CHAPTER 1

INTRODUCTION

This chapter establishes the framework of the study conducted. It addresses the current scenario of energy use in buildings and important factors that enhances the energy efficiency use in buildings. In detail, it discusses about various methods of thermal energy storage which are helpful in improving the indoor thermal behavior of the building and consequently promotes the energy efficiency use in buildings. It also discusses about Phase Change Material (PCM) and its potential in improving latent heat storage capacity of the building envelope. Additionally, various methods of incorporation of PCM in the building envelope or in the building element were described. Lastly, principal of PCM operations when embedded in the building envelope was presented. The chapter is divided into five different sections. Section 1.1 is background study, section 1.2 is Thermal Energy Storage (TES), section 1.3 is Phase Change Material (PCM), section 1.4 contains methods of incorporation of PCM and section 1.5 shows principal of operation of PCM when embedded in the building envelope.

1.1 BACKGROUND

One of the most significant challenge faced by the mankind in the 21st century is global warming. Green house gas emissions from the use of fossil based fuel are the main cause of global warming. Unfortunately, buildings (commercial and residential) have played a major role in further deepening the crisis of global warming. More than one third of the final energy consumption comes from building sector, as shown in Figure 1.1, and are equally responsible for direct and indirect energy related CO_2 emissions (1). In some regions/countries which are highly dependent on traditional biomass, energy use in buildings represents as much as 80% of the total final energy use (2). The shift in global fuel use in buildings is partially due to changing end-use consumption, with space cooling and electrical appliance energy growth leading electricity demand growth in buildings. Electricity share in final energy use in buildings is 31% and because of economic development, improvement in living standard and increase in the population, the demand of electricity is projected to increase to 70% by 2050 in the building sector (3).

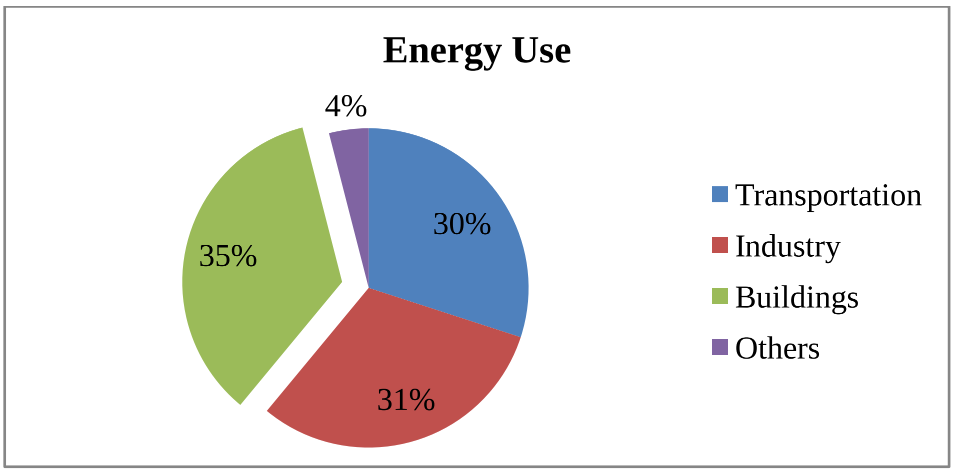

Figure 1.1 Final energy consumption by sector (2)

The end uses of the energy in the buildings are in different forms like, lightening, space heating and cooling, appliances, and etc as shown in Figure 1.2 for a residential and commercial building in USA. Among these, end use of energy for space cooling is growing at faster pace than any other end use of energy in buildings. Space cooling energy use increased globally by more than 20% between 2010 and 2017, while appliance electricity demand grew by 18% and space heating decreased by around 4%. Space cooling and appliances and other plug loads are the fastest-growing building end uses; however, only space cooling has grown in energy intensity per unit floor area.

