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Phase Change Material with Thermal Energy Storage System and its Applications: A Systematic Review

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Abstract

Objective: The purpose of this review leads to use of Energy conservation technologies. **Methods:** There are so many systems which are used for energy saving among them thermal storage system with Phase Change Material (PCM) is well known. In this review majority focuses on the human comforts. It was observed that maintaining the human comfort is the challenging task for living spaces like room, offices etc. such type of required energy which is satisfied by thermal storage PCM based system. If the Phase change materials are applied to building applications they can be used for peak load shifting in cool storage system. **Findings:** Development of the new techniques for getting thermal comfort for building (lowering the heating and cooling demand is required. Also it includes the expenses behind development, maintenance and installation. Moreover this review finds the effective phase change materials. **Improvements:** Such thermal storage system has a potential to replace the conventional methods but the effectiveness or efficiency of that system is less. So it is required improvement in the selection of thermal storage system and phase change material. Also this review presents the potential of the phase change material system.

Keywords: Energy Conservation Technologies, Phase Change Materials, Space Heating and Cooling, Thermal Energy Storage System

1. Introduction

Energy has played an important role in advancing technology. It has also helped in conserving the many natural resources. But as time has passed the use of energy has become more. There has been developing many methods of saving the energy which is wasted in lots of proportion[1]. Many methods such as solar energy storage, hydro energy storage etc. are been developed for conserving energy. As there is always need to find new methods for storing or saving the energy. One of the important and best methods for storing the energy is use of thermal storage by Phase Change Material (PCM). Latent Heat Storage (LHS) is one of the most effective methods for storing the energy and reusing it whenever needed[2]. PCM are materials which has ability to store the heat energy and release them. It absorbs the latent heat from the surrounding and releases it when temperature falls[3].

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The property of low thermal conductivity of PCM decreases the heat transfer at the time of charging and discharging[4]. In phase change process when the heat from surrounding falls on the material, the molecules of the material breaks and the material goes from solid to liquid. Similarly when temperature reduces the material releases the heat and the molecule starts joining and it changes its phase from liquid to solid again. This way the phase change material works and has ability to store the heat[3]. This material uses heat from surrounding which is wasted, when these materials are used in building applications the use of conventional energy reduces for cooling effect.

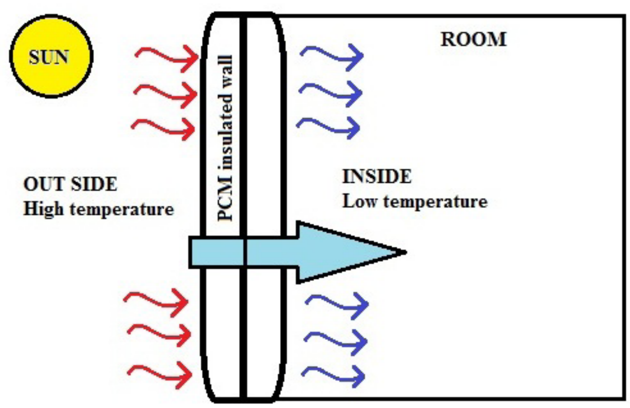

Figure 1. Schematic Diagram Working of PCM.

Figure 1 shows how the PCM works. Temperature of outer surface is more and heat transfer takes place between surroundings and building wall, now if the PCM is installed in the wall as shown in Figure 1, there will be temperature difference created between external side and internal side of the building and the inside temperature reduces without help of any external conventional sources[5].

Conventional sources such as Air conditions, coolers, heaters etc. uses more electrical power so there should be minimum use of these conventional machines. The use of Thermal Energy Storage (TES) keeps the proportion of supply and demand equal. Better reliability and overall efficiency can be also achieved by using TES[6]. Use of TES controls the indoor conditioning and also gives better for storing heat energy. There are basically two types of technologies used in TES.

