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Khaireldin Faraj, Mahmoud Khaled, Jalal Faraj, Farouk Hachem, Cathy Castelain. Phase change material thermal energy storage systems for cooling applications in buildings: A review. *Renewable and Sustainable Energy Reviews*, 2019, pp.109579. 10.1016/j.rser.2019.109579 . hal-02384617

**HAL Id: hal-02384617**

**<https://nantes-universite.hal.science/hal-02384617>**

Submitted on 27 Nov 2020

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# Phase Change Material Thermal Energy Storage Systems for Cooling Applications in Buildings: A Review

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## Abstract

Sharing of renewable energy and reduction of conventional energy consumption as an attempt to ameliorate environmental issues such as global warming has become the main concern for current developing scientific engineering research. Moreover, with the drastic increase in cooling and heating requirements in the building sector worldwide, the need for suitable technology that enables improvement in thermal performance of buildings is addressed. Utilizing phase change materials (PCMs) for thermal energy storage strategies in buildings can meet the potential thermal comfort requirements when selected properly. The current research article presents an overview of different PCM cooling applications in buildings. The reviewed applications are classified into active and passive systems. A summary of the used PCMs and their respective properties are presented as well. Primary results of the studied systems are demonstrated to be efficient in reducing indoor temperature fluctuations and energy demand during cold seasons along with the capability of triggering load reduction or shifting.

## Highlights

- *A state-of-the-art review on cooling applications of PCM in buildings*
- *Cooling PCM applications are classified as active and passive systems*
- *PCM serves as a promising technology for energy-efficient buildings*
- *Combining active and passive systems can be a potential step toward NZEB*

*Keywords:* PCM, latent heat, cooling, thermal energy storage, building.

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Word Count = 7136

## 1. Introduction

The world population and economy are growing rapidly that has led to massive increase in the world's energy demand and consumption, thereby playing a huge role in triggering severe environmental impacts [1]–[8]. According to the data published by Eurostat, European Union member states have seen a remarkable increase in their final energy demand that reached approximately 1084 million tons of oil equivalent (Mtoe) in 2015, of which 422 Mtoe corresponded to building-related sectors that is equivalent to 39% of the total demand [9]. The building sector, being the largest energy-consuming sector, accounts for over 33.33% of final energy consumption on a global basis and is considered an equally important source of CO<sub>2</sub> emission [10]. Furthermore, it was detected that half of the energy consumption in buildings is caused by heating, ventilating, and air-conditioning (HVAC) systems [11]; in another research it was stated that the value is 60% [12]. The trend of cooling demand shows a massive increase from 0.8 EJ in 2010 to an expected 5.8 EJ in 2050 for Asia, Latin America, India, and China. Whereas in China, an expected increase in the cooling demand will reach a value equal to that reached by Latin America and Asia by 2040 [13]. For this purpose, researchers and policy makers are promoting new policies

<b>Abbreviations</b>			
AAC	<i>Autoclaved aerated concrete</i>	LHTES	<i>Latent heat thermal energy storage</i>
AC	<i>Air conditioning</i>	NP-Gyp	<i>Nano-PCM enhanced gypsum boards</i>
CABS	<i>Climate adaptive building shells</i>	NZEB	<i>Net Zero Energy Building</i>
CFD	<i>Computational fluid dynamics</i>	PCM	<i>Phase Change Material</i>
COP	<i>Coefficient of performance</i>	PCMW	<i>Phase change material wallboard</i>
DEU	<i>Direct evaporative unit</i>	PV	<i>Photovoltaic</i>
DHW	<i>Domestic hot water</i>	SBS	<i>Styrene-butyl-styrene</i>
DSC	<i>Differential scanning calorimetry</i>	SSPCM	<i>Shape stabilized phase change material</i>
DSF	<i>Double skin façade</i>	TABS	<i>Thermally activated building structure</i>
DW	<i>Double pane window</i>	TCM	<i>Thermochemical material</i>
GSHP	<i>Ground source heat pump</i>	TES	<i>Thermal Energy Storage</i>
HDPE	<i>High density polyethylene</i>	TW	<i>Triple Pane Window</i>
HVAC	<i>Heating, ventilating, and air conditioning</i>		
<b>Units</b>			
Temperature	°C	Conductivity	W/m.K
Enthalpy	kJ/kg	Specific Heat	kJ/kg.K
Energy	EJ ( <i>exajoule</i> )		

toward more sustainable and energy-efficient buildings, seeking potential solutions to ameliorate energy conservation and energy storage as an attempt to deter the crisis of global warming.

Developing a novel technology to promote energy efficiency and conservation in buildings has been a major issue among governments and societies whose aim is to reduce energy consumption without affecting thermal comfort under varying weather conditions [14]. The integration of thermal energy storage (TES) technologies in buildings contribute toward the reduction of peak loads, uncoupling of energy demand from its availability, allowing the integration of renewable energy sources, and providing efficient management of thermal energy, thus leading to the improvement of energy efficiency in buildings [9]. Latent heat TES using phase change materials (PCMs) have gained extensive attention in building applications owing to their high energy storage density capabilities and their ability to store thermal energy in a constant temperature phase transition process [15]. An extensive TES technique related to cooling improvement by reducing the energy demand in building sectors is the application of PCMs, which have received much attention and have become a topic of great interest among architects and engineers over the past four decades [16]. PCMs, used in latent heat thermal energy storage strategies, are able to fill the gap between energy supply and demand by absorbing excess energy in buildings, thereby making it a promising technology [1]. Presently, the utilization of PCMs covers several fields including applications requiring a wide temperature range from -20°C to 200°C for heating, cooling, and hybrid mixing of heating and cooling [1].

### *1.1 Summary of recent review articles on PCMs and their applications in buildings*

Applications of PCM may include any of the following energy-dependent fields: solar energy, industrial heat recovery, electrical power peaking regulation, textiles, healthcare, liquefied natural gas, green house agriculture, buildings, and aerospace [17]. Reviewers all over the world have studied the feasibility of PCMs, their applications, and their utilization in buildings for heating and cooling purposes.