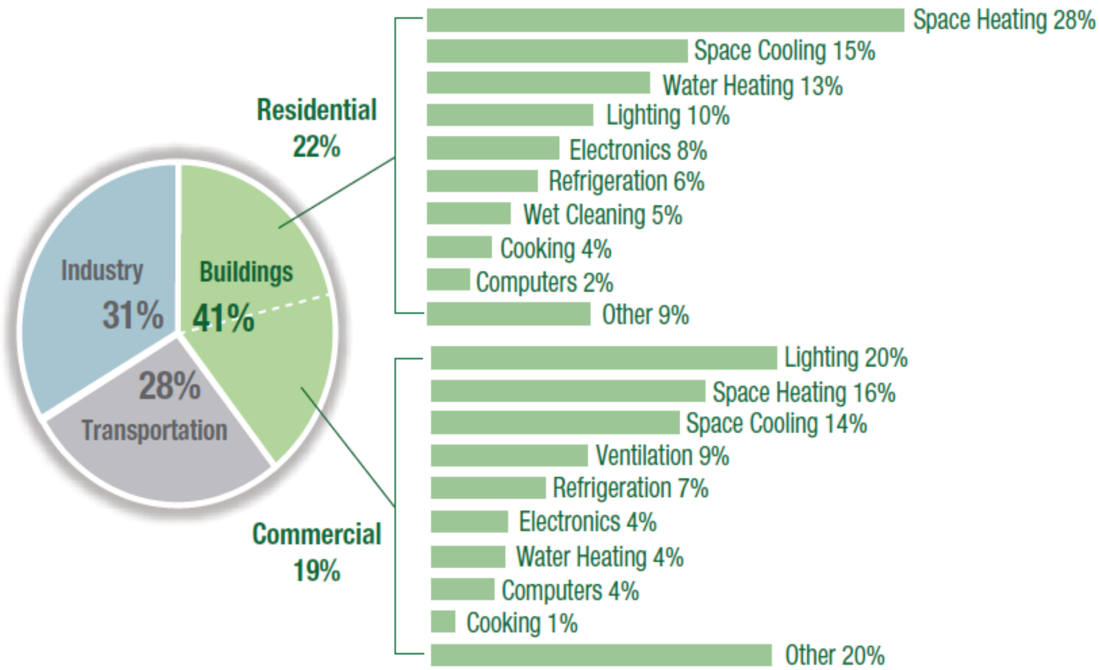

Figure 1.2 Primary energy use in US residential and commercial buildings in 2010 (4)

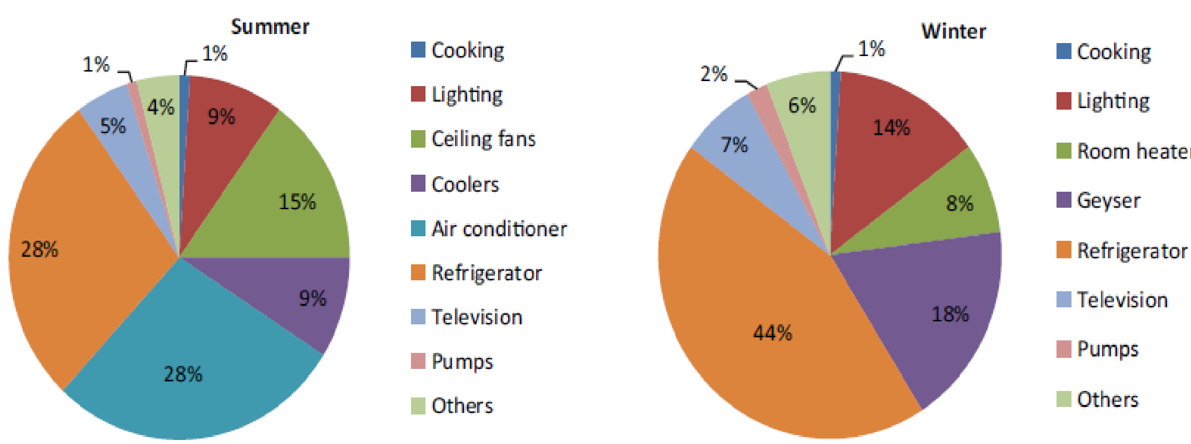

Figure 1.3 Share of end-uses (by appliances) in electricity consumption in Delhi (4)

The demand for space cooling become more intensive in countries having hot and humid climate or/and the countries lying in equatorial/tropical environment as shown in Figure 1.3 at Delhi, India. From 1990 to 2016, the final energy use for space cooling in buildings has been tripled to 2020 TWh. In 2016, space cooling shares 18.5% of the total electricity consumption of the buildings (5). Furthermore, during the period of extreme heat, space cooling may share a large peak demand, which creates an additional stress on power system. Space cooling demand generally rises during extreme weather conditions like sudden rise in temperature or during heat waves.

Building envelope, which includes walls, roofs, floor, façade, windows, and doors, plays an important role on the need for the space cooling (6). An energy efficient building envelope reduces the need of space cooling by regulating the indoor thermal profile of the building. Energy-efficient design of the building envelope not only improves the indoor thermal behavior of the building but it also increases the utilization of renewable sources of energy like solar energy, wind, etc. However, the use of renewable source of energy depends on the availability of that source in that particular region. Talking about availability, solar energy is the most abundant, cheaper, easier, and cleaner source of renewable energy available on the planet (7). Tropical countries like India receive solar radiation almost throughout the year (8). This enormous amount of solar radiation can be used for various applications (9). Additionally, it has enormous potential for space cooling and heating. Although, the energy from the sun comes with many advantages it also carries some limitations like intermittent nature and instability. Also, it is limited to time and space. These problems can be resolved by storing the thermal energy of solar radiation during the day and then releasing and utilizing the same energy during the night.