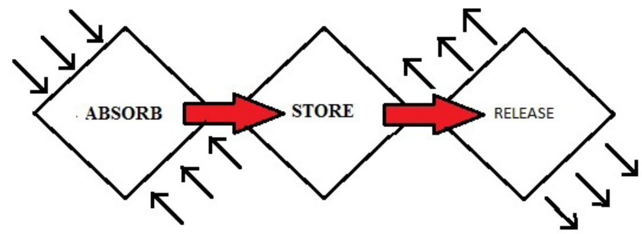

Figure 2. Line Diagram of Phase Change Material Process.

The Figure 2 indicates the process of PCM. As shown, initially it absorbs the energy then it stores it and finally it releases whenever necessary. This way the process of PCM takes place.

1.1 Passive Technology

The main aim of using passive technologies is to reduce the usage of heating, Ventilating and Air Conditioning (HVAC) and get more thermal stability. This technology provides to store energy of high quantity of energy, by giving thermal comfort within the building. The basic materials used in this technology are bricks, concrete or stone[7]. As looking in to the depth of this review more concentration on the passive technology. This type of technology can be easily installed and more effective due to its mixture with the construction material and finally constructed with wall layers[8]. Also these features can help to improve its storage capacity, great potential to improve in building efficiency[9].

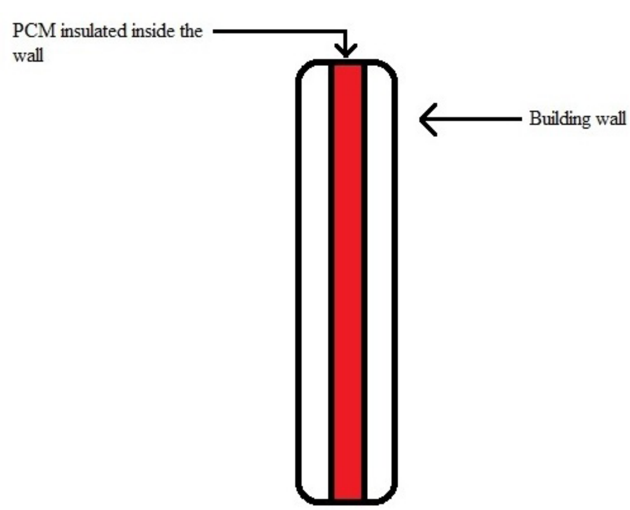

Figure 3. Passive Technologies with Building Wall.

In Figure 3 the PCM (passive) is installed inside the wall of the buildings. These types of technologies contain PCM insulated in it.

1.2 Active Technology

This technology is most appropriate and unique solution for free heating and cooling application of building. This active system can basically working based on renewable sources like Photovoltaic system, solar panels etc. In this technology the insulation of TES in building can be done in crux of the building for example, floor and walls. With the help of TES in active technology we can achieve free cooling, when the building the charged with low temperatures at night and this stored energy is discharged when there is necessary. However this active system is not limited to new building but it can be installed with existing buildings which is also giving the most efficient results in energy saving[9]. This system can help to save the energy during pick load period so heating and cooling of building space should be achieved up to sufficient level.

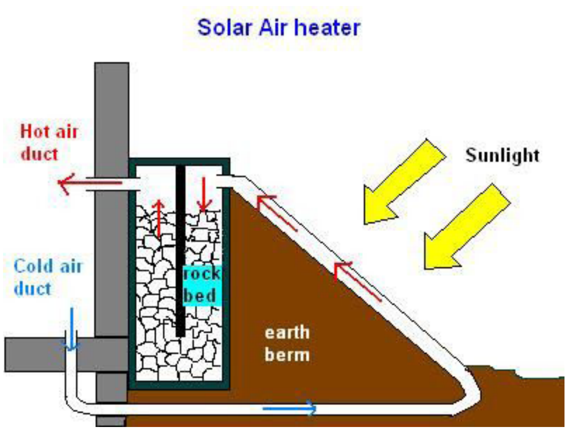

Figure 4. Schematic Diagram of Active Technology.

Figure 4 is an example of active technology. This technique uses solar energy and helps in heating applications. These are also common type of setup used now a day.