Akeiber et al. [12] reviewed PCM sustainable passive methods for cooling applications in building envelopes. The study offered a summary for the organic, inorganic, and eutectic PCMs suitable for cooling purposes. Passive methods of PCMs integrated in building envelopes included four main applications: Walls, roofs, floors, and windows. Literature studied showed that the combination of full-scale experimental investigation and numerical modeling gives a promising detailed and valid methodology for PCM investigations. Further, it was shown that the dominant encapsulation method for passive cooling using PCM is known as macro-encapsulation. Saffari et al. [13] reviewed researches done using whole-building energy simulation software such as TRNSYS, EnergyPlus, and ESP-r, for the applications of PCMs in passive cooling of buildings. Climatic conditions, melting temperature of PCMs, and occupants' behavior were observed to be the main issues affecting the effectiveness of PCMs in cooling purposes. The authors assured the importance of the simulation of passive cooling systems using PCM as a single or multi-objective mathematical optimization problem with suitable models that require further investigation and study. Heier et al. [18] reviewed the literature on TES with focus on journals and review articles starting from the year 2000. Their study was focused on combining TES to buildings where they concluded that the use of PCM and thermochemical materials (TCM) for energy storage require more research owing to their reliability problems, especially subcooling, fire retardation, and low energy transfer rates with respect to PCMs and lack of material and system studies for TCM. Summarizing their work, Heier et al. classified TES into two categories: active and passive; and for each category, they coupled the relevant methods for different building types to conclude that for residential buildings relevant TES systems are sensible TES with water in tanks, domestic hot water (DHW), and solar combi systems, while for commercial buildings relevant TES borehole techniques and snow seasonal storages are the most relevant systems. Finally, they ensured that energy efficiency, economic and comfort aspects are essential for TES design and they recommended studies on real prototypes with combined TES that are not available. A review on PCM for cooling applications in buildings was conducted by Souayfane et al. [19]. Five main applications were discussed: Free cooling, solar cooling system with PCM, PCM air conditioning systems, evaporative and radiative cooling systems, and PCM in building envelopes with emphasis on active and passive systems as well as the principle of ventilated facades and its applications. The authors discussed the factors affecting the selection of PCMs and ended up concluding that: (1) PCM is capable of: decreasing energy consumption and temperature fluctuations, shifting the peak loads of cooling energy demands, and decreasing energy consumption while maintaining thermal comfort. (2) Many drawbacks have been found in PCM applications: lack in the usage of considerable portions of employed PCM owing to low convective heat transfer coefficient values (h-values), incomplete crystallization of PCM at night, and limited contact area between PCM and air. However, active systems can fix the issue of low h-values. It was also concluded that paraffin was mostly used in cooling applications for its high latent heat and suitable melting temperature, where the melting temperature is the most influential parameter. Alizadeh et al. [20] reviewed studies covering free cooling applications in residential and commercial buildings, focusing on the integration of thermal energy storage units containing PCMs, their enhancement techniques, and their technical, geographical, and economical aspects were taken into account as well. The authors concluded that all reviewed researches showed good potential for reducing the cooling load demands and improving thermal comfort whereby satisfying the hopes of residents. A thorough review on passive wall systems for thermal energy efficiency enhancement in buildings was prepared by Omrany [21]. The review covered the applications of several wall types of which two have the possibility for PCM integration from within: Trombe wall and double skin facades, with the others being autoclaved aerated concrete (AAC) walls and green walls. The authors terminated their review with future trends of building facades covering: intelligent facades, kinetic facades, biophilia designs, and climate adaptive building shells (CABS). Studied literature gave the authors the opportunity to state that the trends of buildings are promising in terms of achieving energy-efficient structures that nevertheless require researches to obtain generalized concepts and outcomes. A review on passive cooling potential in buildings under various climatic conditions in India was

conducted by Panchabikesan et al. [22]. The review article covered researches on evaporative cooling, nocturnal radiative cooling, and PCM-based free cooling applications in different regions of India. The major outcome was that for the five selected cities in India, the highest yearly average cooling potential is for hot and dry conditions, whereas, the lowest is referred to warm and humid climates. Kenisarin and Mahkamov [23] published a review paper concerned with utilizing PCM for passive thermal control in buildings. The study summarized the results of fifteen full-scale buildings integrated with PCM in their envelopes, and presented three reduced-scale laboratory models with their characteristics and investigations. Three main advantages were obtained from the researches on PCM embedded in building structures : (1) reduced stratification of room temperature, (2) shifting in cooling/heating loads by several hours, and (3) energy consumption reduction for attempting thermal comfort. Alva et al. [24] prepared an overview on the TES systems. The overview discussed the three classes of TES: sensible, latent, and chemical. Studied literature proved the outstanding role of TES systems for thermal storage in thermal electricity generation plants, and ensured that the main drawback in PCMs used as TES materials is the low thermal conductivity. TES systems were classified as passive and active systems based on the nature of the heat transfer occurring (i.e. if the driving force of the heat transfer was only the difference in temperature, then the system is a passive system, else it would be an active system). Another critical review on the usage of PCM as latent heat TES for buildings' free cooling was published by Zeinelabdein et al. [25]. The authors summarized the recent work done in the field of passive cooling and its most substantial affecting parameters. They found that all reviewed literature showed the ability of PCM passive cooling strategies in sustaining thermal comfort in buildings and decreasing the cooling load. The findings of the review presented a clear assessment for potential enhancement of PCMs used in passive cooling. A specialized review concerning inorganic PCMs used for TES systems and their challenges was conducted by Mohamed et al. [26]. The authors focused on the improvement techniques for overcoming the drawbacks of inorganics such as phase separation and corrosion potential. The study further discussed long term stability, performance of thermal cycling, and heat transfer enhancement for this class of PCMs. Several other review articles that focused on phase change materials and their utilization in buildings for cooling applications, like Oropeza-Perez and Østergaard [27] who published a review article on active and passive cooling in dwellings, Monghasemi et al. [28] who reviewed studies on the integration of solar chimney for heating and cooling in buildings, and Khan et al. [29] who prepared a review on the usage of PCM in solar absorption refrigeration systems. Other PCM topics studied are: Heating and cooling air-PCM-TES [30], studies for specified climatic conditions [31]–[33], measurement methods, specific classes, encapsulation methods, and nanoPCMs [24], [34]–[36].

All reviewed articles illustrate PCM-TES systems as a promising evolving technology for buildings, and ensure the importance of future work in optimizing the best adapted PCMs in each zone in the world toward sustaining buildings and improving their thermal efficiency. Summarized review articles are either generalized for several applications of PCMs, or narrowed within a specified application, classification, method, among others. The purpose of the current review article is to present the cooling applications of PCM-TES in buildings with suitable categorization and to summarize the used PCMs, their properties, and incorporation methods. A summary of used PCMs is obtained with their respective properties, and future trends for using active and passive PCM systems, and their possible combinations are presented, making an added value to the PCM study field. The article covers the subject of PCM cooling applications in buildings in various respects. All active and passive methods are categorized and reviewed to obtain future recommendations for later investigation.

### *1.2 Scope of the review article*

This review is composed of five sections including the introduction. Section 2 deals with the concept of PCMs, their classification, incorporation methods, and enhancement methods. Then Section 3 deals with the applications of PCMs in buildings for cooling purposes. Thereafter, Section 4 discusses and summarizes the reviewed articles. Finally, the study is terminated with a conclusion and critical recommendations.