A building envelope provides physical resistances to the outside heat by not allowing it to penetrate inside and thus reduces the utilization rate of the Heating, Ventilation and Air-conditioning (HVAC) systems, consequently minimizes the energy consumption for space cooling. The physical resistances are the construction/building materials used to develop building structure like bricks, wallboards, concrete blocks, cement plaster, gypsum board, wood, etc. The amount of resistance provided, depends on the thermal mass of the building envelope. The thermal mass of the building envelope plays an important role in quantifying the amount of energy required for space cooling and heating. The thermal mass is the term used to describe the ability of the building material to store heat, or thermal energy storage capacity. The basic characteristic of material with thermal mass is their ability to absorb, store, and release the thermal energy and therefore, they regulates the indoor thermal behavior of the building. If a building have high thermal mass then that thermal mass will definitely stores more thermal energy. Thus, a building to have high thermal energy storage capacity must have high thermal mass or vice-versa. High thermal energy storage capacity of the building envelope will effectively improve the ability of absorbing, storing and releasing the heat which consequently improves the indoor thermal profile of the building. High thermal energy storage (TES) capacity of the buildings can improve the indoor temperature swings (10), shifting of peak cooling and heating loads to the non-peak hours or low tariff hour (11), and maintaining the temperature closure to the comfort value for a longer duration (12).

1.2 Thermal energy storage in buildings

Thermal energy storage is a technique of storing an excessive amount of thermal energy in material and utilizing it whenever required for heating and cooling (13). TES increases the efficiency of thermal energy whenever there is any mismatch between the use and energy generation in terms of time, temperature, location, and power (14). A TES process occurs in three steps i.e. charging, storing, and then discharging as shown in Figure 1.4.

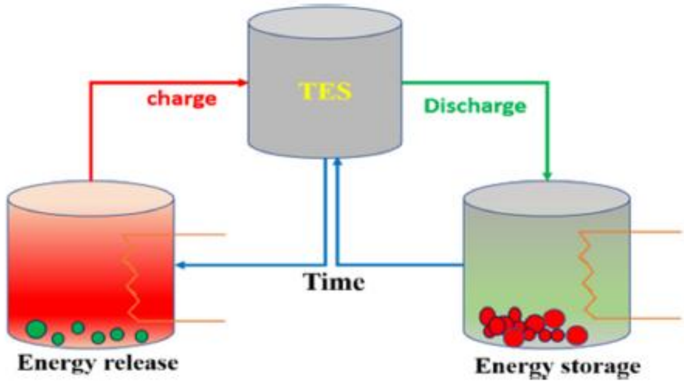

Figure 1.4 Three steps of thermal energy storage (15)

The effectiveness of these three steps depends on the thermo-physical properties of the storage medium. In recent years, researchers have shown a great interest in TES in buildings. TES in buildings improves the building energy efficiency by increasing the share of renewable energy use and reducing energy use for heating and cooling (16). In general, the TES techniques are classified as (17):

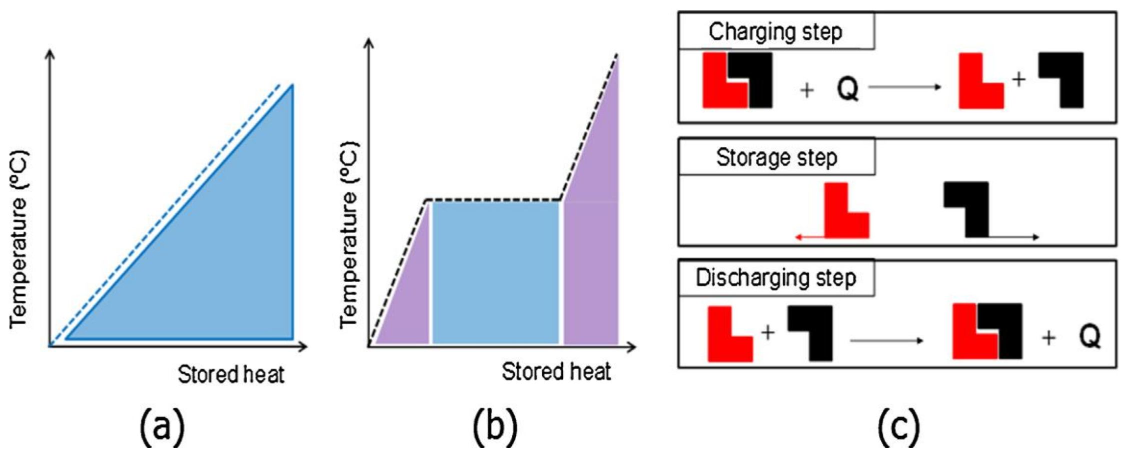

Figure 1.5 Thermal energy storage methods (a) Sensible energy storage (b) Latent energy storage (c) Thermo-chemical energy storage (17)

1.2.1 Sensible thermal energy storage

It is the simplest and easiest form of heat storage technology as shown in the Figure 1.5 (a). The material which stores thermal energy in sensible form does not undergo phase change over the specified temperature limit. For e.g. adding heat to the water may either increase its temperature or change its phase. So, the heat energy required only to increase its temperature without changing its phase is called sensible heat of the water. The sensible heat can be evaluated by using the below-given relation:

$$Q = mc_p\Delta T \qquad [1.1]$$

Where Q (J) is the heat, m (kg) is the mass of the material, C_p (J/kgK) is the specific heat of the material, and ΔT (K) is the change in the temperature of the material in the expression [1.1].