However, both technologies have merits and demerits based on their characteristics. Passive based technologies have good capacity of thermal stability and also reduced the utilization of cooling and heating devices. But this system has required high volume for PCM storage so for this system gets leakage and other problems. Furthermore, to overcome such problems active system can be more suitable for shifting peak load duration. Active system is used basically for free heating and cooling because this technology has renewable sources devices for generating the heating and cooling in the building. Such system has the drawback of high initial cost of installation.

Finally thermal energy storage system with phase change material is the best technology to save the energy and free heating and cooling of building space. Also system can meet the requirement of energy supply and demand. Also this paper explores the literature survey, classification, properties and its applications etc.

2. A Systematic Survey of Phase Change Material based System for Energy Conservation

To save the energy and to meet the supply and demand of required energy for heating and cooling of the building or space such PCM based technologies are most appropriate as dissected in previous section. Such technology development is continuously growing to protect the environment and convection energy sources. As briefly discussed in the Table 1 PCM based system is one of the optimum solution among the energy conservation system[2]. Also recent development in thermal energy storage systems are the most promising and user-friendly technology for space heating and cooling. Table 1 show an extensive review of PCM based system integrated with buildings. However this literature survey includes PCMs are installed into the various building components and shows its effectiveness. From the many different studies and experiments it has been concluded that the PCM installed buildings has good thermal conditioning than other technologies. Moreover it is also observed that the selection of PCM plays major role in system efficiency. So classification, characteristics and its properties are discussed in next section.

3. Energy Storage Methods

Looking towards the global energy scenario, day by day demands of convection energy sources leads the high cost and shortage and greenhouse effect problems advice to find out some alternate of the limited energy sources. To resolve such kind of problem renewable energy resources are the vital source. However, these types of renewable sources are intermittent in nature. Also these sources have intensity variations characteristics for working in different climate conditions and environment. Therefore such

Table 1. A Review of PCM based system integrated with buildings

Building Components	PCM Variety	PCM Amalgamation Method	Significant Discovery
1.Casement / Persiennes	Paraffin	Not mentioned	According to this experimental knowledge we can conclude that solar energy gained by modern casement arrangement is 48-50% more than traditional arrangement. It was noticed that there was a drastic change in solar gain during winters. PCM offered good conditioning in the room[10,11].
Not mentioned		Immersion	According to this experiment we can say that liquid PCM gives good thermal conditioning. It protects window glass from UV radiations[12].
2.Wall / Panel	Paraffin	Microencapsulated	According to this experiment the temperature is reduced by 2-3°c in rooms without PCM[13,14].
	Eutectic mixture of capric acid and lauric acid	Not mentioned	According to this study we can reveal that the temperature of the south wall of the room rises up to 2-3°c in midday without PCM. It also shows that the higher temperature is increased by 1°c and minimum temperature reduced by 2°c without PCM[15].
	Organic PCM	Not mentioned	This study shows that the honeycomb pattern PCM walls gives good conditioning of the room by reducing the day temperature swing from 5.6°c to 3°c.it also lowers the peak temperature by 1°c and whole day temperature by 3°C [16].
3.Ceiling housing	Bio-based PCM	Macro encapsulated	According to this investigation it has been revealed that PCM installed with solar panels in loft on the roof reduces heat demand by 29% in minimum temperatures and cooling load by 54% in higher temperatures[17,18].
	Eutectic mixture of $CaCl_2$+NaCl+KCl+H_2O	Macro encapsulated	This investigation concludes that ceiling with PCM maintains good thermal conditioning of the room than ceiling without PCM[21].
4.Floor	Paraffin	Macro encapsulated	This investigation says that PCM combined with radiant floor heating system saves roughly 23-25% water demand for cooling purpose. It also ensures good warming capacity in minimum temperatures. Hence flooring system with PCM is more reliable than standard flooring system.
	Paraffin	Microencapsulated	This experiment shows that use of PCM improves thermal conditioning by increasing time lag and reduces surface thermal degrees by 2°C.