## 2. Phase Change Materials (PCMs)

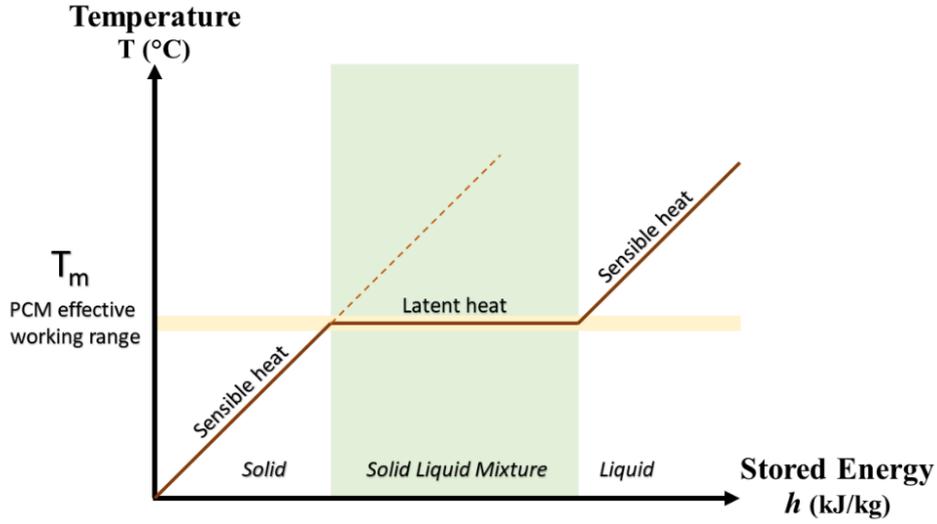
According to Sharma et al. [37] TES is classified as thermal or thermochemical, where the thermal category can be sensible or latent [38]. However, thermochemical TES systems are still commercially unavailable except in very limited applications, owing to their unknown life span and high costs [18]. Accordingly, TES techniques can be categorized mainly as latent or sensible [10],[39]. A comparison between sensible storage and latent storage is tabulated in **Erreur ! Source du renvoi introuvable.** It is worth mentioning that the capability of energy storage for latent heat TES is between 5 and 14 times more heat per unit volume than sensible heat storage materials like water, masonry, and rock [10] which is illustrated in **Table 1**, where the relative storage mass of rock is 15 times greater than that of the inorganic PCM.

**Table 1** Comparison between latent and sensible TES materials for a temperature rise of 15 K and an energy storage of 300 kWh [40].

Stored Energy		Property of material							
		Density	Specific Heat	Latent heat	Latent heat	Storage mass for 10 <sup>6</sup> J	Storage volume for 10 <sup>6</sup> J	Relative storage mass	Relative storage volume
E = 300 kWh		kg/m <sup>3</sup>	kJ/kg.K	kJ/kg	kJ/m <sup>3</sup>	kg	m <sup>3</sup>	-	-
Temperature rise		TR =15 K							
Sensible TES	Rock	2240	1	-	-	67000	30	15	11
	Water	1000	4.2	-	-	16000	16	4	6
Latent TES	Organic	800	2	190	152	5300	6.6	1.25	2.5
	Inorganic	1600	2	230	368	4350	2.7	1	1

### 2.1 Concept of PCM heat storage

PCMs are materials that use the latent heat during the change of phase process to control temperatures within a specific range [41]. The phase change process could be changing the state between liquid and gas by condensation and vaporization, known as liquid-gaseous LHTES; or changing the phase between two solid states, known as solid-solid LHTES; or a change of state between solid and liquid by melting or freezing, known as solid-liquid LHTES. Owing to certain technical limitations of the solid-solid and liquid-gaseous categories of latent heat strategies, only solid-liquid PCMs are considered suitable for building heating and cooling applications [12]. When the temperature of the PCM's surrounding rises such that the PCM reaches its melting point, the chemical bonds initiates its breakage with an endothermic process allowing the PCM to absorb energy, while the material melts changing its state from solid to liquid. This is the charging process of PCM. Next, when the temperature decreases to reach the freezing point of the PCM, bonds will regenerate and heat will be released exothermally while the PCM is regains its solid state. PCM thus is described to be a thermal reservoir [42]. The whole process of charging and discharging is accompanied with a small volume change, less than 10% of its initial volume [43]. An illustration of the process is presented in **Figure 1**.



**Figure 1** Latent energy storage by PCM with temperature change [43].

In fact, PCMs undergo sensible and latent heat processes based on the instantaneous PCM temperature compared to the melting/freezing range. When the change in temperature occurs below or above the range of phase transition, i.e. at a specific phase (liquid or solid), the sensible energy stored is given as [44]:

$$Q = mC_p\Delta T \quad (1),$$

where  $C_p$  is the specific heat of the PCM at constant pressure (J/kg.K),  $m$  is the mass of the PCM (kg),  $\Delta T$  is the temperature difference (K).

However, when the process of phase change takes place, at a near constant temperature, the latent heat stored is a function of enthalpy change, and is given by:

$$Q = \Delta H \quad (2),$$

where  $\Delta H$  represents the enthalpy of phase change (kJ/kg), also called melting enthalpy or heat of fusion, and  $m$  is the mass of PCM (kg).

The total thermal energy stored in a PCM of melting point  $T_m$  is then calculated as follows [25]:

$$Q = \int_{T_i}^{T_m} mC_{pi}dT + ma_m\Delta h_m + \int_{T_m}^{T_f} mC_{ps}dT, \quad (3)$$

where  $C_{pi}$  is the average specific heat between  $T_m$  and  $T_i$ ,  $T_i$  is the initial temperature, and  $T_f$  is the final temperature both in (K),  $C_{ps}$  is the average specific heat between  $T_f$  and  $T_m$ , and  $a_m$  is a fraction of the melted material.

## 2.2 PCM classification

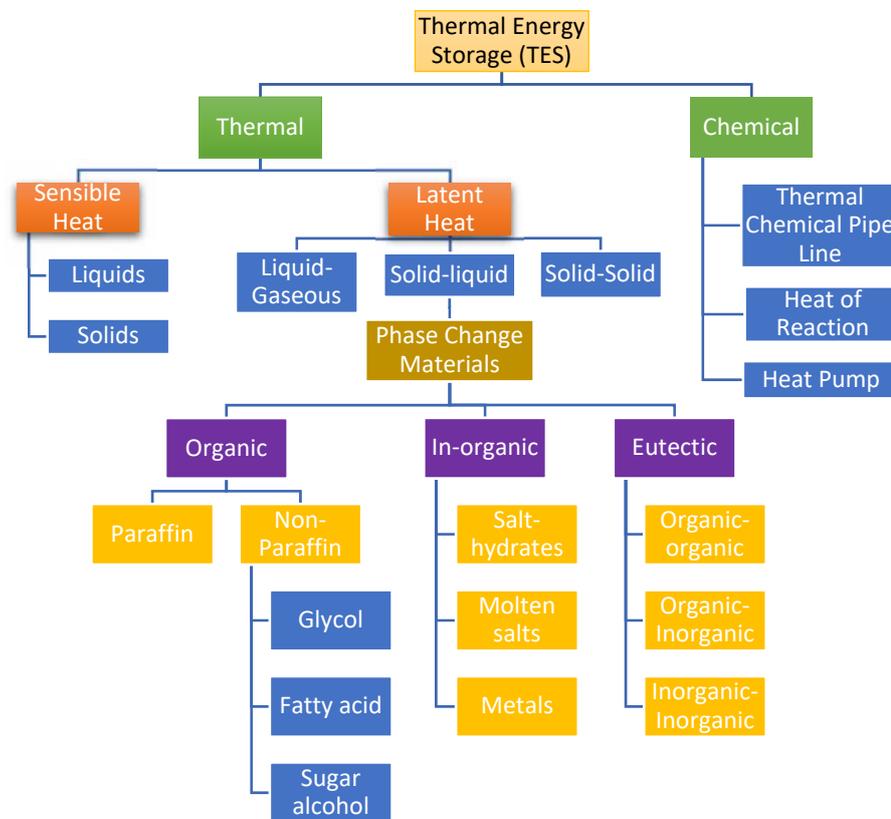
Phase change materials that have their charging/discharging process within solid-liquid transition category are classified into three main classes: Organic, inorganic, and eutectic PCM [41],[43]. These classes are subdivided further into sub-categories. Organic PCMs covers paraffin and non-paraffin materials by which the latter contains fatty acids, sugar alcohols, and glycols as subdivisions. Inorganic PCMs are classified as salt-hydrates, molten salts, or metals. In addition, eutectic PCMs are obtained by mixing two or more organics, inorganics, or organic

with inorganic PCMs [25]. **Figure 2** summarizes the TES classification in connection with the classifications of PCMs.