Table 1.1 Potential sensible thermal energy storage material for building application (17–20)

Material	Type	Temperature range (˚C)	Density (ρ in kg/m^3)	Specific heat (kJ/kgK)	Thermal conductivity (W/mK)
Water	Liquid	0-100	1000	4.19	0.608
Steel	Solid	20-70	7800	0.502	16.3-18
Reinforced concrete	Solid	20-70	2500	1020	-
Granite	Solid	20-70	2650	0.900	1.73-3.98
Plain concrete	Solid	20-70	2100	1020	0.92
Brick	Solid	20-70	1600	0.84	0.15-0.6
Wood	Solid	-	800	2.093	0.04-0.17
Gypsum board	Solid	-	750	1060	0.17
Sandstone	Solid	Up to 160	2200	0.71	2.327
Granite stone	Solid	Up to 160	2640	0.82	2.12-3.12
Glass	Solid	-	2710	827	0.8-1.4
Iron	Solid	Up to 160	7900	452	80.3
Fiber board	Solid	-	300	1	0.3
Aluminium	Solid	Up to 160	2707	0.896	237
Oil	Liquid	12-260	888	1.88	0.14
Clay or Silt	Solid	-	1200-1800	1.2-2.65	1.5
Cement mortar	Solid	-	1800	1	1

Limestone	Solid	-	1600-2600	1	0.85-2.3
Asphalt sheet	Solid	-	2300	1.7	1.2

- n.a (not available)

The sensible heat of the material depends upon the mass and the specific heat of the object (21). Sensible heat storage can be achieved either by a liquid storage medium or by solid storage medium (22). Moreover, in buildings, this type of thermal energy storage technique suffers from a major drawback of low energy density, which makes this technique unsuitable for the large amount of heat storage and for the longer duration. Commonly used material for sensible heat storage in buildings is listed in Table 1.1.

1.2.2 Latent heat energy storage

Latent heat energy storage (LHES) allows a material to store the heat by changing its phase (Solid-liquid, liquid to vapor and solid to gas) at an almost constant temperature as shown in the Figure 1.5 (b) (23). This increases the energy density storage capacity of the phase change material (PCM) within a small temperature range. In buildings, the solid-liquid phase change is extensively used to improve the LHES capacity (24). The amount of heat energy stored in the material depends upon enthalpy of fusion and specific heat and is given as (25):

$$Q= \int_{T1}^{Tm} mC_{pi}dT + ma_m\Delta h_m + \int_{Tm}^{Tf} mC_{ps}dT \quad [1.2]$$

Where, m= Mass of the PCM (kg)

C_{pi}= Average specific heat of the material between the temperature range T_1 and T_m (kJ/kgk)

C_{ps}= Average specific heat of the PCM between temperature range T_m and T_f (kJ/kgK)

T= Temperature of the PCM

a_m= melt fraction of the PCM

Δh_m= Enthalpy of fusion of the material (kJ/kg)

LHES of the PCM offers various advantages like (26,27), (a) Energy can be stored and can be retrieved as per the requirement/application (b) PCM stores 5-14 time more heat per unit volume (c) Phase transition of the PCM occurs nearly at constant temperature (d) Easy availability of PCM for wide range of temperature applications (-10 ˚C to 300 ˚C). Because of these advantage PCM have been extensively used for the thermal energy storage in varieties of applications like in photovoltaics (28), electronic components (29), automotive applications (30), water heating (31), textiles (32) and many more.

When PCM is incorporated in the building envelope the LHES capacity of the building will increase significantly. Now, when the temperature rises because of the increase in solar radiation intensity the incorporated PCM will start melting and phase transition from solid to liquid occurs. During this phase transition, a large amount of thermal energy is stored in the PCM. As the temperature decreases during the night, PCM releases its energy to the surrounding and again changes its phase from liquid to solid. The process looks simple, but complexity arises when it comes to integration of PCM in building material. Since PCM has repeatedly changed their phase from solid to liquid and from liquid to solid it is, therefore, difficult to directly incorporate them into the building materials. This complexity also includes various design parameters like phase change temperature of PCM, quantity, and the location of the thermal energy storage system within the building.

1.2.3 Thermochemical energy storage

Thermochemical energy storage is quite a new method and is under research and development phase at various levels (33). In this technique, the energy is stored and released in the form of chemical reaction and is generally classified under heat storage process as shown in the Figure 1.5 (c). The thermochemical material, used to store thermochemical energy storage, undergoes either a physical reversible process involving two substances or a reversible chemical reaction as given in expression (1.3).

$$AB + Q \longleftrightarrow A + B \qquad [1.3]$$

Where Q is the amount of heat required to dissociate A and B. The dissociation of AB, which results in the formation of A and B is an endothermic reaction, while reversible of this chemical reaction is an exothermic reaction (34). Hence, during the forward reaction the energy is stored and during backward the energy is released which can be used for various applications.