kind of economic and effective idea for thermal energy storage systems satisfied the low temperature application for heating and cooling of building space. Moreover, other features like operational and investment expenses are considered for selection of energy storage systems. There are basically three types of storage system 1. Mechanical Energy storage system, 2. Electrical Energy storage system and 3. Thermal Energy storage system

3.1 Mechanical Energy Storage

Mechanical energy storage systems consist of compressed air energy storage, flywheels, pumped hydropower storage or gravitational energy storage. Mostly pumped hydropower and compressed air energy storage are widely used in heavy pick loads and its storage whereas flywheels are used for intermediate storage. Storage of the energy is possible when the off pick hours or day. In this type of storage power can be easily discharge during pick hours because inadequate supply from the base-load plant.

3.2 Electrical Energy Storage

Electrical energy storage systems are most common storage phenomenon. In this storage systems energy stored in to the batteries and supply. Battery is charge during directly connected to the electrical sources. Also during discharge the stored chemical energy is transformed in to electrical energy. Electrical energy storage through batteries is widely used in load levelling, off-peak power and photovoltaic plants. Ni–Cd and lead acid batteries are the most common types for electrical storage.

3.3 Thermal Energy Storage

Thermal energy storage has three main types; 1. Sensible, 2. Latent and 3. Thermo chemical storage system. Figure 5 shows the types of thermal energy system. 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. However such system can be used in energy production sectors. On the other hand a huge development in thermal energy storage technologies based on sensible and latent storage techniques. These two techniques are most permissible and high potential thermal storage systems. Now looking to the scenario of sensible energy storage systems are simple and cheap because of its storage medium water is easily available. Likewise in the latent heat storage systems are most convenient and viable. In latent storage systems have ability to storage 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[2].

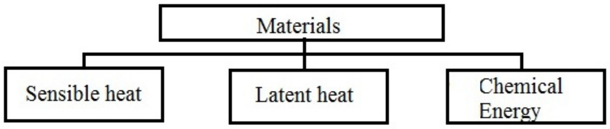

Figure 5. Classification of Thermal Energy Storage.

Basically Thermal energy storage is divided in to three parts, Sensible heat, latent heat and chemical energy. Where Sensible heat storage and Latent heat storage are two parts in which thermal energy is stored by changing the internal energy of the material used[10]. Sensible heat is related to change in temperature. Energy can be stored by increasing the temperature of a solid or liquid in Sensible heat storage. Specific heat, temperature change and quantity of the material are the important factor that affects the quantity of storage of heat in the material. But in compare to sensible heat, chemical energy and latent heat, latent is applicable in PCM[11].

$$\int_{Ti}^{Tf} m \; C_p dT = mC_{ap}(T_f - T_i) \quad (1)$$

Where m = Mass of substance, C_p = Specific heat of substance, dT = Temperature difference,C_{ap}=Specific heat of absorption, T_f =Final temperature, T_i=Initial temperature

When a material changes its phase form solid to liquid or liquid to gas or vice versa, the absorption of heat and release of heat are basic factors in which Latent heat is dependant[5].

To store the thermal energy, heat storage system uses the latent heat of the material[1]. The below equation shows the quantity or amount of thermal energy stored in material in the form of latent heat.

$$Q = m \times LH \quad (2)$$

Where, Q= Amount of thermal energy stored or released (kJ), m = Mass of the material (kg), LH= Latent heat of fusion or vaporization (kJ/kg)

The equation (2) is also known as "Equation of storage capacity of Latent heat with PCM medium".

It is very clear that mass and latent heat are only factors on which the quantity is based on. PCMs are materials used to store thermal energy in form of latent heat[1]. Storage of Latent heat is very appealing as it has ability to store high-energy and can store energy at very constant temperature in limited range of temperature[11].

It concludes that PCMs can store the latent heat very efficiently and are very useful materials for cooling applications.

3.4 Latent Heat Storage System

As discussed in previous section latent heat storage system for thermal energy is the promising technology. Thermal storage system is used with phase change materials will satisfy the domestic energy requirements.

