.) investigated and developed the Trombe wall in the south façade direction. This recently developed experiment measured the effect of phase change material and its use in Mediterranean climate for decreasing the heating and cooling demand.

Bourdeau (Bourdeau, 1980) did the study on two types of the passive storage collector walls. Calcium chloride hexahydrate was the phase change material. This material has 29°C melting temperature. They had taken a 8.1 cm phase change material wall. Their performance was better than the masonry 40 cm thick wall. Similarly to check the ability of phase change material on Trombe wall, few experiment were done practically and
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theoretically (Ghoneim et al., 1991; Chandra et al., 1985). In this research they had used sulfate decahydrate as phase change material in south faced trombe wall. This PCM melting point is 32 °C. Their results concluded that the effectiveness of the trombe wall was more on thin wall in contrast of masonry constructed wall for thermal energy storage. Figure 3.35 showing the trombe wall setup.

![Fig. 3.35 The trombe wall test configuration.](image)

Stritih and Novak (Stritih and Novak, 1996) had used the black paraffin wax with 25 to 30 °C melting point material for storing the solar energy. This application was for building ventilation. This stored heat by PCM can be used for heating air. Total absorption efficiency was 79% observed. The key results found from this study was melting temperature affects the output air temperature. The optimum thickness of wall was 50 mm for heating climate.

3.15 Conclusions and Discussions

In this chapter the brief discussions is provided on the recent work done in the field of thermal energy storage by using the phase change material. Also, it includes the current technology design, development and its applications were discussed in terms for energy
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having in different sectors. However, with a major focus on the phase change material technologies for its storage and efficiency improvement.

Moreover, the energy is playing an important role for any commercial and economic growth of country or any sector. Therefore, increasing demand of the conventional energy which is associated to environmental concerns have paid the more attention towards the alternative energy source development. So, in this chapter also, a brief discussion on the high energy consumption sectors and different types of techniques for energy saving like shading, thermal chimney, surface shading, rigid vent, roof vent, roof spry, Earth Cooling Tubes, vegetation, Wet Fiber Pads, white roof, Movable Insulation Systems, Radiative cooling were discussed. These all technologies are the appropriate for less power consumption sectors and few of them only related to the design of the structure in proper directions of opening and closings for comfort temperature. Also, such system has no option to store the high amount of energy to work in off peak hours.

In the summary of this it was noticed that the in the world the people have started to use renewable sources. The solar energy is the vital source of the alternative energy. In many cities of the world it can be used directly to generate the energy and saving purpose. The researcher and scientist are doing research in the field of new technologies for utilizing the renewable sources. In the direction of the energy consumption, low cost energy development and energy available in no power condition, the novel and impressive technology found by the research is use of energy storage devices.

The energy can be stored by mechanical, electrical, thermochemical and thermal energy storage. The mechanical energy storage systems contain hydro pump, flywheel equipment for its storage purpose but they can provide the stored energy (in the form of electricity) for limited time period and storage capacity is very low compare to others. Similarly, in the electrical energy storage systems the batteries are used as storage purpose but it cannot store high amount of energy. Even the leakage from the battery is the main barrier. The chemical reaction restricts the use of thermochemical energy storage system. Also, thermochemical storage is hazardous to people. Therefore, storage of energy in appropriate forms and changes or converted
in to suitable form and proper amount of storage are the challenges of storage technology. Looking towards such challenges the thermal energy storage is the most significant method to satisfy the all application demand and meet to the energy supply and demand. However, few remedies of thermal storage technology are but there are in development stage and not affect much in specific applications. Thermal energy storage is the prospective storage technology among the others.