This technique of energy storage has gained popularity because of higher energy density and lower heat losses. However, there are various bottlenecks which limit the application of this technology in buildings like, unsuitable operating condition (i.e. too high charging condition), corrosiveness, environmentally-unfriendly production, chemical instability and high cost.

1.3 Phase Change Material

1.3.1 Types of PCM

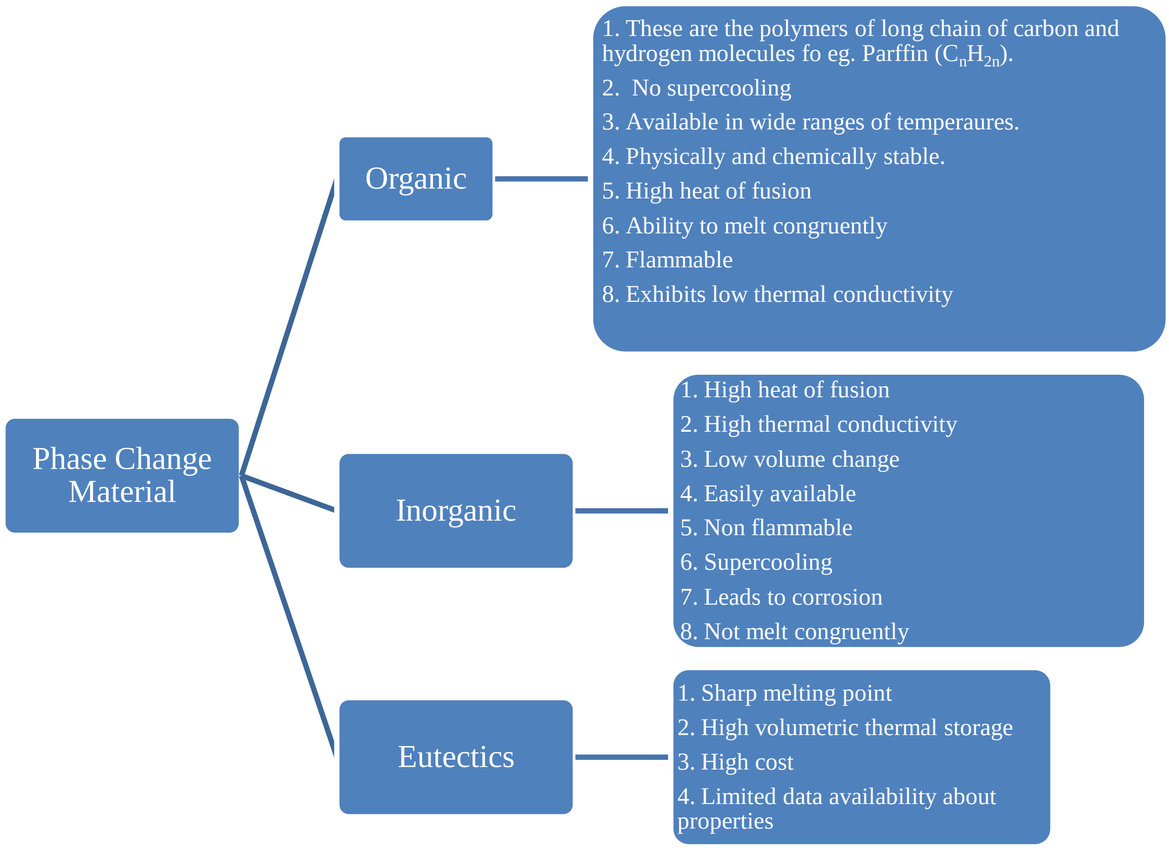

Figure 1.6 Classification and properties of PCM (35)

Phase change materials are available abundantly in various forms in the market for various thermal energy storage applications. In general, the PCMs are classified in three categories as shown in the Figure 1.6. The selection of the PCM depends upon the type of application, for example, applications like indoor space cooling and space heating requires low-temperature thermal energy storage (≤50°C) whereas electrical power generation system requires high thermal energy storage system (≥150°C). The use of PCM in buildings for energy savings has been studied by many researchers, but still, there is no such single PCM is available which can be compatible for all building environmental conditions.

1.3.2 Thermo-physical properties of PCM

In recent years a lot of research has been done on enhancing the thermal properties of the PCM in order to make them compatible for the application of thermal energy storage in buildings. In general, the selection of the PCM must be done on the basis of the ambient environmental condition and the type of building envelope. A comprehensive list of PCM, along with some thermal properties is shown in Table 1.2, which can be incorporated in the building envelope for energy savings. The selection of suitable PCM is a critical issue because it is not possible to have all the desired properties in one PCM. Therefore, the selection of PCM requires a certain degree of compromise with certain properties and therefore, it should be done very carefully.