Normally design and construction of latent heat storage is of PCM, working fluid and an appropriate well designed heat exchanger. These systems process consist of thermodynamic cycle in which progressive melting (charging) and solidification (discharging) is to be done. Several studies have been carried out on phase change materials characteristics, selection, classification, its design and construction, its applications and appropriate techniques for heat exchange.

Phase-change heat transfer problems are relevant both to the storage of thermal energy from intermittent source such as the sun and to various processes in geophysics and technology.

4. PCM Classification, Characteristics, Its Selection for Efficient System and Applications

There are several types of materials are invented among them few has characteristics of change in its phase according to the different temperature. Every material has own properties to change its phase during change in temperature. Furthermore latent heat and thermal conductivity is various 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 utilised 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 behaviour during process. The efficient system latent heat storage is desirable when the small temperature changes. This is only happened because of its phase change enthalpy, high storage density etc.

4.1 Classification of Phase Change Material

Basically there are three types of phase change materials which includes; 1. Organic Materials, 2. Inorganic Materials and 3. Eutectic Materials. The brief description of the each classification is mention in below section[10]. Figure 6 indicates the types of Phase change material.

4.1.1 Organic Phase Change Materials

This type of PCM classify in to paraffin and non-paraffin. Majority Phase change materials (PCMs) are characterized by their capability to freeze and melt under the different temperature condition. Paraffin is saturated hydrocarbons from CnH2n+2 groups[12]. It has very similar properties in which C5 and C15 paraffin are in liquid state and others are in wax solid state. The paraffin wax contains the straight chain hydrocarbons and it has low melting temperature in the range of 23°C to 70°C. So paraffin wax is most effective PCM for domestic applications. Similarly non paraffin organic phase change materials have various properties. The review states that it includes alcohols, glycols are used for thermal energy storage[13].

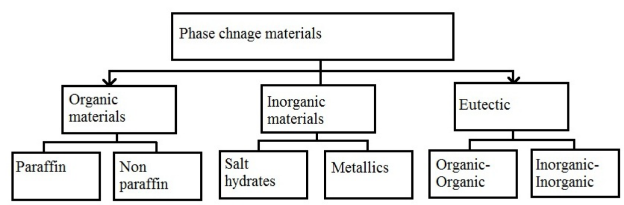

Figure 6. Classification of Phase Change Material.

4.1.2 Inorganic Phase Change Materials

Salt hydrates and metallic are the classification of inorganic Phase change materials. In salt hydrates contain the water and salt. This combination of water and salt create the crystalline matrix after getting the solidification. 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 caused due to salt hydrates. Likewise metal eutectics and low melting metals are the parts of metallic[14].

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.

4.1.2 *Eutectics*

The eutectics comprise of at least two segments where each of them melts and stops consistently framing a blend of a segment that precious stone amid crystallization prepare. 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. The latent heat fusion is very high. Inorganic compounds are corrosive and are not easily available. They also undergo super cooling and decomposition rate is very high. Most of inorganic materials are salt hydrated[15].

From discussed in previous section materials organic materials are selected as these materials are cheap 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.

4.2 Characteristics and its Selection for Efficient System

Selections of Phase change materials are important part to developed efficient thermal storage systems. There are different types of PCMs available in Organic and Inorganic form. Some of them are listed in Table 2.

Different types of PCM with their melting points are shown in Table 2. Generally Organic PCMs have low melting points and Inorganic PCMs have high melting point. Organic PCMs are less corrosive then that of inorganic due less proportion of water content. Following are the desirable characteristics and properties.

4.2.1 *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, High value of specific heat to give additional benefits of sensible heat storage.