Organic PCMs are materials found in nature that mostly consist of carbon-hydrogen chains. The advantages of organic PCMs are several, with certain drawbacks that limits their effectiveness. Organic PCMs are capable of having continuous melting and freezing without phase isolation or degradation. They are chemically stable, do not have super-cooling, are non-corrosive, and recyclable. However, they have low thermal conductivity [45] and are flammable.

Inorganic PCMs are materials that offer the advantages of very high latent heat storage capacity, non-inflammability and sharper phase transitions, however their main drawbacks are being naturally corrosive, featured with phase segregation and super-cooling [46].

Eutectics are available as alloys of organics and/or inorganics and mostly (inorganic salt-hydrates) that feature congruent melting/freezing with no phase segregation [47].



**Figure 2** TES and PCM classifications [25],[37].

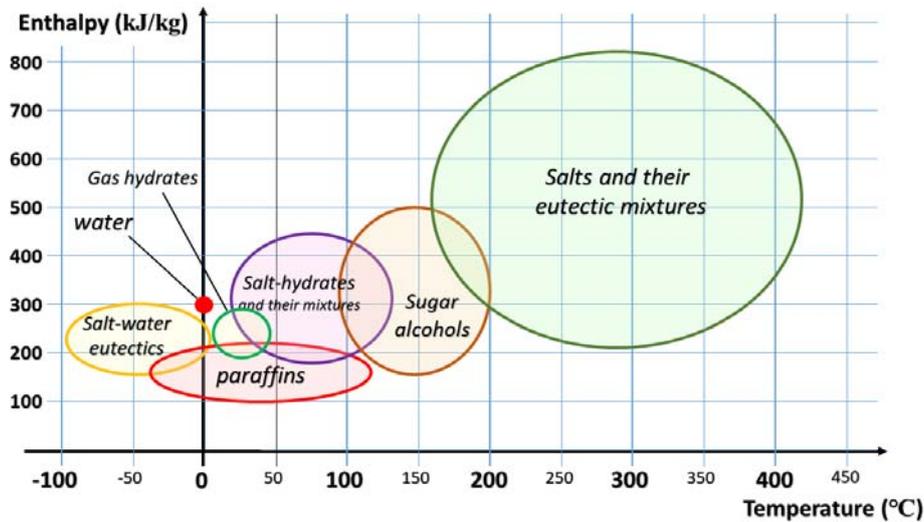


Figure 3 Melting range and melting enthalpy for different PCM types [48].

PCMs with their different classes and categories have a wide range of melting temperatures whereby each has a specified latent heat capacity of melting (see *Figure 3*). This is the main variable to be taken into account while choosing a suitable PCM for a specified application. In fact, some properties are required to ensure maximum thermal performance. These properties are thermo-physical, kinetic, chemical, economical, and environmental; and the list of these properties is given in *Figure 4*.

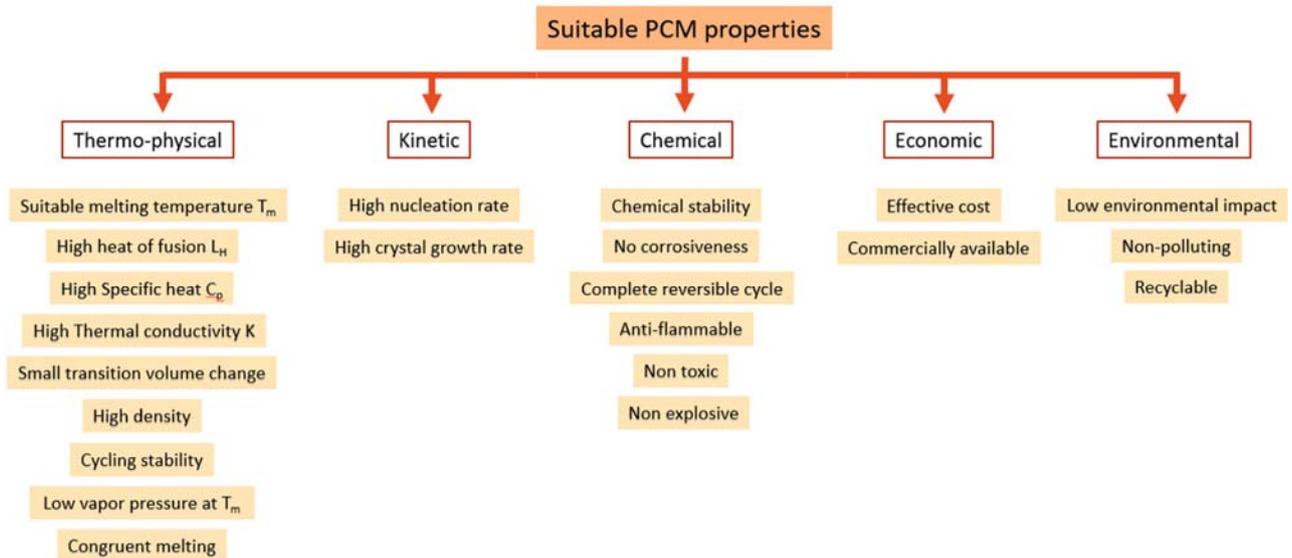


Figure 4 Suitable PCM required properties [32], [35], [49]–[51].

### 2.3 PCM applications

PCMs can be applied either in new buildings upon their construction or for the retrofitting of existing constructed ones [41].

### 2.4 PCM incorporation methods

PCMs can be integrated into building envelopes and elements by five incorporation methods: (1) Direct impregnation (direct mixing), (2) immersion or imbibing through materials' pores, (3) shape-stabilization, (4) microencapsulation and (5) macro-encapsulation.