The selection criterion of the PCM, for the TES in buildings, strictly depends upon the thermal, physical, and chemical properties of the PCM. As stated above, out of the numerous available PCM in the market, the PCM, which is helpful in fulfilling the following purposes after getting incorporated in the building must be used: (a) It must maintain the indoor temperature under thermal comfort range (b) Helpful in shifting the peak load to the off-peak hours (c) It must reduce the overall energy demand for space cooling. Below are some important characteristics that PCM should have before using it in the building envelope.

1. Melting temperature: The PCM must have solid-liquid and liquid-solid phase transition temperature near the required operational temperature range.
2. Phase change enthalpy: The PCM should have a very high enthalpy of fusion (≥200 kJ/kg). High phase change enthalpy improves the energy storage density of the system.

3. Specific heat capacity: The specific heat capacity of the PCM should as high as possible. In general, it should be more than 2.5 kJ/kg K.
4. Thermal conductivity: High thermal conductivity (≥0.6 W/m°C) in both the phases for the PCM is desired. This will enhance the thermal charging and discharging rate.
5. Thermal cycles: The thermal cycle is referred as, one complete thermal charging and subsequent complete discharging of the PCM. The PCM must be capable of undergoing more than 5000 thermal cycles.
6. Supercooling: The PCM should not undergo supercooling. Supercooling refers to a liquid existing below its normal melting temperature, i.e. the PCM does not solidify completely below the freezing point. This property will reduce the withdrawal of the heat during freezing.
7. Change in volume: During the phase change, i.e. solid-liquid and liquid-solid, the PCM should undergo a minimal change in volume. A large change in volume will increase the size of the container.
8. Congruent melting: Congruent melting ensures that the PCM must melt and freeze completely so that there is homogeneity in solid phase as well as in liquid phase. Non-congruent melting will lead to segregation because of differences in the densities of solid and liquid phases.
9. Vapor pressure: The PCM must have a low vapor pressure in the operating temperature range to avoid containment problems.
10. Non-corrosive: The PCM must be non-corrosive and non-toxic to the surrounding.
11. Economic and availability: The PCM must be available on a large scale and at a cheap price.

12. Nonflammable: Due to its direct application in buildings the PCM must be non-flammable to avoid any danger of fire.

Table 1.2 List of PCM which can be used in buildings for improving energy efficiency

PCM	Type	Thermal Conductivity (W/mK)	Melting Temperature (° C)	Heat of fusion (kJ/kgK)	Ref.
Coconut oil/xGnp	Organic	1.33	26.93	82.34	(36)
Palm oil/xGnP	Organic	1.268	18.33	77.18	(36)
Xylitol pentastearate	Organic	-	32.35	205.65	(37)
Xylitol pentapalmitate	Organic	-	18.75	170.05	(37)
n-Octadecane	Organic	0.26	28.0	256.5	(38)
n-Hexadecane	Organic	0.668	18.65	232.41	(39)
Pure paraffin	Organic	0.356	54.38	142.72	(39)
n-Heptadecane	Organic	0.39	22.32	228.89	(40)
Dodecanol	Organic		23.44	205.88	(40)
Hydrogenated palm kernel vegitable fat	Organic	0.2	26.53	74.35	(41)
$Na_2SO_4 \cdot 10H_2O$-$Na_2CO_3 \cdot 10H_2O$ salt hydrate	Inorganic	-	25.41	195.3	(42)
PEG1000 (45 wt%)/HNT@Ag-1	Organic	0.73	35.2	72.5	(43)
PEG1000 (45 wt%)/HNT@Ag-3	Organic	0.90	33.6	71.3	(43)
Dodecanol/diatomite	Organic	0.15	23.3-29.5	75.8	(44)
$CaCl_2 \cdot 6H_2O$-$MgCl_2 \cdot 6H_2O$(10-25 wt %)	Inorganic	0.732	20.2-24.5	130.3-162.1	(45)
$CaCl_2 \cdot 6H_2O$-8wt% $Mg(NO_3)_2 \cdot 6H_2O$ /EG	Eutectics	5.5	21.17-27.87	105.4	(46)
Paraffin (RT27)/ hydrophobic expanded Perlite/ GnP	Organic	0.5	24.50-26.95	79.35	(47)
Silica fume/Capric acid-Palmitic acid/CNT (1-5 wt%)	Eutectics	0.35-0.47	22.78-24.18	48.19-46.21	(48)
Neopentylglycol/Cuo(0.1 wt%)	Organic	-	40.22	104	(49)
Capric acid/Steric acid/White carbn black	Eutectics	0.38	24.89	78.74	(50)
Paraffin/expanded perlite	Organic	-	27.60	67.13	(51)
$CaCl_2 \cdot 6H_2O$ -	Inorganic	-	35.2	207.9–	(52)