Now thermal energy can be stored by the sensible heat storage and thermal heat storage. The sensible heat is generated by heating an objective. The heat which is generated by an objective which adds or reduces the temperature is called sensible heat. The water, oil, rock is the sensible heat storage material which cannot make any changes in volume or pressure. Also, sensible heat storage systems are less efficient. On the other hand, latent heat storage system is the most promising method for thermal energy storage. There are several reasons but the most significant reason is that it can store the energy by changing its phase (i.e. liquid to solid, liquid to gas), its can release and absorb the heat at constant temperature. Also, latent heat can store 5 to 15 times more heat in comparison of sensible heat storage. Finally, thermal energy storage by latent heat is the most preferable technique.

Furthermore, the selection of the material is the important parameter. Among the many materials, phase change materials have been most convenient and suitable for storage purpose. Every phase change materials have their own specifications of their internal properties. Organic materials are the most appropriate and have many applications. These materials have suitable characteristics like melting point, no supercoiling, high specific heat, non-acidic and very less chemical reaction can lead the scope of its use. Also, organic materials are efficient to store the latent heat. In its context the paraffin wax was found the most useful and cheap material for many applications.

However, other phase change materials are based on inorganic. Inorganic material includes the salt hydrates and metallic material. There are many applications based on this phase change material. This material requires the additives to improve its storage capacity.
Also, it has limitation of material weight especially for metallic in-organic material. Sometimes these materials are showing corrosive nature and super cool. So, they are not used in high storage capacity applications.

In the phase change material containment costs and attendant problems are found. That can be resolved by the immersion, encapsulation and direct incorporation materials for incorporating with the PCM. Encapsulation is the containment of phase change material. The Encapsulation materials are available in the market in the form of capsule with different size. The macro- encapsulation and micro encapsulation have their own drawbacks and limitations. Both encapsulation can be used as per the application. However, to it was found that the poor conductivity in micro encapsulation can be satisfied by the other.

Regarding the discussion about the passive technology for thermal energy storage purpose, it can be used for the sensible heat storage, minimum use of active cooling and heating devices and to maintain thermal stability. Moreover, it was found that the phase change material does not require the high volume for its storage purpose which will be the benefits for applications. Major demerits of the passive technology are its leakage and thermal stability. So, it is not much used for major applications where high energy storage are required and generated.

On the other hand, active technologies play a key role for thermal storage purpose. The active technology is incorporated with thermal energy storage system for cooling and heating application by using renewable energies. This technologies development is high but it has long time benefits and more used in peak load shifting.

After a brief understanding of the thermal energy storage with proper phase change material, appropriate techniques and methods their application survey is discussed. Many applications of were the TES with PCM storage system can be applied but here considering few of them those are consuming high electricity or power. The applications such as Air conditioning and refrigeration, Textiles, Solar water heating system, Solar air heating
systems, Solar green house, Telecom Shelters, Automobiles Transportation of Temperature Sensitive Materials and solar cooker.

The consumption of electrical power or energy saving in above mentioned applications is for heating or cooling of the space, domestic requirement of hot water and sustaining the comfortable climate. However, above mentioned sectors are not applicable in every cities or area of the country but limited to the particular area of the concerned sector. No doubt these sectors are to be in consideration for development of the thermal energy storage system.

Another sector building application is the key source of high energy consumption. Either the new building or old building can satisfy their use of energy by thermal energy storage system. Building sector is the biggest sector to consume high amount of power or energy in comparisons of others. These building applications for cooling and heating are the most common need of the society and have wide applications of it. As per the extensive survey of phase change martial based latent heat thermal storage material system are most appropriate and efficient system which can perform very effectively for free cooling and heating.

The next chapter 4 provides the mathematical model experimental setup of the photovoltaic solar thermal collector for domestic hot water application and for improving the efficiency of the system. In chapter 5, the setup for heating and cooling of the building space is demonstrated theoretically and experimentally. The study is applied by common standardized assessment methods for latent heat thermal energy storage system with phase change material. This novel development and study performance satisfies energy demand of cooling and heating. This novel experiment provides after specific period, free heating and cooling by thermal energy storage by phase change material in buildings.