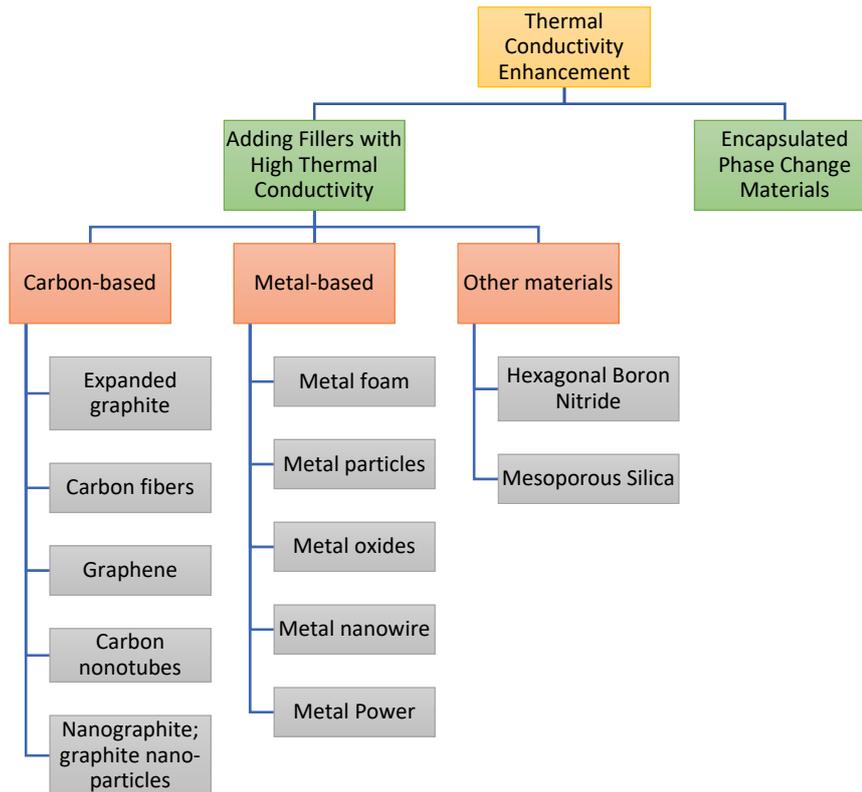
Direct impregnation is a method where liquid or powdered PCM is directly added to building materials such as gypsum, concrete, plaster or insulation materials such as cellulose during manufacturing. The technology of imbibing is referred to the dipping of manufactured building materials into melted PCM bath to allow the absorption of the latter through the materials internal pores [52].

A majority of PCMs used for building materials undergo a phase change between solid and liquid phases, which permits the possibility of leakage and diffusion of low viscous liquids through building materials. For this purpose, shape-stabilization, macro-encapsulation, and microencapsulation methods are more suitable for long term applications [41]. Shape-stabilization refers to the dispersion of PCM into another phase of supporting material such as high density polyethylene (HDPE) or a composite such as styrene-butyl-styrene (SBS) with powder like HDPE and graphite or carbon fibers, to form a stable composite shape-stabilized PCM material [53].

Macro-encapsulation involves the usage of any type of container that is usually larger than 1 cm in size. Such containers include tubes, spheres, or panels.

Microencapsulation refers to the packing of PCM in capsules that range from less than 1  $\mu\text{m}$  to 300  $\mu\text{m}$ , where the end product (mPCM) is formed of an outer shell, consists of organic polymers or silica, and the PCM filling the center [41]. Microencapsulation is usually one of two methods: physical or chemical. Physical microencapsulation involves spray cooling, spray drying, and fluidized bed processes, but limited in their granulated sizes. However, chemical microencapsulation can produce much smaller microencapsulated PCMs and the respective methods are: (1) In-situ polymerization, which includes: interfacial polycondensation, suspension polymerization, and emulsion/mini-emulsion polymerization; (2) Complex coacervation; (3) Solution-gelling method; (4) Solvent extraction/evaporation method; (4) Phase-separation method; (5) Internal phase separation method; (6) pre-polymer mixing method; and (7) self- assembling method[54].

It is also very important to be aware of the purpose of encapsulation. Encapsulation, in addition for solving leakage problems, it is one of the various methods for enhancing the thermal conductivity of PCMs. A helical diagram representing other techniques for thermal conductivity enhancement is presented in *Figure 5*.

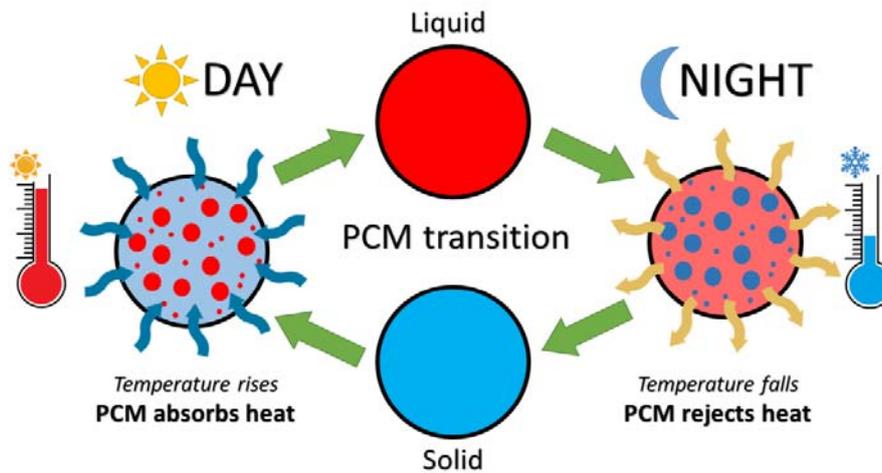


**Figure 5** Summary of thermal conductivity enhancement methods for PCM [55].

### 3. Use of PCM–TES for Cooling Applications in Buildings

PCMs applications are suitable for both new buildings and the retrofitting of existing ones [41]. The technique of incorporation, melting range, and desired utility characterize the functioning mode of the used PCM–TES system. PCM–TES can be used for heating, cooling, or for both heating and cooling, which are referred to as hybrid systems. The fundamentals behind cooling applications using PCM states that: when the considered thermal zone is subjected to an increase in ambient temperature that might pass the comfort range provided by the American Society of Heating, Refrigeration and Air-Conditioning Engineers, during hot condition (24°C for a humidity less than or equal 50%) [56], then PCMs take their role in storing the excess heat through their constant temperature absorption capabilities. **Figure 6** illustrates the phase transition phenomena during cooling application of the PCM. The melting range of PCM is then dependent on the placement of the PCM in the zone, type of application utilizing the PCM, and desired cooling set point. Each mode is subdivided into passive and active categories. Heier et al. [18] states that the difference between active and passive systems is the driving force of charging and discharging the storage where active storage utilizes pumps or fans while passive storage depends only on the temperature difference between the storage and surroundings.

According to Suayfane et al. [19], the cooling demand in the building sector has increased rapidly owing to: (1) high requirement for occupants' comfort, (2) rise of buildings internal heat gains, (3) impact of urban heat island experienced in overcrowded cities, and (4) reduced cost of cooling equipment. Integrating PCM into buildings can decrease the cooling cost and improve the thermal comfort during hot seasons.



**Figure 6** Phase transition of PCM during hot climates.

### 3.1 Cooling passive methods

The adaptation of PCM in passive application includes integrating them in: free cooling, Trombe wall, passive solar façade, solar chimney, building envelope components such as floors, ceilings, walls, windows, shutters, and blinds.

#### 3.1.1 Free cooling

Integrating PCMs into various heat exchangers for improving air-conditioning systems and increasing their coefficient of performance (COP) was the aim of Zhao and Tan et al. [57] in their numerical analysis. A shell and tube latent heat storage unit was installed in a combined system utilizing an AC system. Water and air were the two media incorporated in the charging and discharging processes of the latent energy. It was clear from the results that the achieved effectiveness of the latent heat storage system is higher than 0.5. A case study of replacing conventional cooling tower by the proposed PCM system shows that the COP value increases by 25.6%.

#### 3.1.2 Trombe walls

In the experimental aspect, a study by Thantong et al. [58] on a solar wall collector with PCM integrated into the wall of a prototype house that was compared to another identical reference house. Results revealed that the solar wall with PCM delayed heat transfer and accumulated more heat with a reduction of 59.63% in heat entering the house compared to the conventional wall in the reference room. Such results guaranteed that a solar wall with PCM is capable of lowering heat accumulation, promoting the use of solar energy, and saving electricity from using AC systems.