$SrCl_2 \cdot 6H_2O$/ Graphene oxide				206.44	
Lauric acid (40-80 wt%)/Asphalt (60-20 wt%)	Organic	-	31.81-38.65	50.14-128.1	(53)
Methyl cinnamate/ Cu-TiO_2 (0.05-0.5 wt%)	Organic	0.212-0.323	35.59-35.45	108.2-101.3	(54)
Capric acid (75 wt%)/myristic acid (25 wt%)	Eutectics	-	22.17	153.19	(55)
n-octadecane/Diatomite/ carbon nanoparticle	Organic	0.73	27.21	134.3	(56)
Capric/palmitic/stearic acid/ Nano-SiO_2	Eutectics	0.082	21.86	99.43	(57)
Lauric-myristic-stearic acid/ Al_2O_3/EV	Eutectics	0.671	28.6	113.17	(58)
$Na_2CO_3.10H_2O$ to $Na_2HPO_4.12H_2O$ (40:60)	Eutectics	-	27.3	220.2	(59)
$KF.4H_2O$	Inorganic	-	18.5	231	(60)
$Mn(NO_3)_2.6H_2O$	Inorganic	-	25.8	125.9	(60)
Polyethylene glycol /expanded perlite	Organic	0.47	55.19	134.93	(61)
Butyl stearate	Organic	-	19	140	(62)
Lactic acid	Organic	-	26	184	(62)
$LiNO_3$ -$3H_2O$	Inorganic	-	30	189	(1)

1.4 Techniques of Incorporation of PCM in the building

To enhance the heat storage capacity of the building envelope, PCM must be incorporated in the construction material suitably. Incorporation method must ensure minimum or no leakage during phase transition along with maximum utilization of latent heat storage capacity of the PCM. Figure 1.7 depicts various methods that have been developed by researchers for incorporating the PCM in the building envelope. The PCM can be incorporated in the building envelope either through direct incorporation techniques or through indirect incorporation techniques. Direct incorporation technique is the simplest and economical method in which PCM is directly mixed with the construction materials like cement, concrete, wallboards during production (63). Direct incorporation of PCM was carried out by two methods: wet mixing and immersion. In wet mixing technique the PCM is directly mixed with the construction material, e.g. concrete, mortar, cement, at the production site. Mixing PCM directly will enhance the thermal energy storage capacity of the building material several fold.

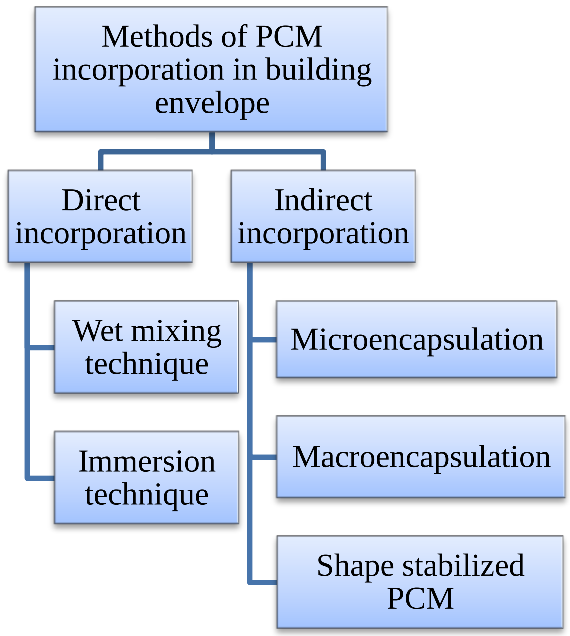

Figure 1.7 Incorporation methods of PCM in building envelope

The successful application of this technique depends on the following two factors: the PCM must not interfere the hydration process and must not react with any component of the mix (64). In immersion technique, the porous construction elements (concrete block, gypsum wallboard, porous aggregate, etc.) are dipped in a container filled with liquid PCM. The construction element absorbs the PCM through capillary action. The effectiveness and the time required to fully soaked into the porous construction element depends on: absorption capacity of the concrete, the temperature and the type of PCM employed (65). These two methods of direct incorporation of PCM in the building material suffered with various critical demerits (66) (67). Some of which are: (a) Leakage of PCM may interfere with the hydration process (b) Loss of PCM may occur due to leakage after large number of heating-cooling thermal cycles (c) immersion process takes more hours (almost 4-8 hours) (d) wet mixing may affects the mechanical strength of the construction element. Another method of integrating the PCM in the building envelope is indirect incorporation. In this technique, initially the PCM was encapsulated before being integrated into the building element. Encapsulating the PCM with suitable coating or shell material will have the following benefits (68): (a) Reduced the leakage and loss of the PCM (b) enhances the heat transfer rate because of increase in surface area (c) increased structural stability and ease in handling (d) act as a barrier to protect the PCM to come in direct contact with the surrounding environment (e) meets the requirement of strength and durability (f) enhances the thermal reliability. Because of these merits, a detailed literature review of all types of indirect incorporation technique of PCM incorporation in building envelope was presented in the next chapter.