Table 2. Different types of PCMs

Name	**Type**	**Melting Temperature in °C**
Lauric Acid	Organic	44.2
Paraffin carbons	Organic	5.5 to 75.9
Formic Acid	Organic	7.5
Caprilic acid	Organic	16.3
Glycerin	Organic	17.9
Paraffin 18 carbons	Organic	28
p-Lattic acid	Organic	26
Methyl palmitate	Organic	29
Paraffin 19 carbons	Organic	32
Methyl eicosanate	Organic	45
Methyl fumarate	Organic	59.5
Diphenyl amine	Organic	102
$NaNO_3$	Inorganic	310
$NaNO_2$	Inorganic	282
$Na_2SO_4{\cdot}10H_2O$	Inorganic	32.4
KOH	Inorganic	360
NaCl	Inorganic	284
Zinc	Inorganic	420
KNO_3	Inorganic	337
Titanium	Inorganic	1500
$Na_2SiO_3{\cdot}5H_2O$	Inorganic	72.2
Silver	Inorganic	961.78

4.2.2 *Chemical Properties*

Chemical properties are the important due to their chemical reaction with different material and atmosphere condition. Among all such properties like non-corrosive, on-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 the vital factor for the thermal storage system. Also it is observed that the cost and availability of material should be Abundant and Cheap.

4.3 Applications of PCMs

PCMs help in storage of thermal energy, solar cooking, cold energy battery, ice storage i.e. conditioning of buildings, keeping the heat and electrical engines cool also in Medical such as blood transportation, hot-cold therapies[15]. They can be applicable in spacecraft thermal systems, protection of electrical devices from heat, Computer cooling, turbine inlet chilling with thermal energy storage, Shelter for telecom in various tropical regions[16]. Figure 7 shows comparison of rock water and reinforce concrete cement storage capacity.

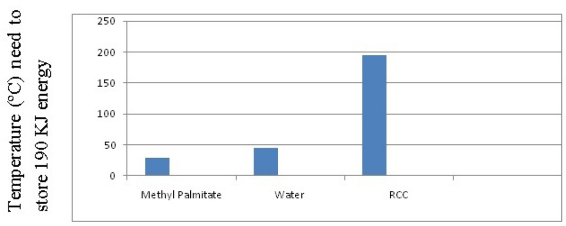

Figure 7. Comparison for Storage of Energy in Different Mediums.

Here an example is shown of capacity of storage of 190KJ of energy at different temperature of different material. Here Methyl palmitate is taken as base material. Methyl palmitate stores 190 KJ of energy at 29°C, water stores same amount energy at about 50°C and RCC store 190KJ energy at 190°C. So by the given graph it is clear that PCMs stores the energy at very low temperature in compare to other materials. PCMs are very efficient in storage of energy.

5. 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[17]. 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[18]. 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 are 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[17]. 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[18]. In this method PCM were placed in a protective coating. System was also known as phase change slurry (PCS). Figure 8 shows the micro-encapsulation.

Figure 8. Micro-Encapsulation Wall.

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[19]. Molecular encapsulation is shown in Figure 9.

Figure 9. Molecular-Encapsulation.

AS PCMs gives best efficiency in small containers, so they are generally divided into cells. The material of packing should be good conductor of heat. Also it should strong enough to accept changes to storage material's volume as phase changes. Materials should not dry out[20]. The packaging must be corrosion and leakage resistance. Stainless steel, polypropylene and polyolefin are common packaging materials which has chemical compatibility with room temperature.

6. Conclusion

Many observations show the importance of the PCMs in different application for heating and cooling. Among the all application, a major focus on the heating and cooling of the building through PCMs based thermal storage technology is required. Technology has potential to fulfil the energy requirement of the building during the peak load and save the energy. Basically active and passive systems are used for replacement of conventional energy system. It was observed that the less thermal storage, leakages, thermal stability and required special designs for manufacturing are the limitations of the passive system and it can be achieved by the active system. Furthermore unique features of the thermal energy storage active systems play important role in space heating, replacing convectional energy system and improving efficiency of the systems during the peak load. Significantly, this review explores the environmental aspects for installed system for building. Moreover, this study highlighted the cost effectiveness and other factors like compactness of the system, development of material etc. The relationship of PCMs for building cooling application with mechanical cooling must be developed in near future.

An overall finding of this review is amalgamation of the PCM based thermal storage systems have great potential to replace energy consumed systems and provides the efficient energy conservative system. Also such systems can replace the mechanical based system and provides free cooling thermal comfort for building during peak load.

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