**Table 2** Advantages and disadvantages of Trombe wall system [21].

Advantages of Trombe walls	Disadvantages of Trombe walls
<ol style="list-style-type: none"> <li>1. Capability to be integrated with new technologies such as PV systems.</li> <li>2. Reduction of building's energy consumption, and decrease of moisture and humidity of interior spaces in humid regions.</li> <li>3. The indoor temperatures are more stable than in most other passive systems. Prevention of excessive sunshine penetration into the inhabited space.</li> <li>4. Trombe walls are esthetically appealing.</li> </ol>	<ol style="list-style-type: none"> <li>1. In regions with mild winters and hot summers, overheating problems may outweigh the winter benefits.</li> <li>2. In a climate with extended cloudy periods, without employing the adequate operable insulation, the wall may become heat sink.</li> <li>3. Trombe walls have low thermal resistance causing to transfer the heat flux from the inside to the outside</li> </ol>

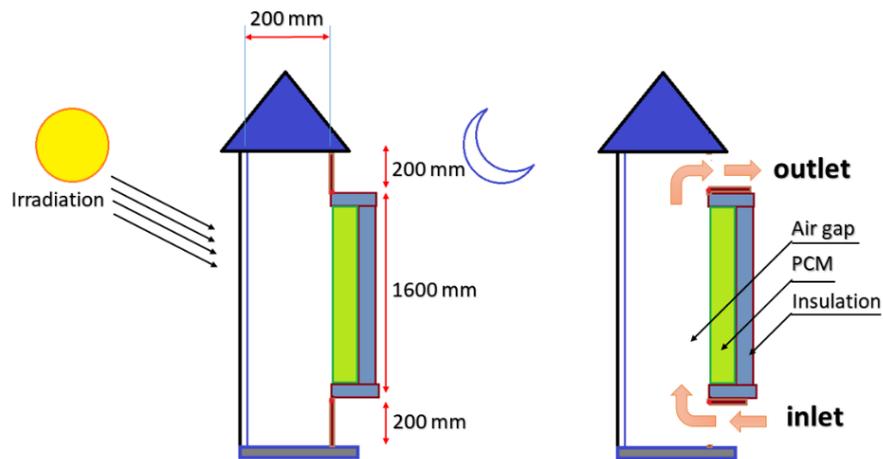
5. The time delay between absorption of the solar energy and delivery of the thermal energy to the living space can be used for night-time heating.	of a building during the night or prolonged cloudy periods.
6. Trombe wall not only provides thermal comfort in the spaces connected to itself, but also contributes to the enhanced thermal comfort condition of adjacent spaces.	4. The amount of gained heat is unpredictable due to changes occur in solar intensity.
	5. Installation is relatively in expensive, where construction would normally be masonry or requires retrofitting existing buildings with uninsulated massive exterior walls.

### 3.1.3 Passive solar facades

The integration of solar active facades in buildings for cooling seasons has a big role in reducing stratification effect during hot sunny days, and is able to regulate the indoor temperature reaching comfort levels even in extreme sunny days based on the appropriate installation and choice of the PCMs in the solar façade. Resch-Fauster et al. [59] prepared a solar passive façade equipped with a solar thermal collector and PCM storage plates. The PCM used was RT 82, which was mixed with polypropylene BB412E to form a composite PCM-polymer. The modeled prototype was tested in a solar simulator, and results showed that placing the PCM panels in the insulation layer behind the collector prevented the overheating of the interior surface of the façade (facing indoors) even at high irradiation rates (900 W/m<sup>2</sup> peak irradiation). The study proved that a panel of 15 mm thick and 10 mm far from the collector gives the best effectiveness if such a PCM in this façade prototype is tested.

### 3.1.4 Solar chimney

Similar to Trombe walls, solar chimneys represent a good technique for applying effective PCM for building cooling. A numerical study by Li et al. [60], who investigated the thermal performance of a PCM-based solar chimney (see **Figure 7**), showed favorable results affected by PCM. The study followed a parametric approach allowing the investigation of the effect of air flow rate, melting/freezing time, and air temperature difference. Enhancing the thermal conductivity of the used PCM (0.2 to 0.6 W/m °C) triggered an increase in air flow rate (0.033 to 0.038 kg/s) and the air temperature difference between the inlet and outlet (1.5 to 2 °C). PCM charging times were: 7.8 h, 6.6 h and 5.3 h for the three considered phase change temperature differences: 3 °C, 5 °C and 7 °C, respectively. However, the discharging duration was identical in the three cases (16.5 h). Thus, according to the authors, it was depicted that when the phase change temperature become wider, complete melting is achieved earlier than when the range is narrowed. An experimental study on the combination of a PCM with a solar chimney was prepared by Li et al. [61]. The study investigated the thermal performance of a 2 m high, 1 m wide, and 0.2 m deep solar chimney equipped with a macro-encapsulated RT42 PCM steel container having 30 steel fins for thermal conductivity enhancement. The PCM plate is located behind the absorber plate which is painted black for maximum absorption purposes. Tests were performed under laboratory conditions with the assistance of a solar simulator that produces three different heat fluxes: 700, 600, and 500 W/m<sup>2</sup>. Results showed that during the charging time of the PCM (3.833 h), complete phase transition was attained with 700 W/m<sup>2</sup> only. However, for all cases the ventilation period was extended owing to a discharging time of 13.833 h. During ventilation, the average air flow rates through the chimney duct were 0.04 kg/s, 0.039 kg/s, and 0.037 kg/s for 700 W/m<sup>2</sup>, 600 W/m<sup>2</sup>, and 500 W/m<sup>2</sup>, respectively. On the other hand, the minimum outlet temperature from the chimney was achieved in the case of 700 W/m<sup>2</sup>, while the best thermal efficiency (ranging between 63% and 80% during 24 h test) was attained by the system for 500 W/m<sup>2</sup> radiations.

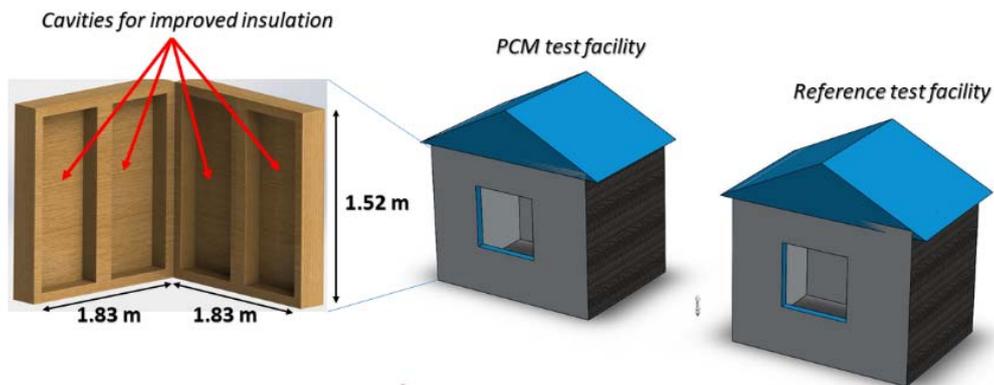


**Figure 7** Operation of the solar chimney integrated with PCM during day and night [60].

### 3.1.5 Building envelope (walls, wallboards, floors, ceilings, windows, shutters, and blinds)

#### 3.1.5.1 Walls and wallboards

Lee et al. [52] performed field tests on two identical prototype rooms subjected to full weather conditions. The research was directed to investigate the thermal performance of PCM-enhanced cellulose insulation installed in the cavities shown in **Figure 8**. Paraffin-based PCM was mixed with cellulose insulation and it was proven by the DSC curves that no adverse effect is contributed by the cellulose on the PCM latent heat. The results showed that on an average, peak heat fluxes were time delayed by about 1.5 h, an hourly peak heat flux reduction of 26.6% from the sum of all four walls was achieved, and the relative average cost savings were 3 cents/m<sup>2</sup>. However, for individual wall thermal performance, it was shown that the west-facing wall was the only one showing significant peak heat flux reduction.