1.5 Operating principle of PCM in buildings

The use of PCM inside building envelopes (both walls and roofs) increases the heat storage capacity of the building and might improve its energy efficiency and hence reduce the electrical energy consumption for space heating and cooling. Figure 1.8 shows the principle of working of the PCM when embedded in the building element. In summer, during daytime the sunshine and high temperatures result in a heat wave penetrating the walls of the buildings. PCM absorbs the excess heat through melting process, delaying the heat wave inside the building, and even reducing the peak. During most of the day the room temperature remains comfortable and the cooling system consumes less energy. During night time, when temperatures are lower, the PCM releases the stored heat to both the internal and external ambient, keeping again the room temperature comfortable and closing the cycle by solidifying. The essential difference between PCMs and more traditional thermal mass is that: while masonry absorbs and releases heat slowly, PCMs absorb and release heat quickly. This makes them tremendously useful in buildings where traditional passive design techniques cannot be easily applied, such as lightweight construction. Having said this, a PCM will only be useful if it is appropriately designed into any building. Like all the best sustainability solutions, many PCMs are also long-lasting, with no loss of performance over time.

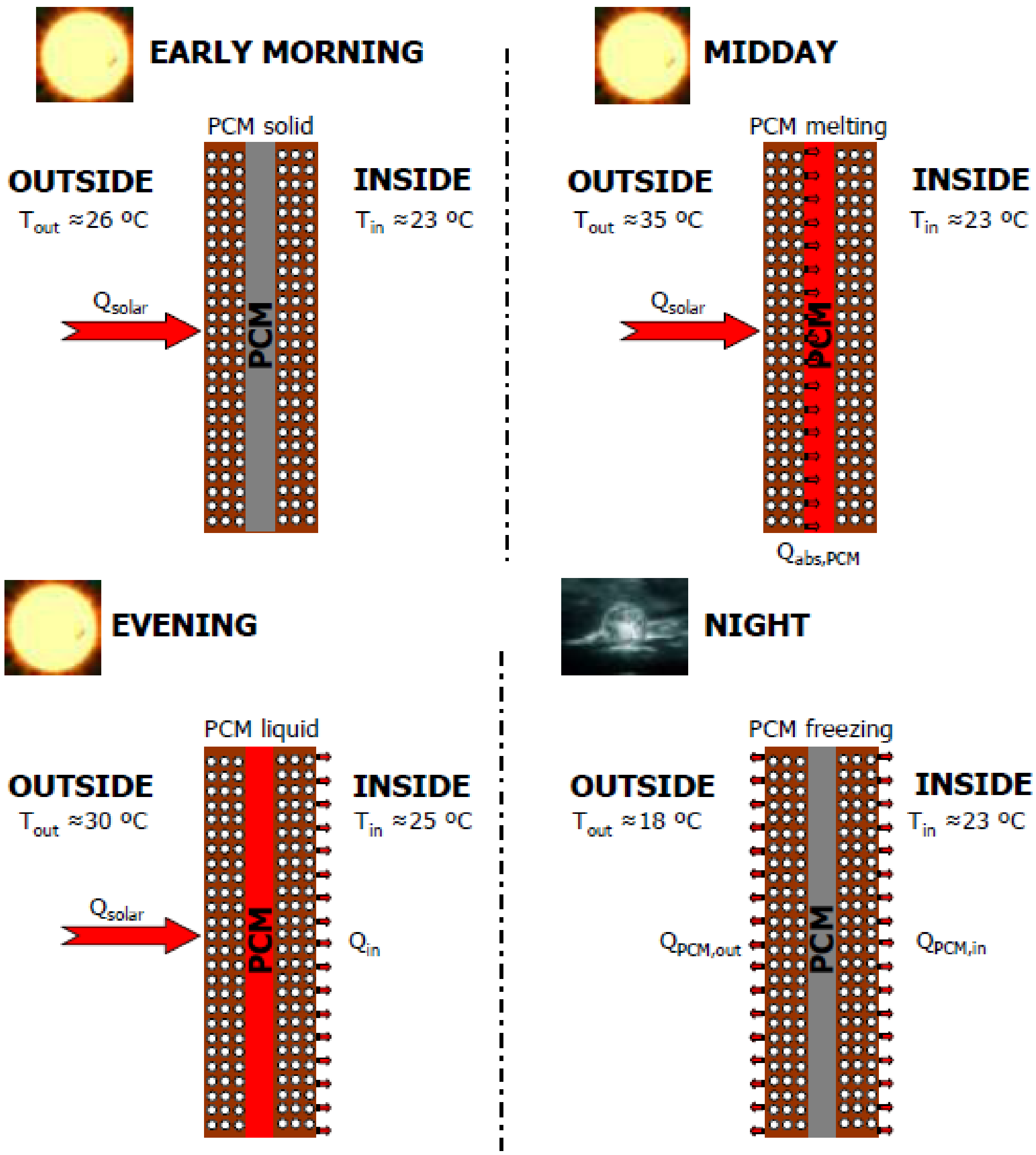

Figure 1.8 Operating principle scheme of the PCM