**Figure 8** Tested facilities and the respective internal walls configurations for PCM adaptation.

Using type 101 in TRNSYS 15 software, Strith et al. [62] conducted a simulation for the thermal behavior of passive PCM technology prepared for ameliorating the energy savings in nearly zero energy buildings. The tested model was an office of 28.2 m<sup>3</sup> volume. A reduction in building energy using different PCMs in composite walls creating the model was achieved with their ability to contribute to the improvement of conventional buildings to be net zero energy buildings in the future. The study results show that the greatest difference of 14.5 °C in the ambient temperature was reached in five days for RT20 PCM type and 100% PCM ingredient. It was further shown that the wall material, PCM type, and PCM proportion all affects the cooling energy; 12.09 kWh/day as a difference between wool wall and polyurethane panels which is due to the thermal conductivities differences.

PCM SP22A4 saved the maximum amount of cooling energy which have the highest melting temperature (24°C) and the second largest storage capacity (165 kJ/kg); and finally it was concluded that the idea of “the more the amount of PCM, the more energy can be saved” doesn’t always apply, where it is of great importance to accommodate to the effect of thermal conductivity of the PCM.

A novel shape-stabilized phase change material wallboard (PCMW) was prepared from expanded perlite as a supporting material and paraffin as a PCM in a research conducted by Yao et al. [63]. The fabricated PCMWs were tested for their thermophysical properties and reliability, and it was found that their initial melting and freezing points were 23.98 and 25.81 °C, with latent heats of 67.13 J/g and 69.06 J/g for melting and freezing respectively, being obtained from the DSC measurements. Life cycle analysis showed that the PCMW is reliable. The study focused on both experimental and numerical analysis, where experimentally, PCMW integrated into walls and roofs of a tested prototype in cold Tianjin climate - China, particularly during the summer period, improved thermal comfort, smoothed indoor temperature fluctuation, and increased the building energy efficiency. On the numerical level, the proposed module (Type 269) was validated with a confidence level over 95% using TRNSYS software. Moreover, thermal performance analysis for a 4000 m<sup>2</sup> office was prepared numerically. The results presented a cooling load reduction of 22.16%, a payback period of 5.84 years, and a lifespan of more than 20 years. At the end of the study, the authors performed an optimization analysis that proved for PCMW having a phase change temperature range of 25-26 °C and a thickness 10 mm are most applicable for buildings.

Nano-enhanced paraffin-based PCM wallboards (n-heptadecane with graphite nanosheets) installed in a natural exposure test facility, and their thermal behavior in summer conditions at Charleston, South Carolina, USA was the topic of a study published by Biswas et al.[64]. The research covered both experimental and numerical aspects with the first outcome being the validation of the numerical models with experimental measurements. Annual simulations using meteorological data were then conducted including the direct comparison between regular gypsum boards and nano-enhanced PCM boards (NP-Gyp). It was shown that NP-Gyp was sensitive to heating and cooling set points being a discussed issue in the research. The best cooling set point was 21°C which lies in the center of the melting range of the PCM. Results emphasizes that the nano-PCM wallboards contributed to the decrease in heat gains and to a delay in heat flowing into the interior space, thus shifting the electricity load yielding higher load factors. The authors’ recommendations were set for studies beyond their scope, emphasizing the importance of other climate types, whole-house modeling, thickness of the wall boards, and the chance of removing latent heat of freezing such that it is not released to the interior of the building.

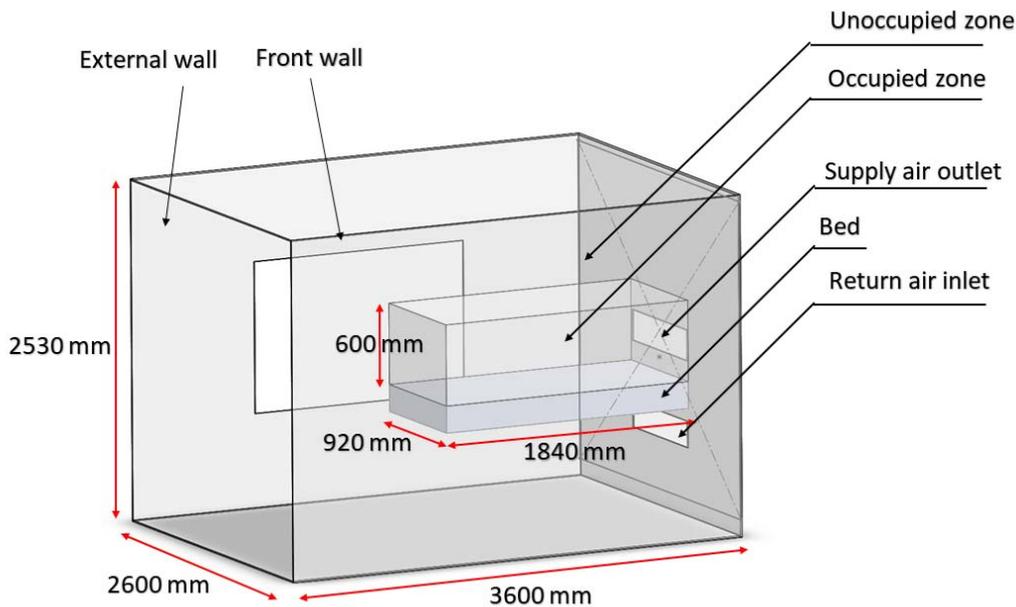
A numerical parametric quasi-steady state analysis of using PCM in walls for heating load reduction during hot summer periods at Chinghai climate has been investigated by Wang et al. [42]. A wall with a window at its center was modeled, and using the SIMPLE scheme presented by Patankar [65] energy equations were calculated by dealing with the window and wall separately. After validating the model with experimental results from previous studies, comprehensive investigations were performed for the simulated performance of the wall based on using six different types of PCMs (RUBITHERM RT-line commercial PCMs with different melting points), different thicknesses, and different positions in the wall. Results showed that the heat flow into indoor space has been reduced significantly when using a PCM layer, and with its 100% effective ratio, RT42 PCM was the best in performance. Heat transfer rate and indoor temperature with PCM layer thickness varied inversely and the best position was outside. At the closure, the optimal choice in all simulated cases was using a 20 mm RT42 layer at the outside of the wall.

### *3.1.5.2 Floors*

Wang et al. [66] studied the daily thermal performance of a (30 cm × 30 cm × 3 cm) mPCM honeycomb wallboard. The prepared module was composed of three basic layers: (1) a heating plate playing the role of outdoor irradiation, (2) a copper plate for even distribution of heat within the exterior wall of the test cell, and (3)

the 8-mm core cell aluminum honeycomb plate that is filled with paraffin ( $T_m = 37^\circ\text{C}$ ) as an mPCM. The test cell was subjected to indoor forced convection during the 24 hours of testing (case 1), 10 h of daytime indoor forced convection, followed by 14 h of night natural convection (case 2), and 24 h of natural convection (case 3). The results showed that the effective thermal protection period of the mPCM honeycomb wallboard reached 4 h, 4.7 h, and 4.7 h for cases 1-3 respectively, the heat releasing periods 2.8 h, 3.3 h, and 3.8 h, respectively. This indicates that the indoor conditions influence the thermal performance of the tested wallboards.

Ning et al. [67] performed a numerical investigation for a bedroom envelope equipped with PCM boards in the coastal area of Yantai, China. The geometric model is shown in **Figure 9**. The study was directed toward studying the effect of the PCM transition temperature and thickness on the thermal performance enhancement. PCM obviously weakened the effects of variation of the outdoor thermal environment, and it was shown that increasing the melting temperature of PCM helped reduce the variation of return air temperature at noon when the equivalent envelope temperature ( $t_e$ ) was at the highest level. However, no effect was attained at night. Moreover, an increase in the thickness of the PCM, thus its amount, can effectively weaken the impact of PCM on return air temperature variations.



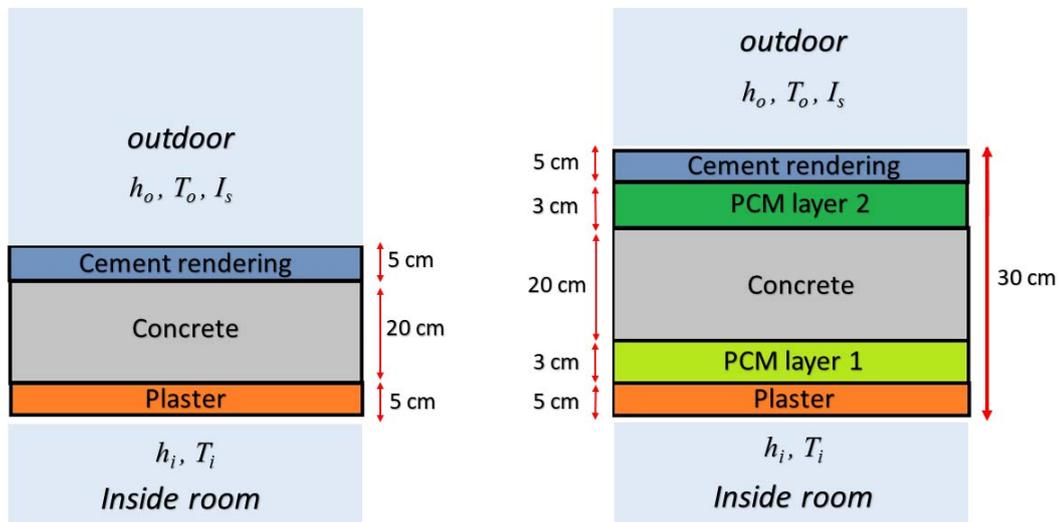
**Figure 9** Geometric model of the simulated bedroom [67].

### 3.1.5.3 Ceilings and roofs

The thermal performance of a 15 m<sup>2</sup> office cubicle integrated with bio-based PCM in its ceiling was experimentally investigated by Vik et al. [68]. The study included different scenarios including suspended ceiling with PCM covered with ceiling plates, and that without supporting ceiling plates. The test cell was constructed at a Laboratory in Oslo, Norway and tested on a hot summer day with integrating heaters into the center of the room for representing the internal heat gain. The used PCM was Bio-PCM with the code Q23 M51 manufactured by Phase Change Energy Solutions Inc., USA, with melting and freezing points, conductivity, and specific heat capacity of 23°C, 18.5°C, 0.2 W/m.K, 1.97 kJ/kg.K, respectively. The chief results showed that when using exposed PCM integrated in suspended ceiling and in one wall of the room, a drop of operative temperature reached 3.3°C, allowing the operative temperature to remain under 26°C during operative hours, revealing that the recommendation of Norwegian building code is achieved. The author recommended including void ventilation for PCM inside the walls by down and up holes, allowing more ventilation at night and the usage of a PCM with slightly higher melting temperature. Finally, the authors stated that although the exposed PCM in building have great benefits, it is challenging in terms of acoustic and aesthetic concerns.

Alqallaf and Alawadhi [69] analyzed the thermal behavior of a building concrete roof with vertical cylindrical holes filled with PCM numerically with experimental validation. The study focused on determining the effect of the holes' dimensions, particularly the diameter while maintaining the volume constant, and the impact of the melting temperatures of the used PCM as well as the operating month. Results showed that heat gain can be reduced more with larger PCM hole diameters, and that the PCM melting temperature has a great impact on the heat gain during summer. For best performance, the authors concluded that the selection of a suitable melting temperature should be based on the operating month and working hour period, where according to the results, the heat flux at the indoor surface of the roof can reach a reduction value of 12.04 to 17.26% depending on the operating month, during working hours of 12-5 pm.

A numerical analysis on the thermal behavior of a PCM-filled double glazing roof for cooling energy consumption reduction and thermal comfort improvement was prepared by Liu et al [14]. The study showed that the effect of the semi-transparent property of the glazing and the zenith angle on temperature time lag, transmitted solar energy, and the total transmitted energy is large. In another numerical simulation, Hanchi et al. [39] investigated the effect of adding two layers of different PCMs into the roof of a room subjected to variable weather conditions. The configuration of their roof design is illustrated in **Figure 10**. Results showed that the insertion of PCM is always beneficial for building passive components such as the studied roof.



**Figure 10** Illustrations of the reference roof and roof with the two integrated PCM layers [39].

#### 3.1.5.4 Windows

An experimental investigation of the adaptation of PCM in a novel triple-pane window (TW) was presented by Li et al. [70]. The authors aim was to solve the two problems of double-pane windows with PCM (DW+PCM) presented as night latent heat release into the room during an overheating risk from completely melted PCM. The study focused on a direct comparison between DW+PCM, TW, and TW with its outer cavity filled with PCM (TW+PCM). It was shown that a respective reduction of 2.7 °C and 5.5 °C on the interior surface of the TW+PCM compared to DW+PCM and TW corresponding to a reduction in the heat entering the building through the windows of 16.6% and 28%, respectively. This ensured the evasion of overheating risk. Further, it was shown that in rainy climate, the novel window technology was responsible for alleviation in temperature fluctuations of the interior surface and heat entering the building.

#### 3.1.5.5 Shutters and blinds

Silva et al. [71] performed an experimental study of the thermal performance of a window shutter containing PCM and validated a numerical model based on their results utilizing CFD analysis. Experiments involved a real scale test cell with two identical compartments each utilizing window shutters, one with PCM and the other

lacking it. Results indicated that the compartment with PCM shutter perceived a decrease in the maximum indoor temperature of 8.7% and an increase of 16.7% in the minimum indoor temperature for the night period. A respective corresponding achieved delay of 1 h and 30 min of the maximum and minimum temperature peaks were observed.

Li et al. [72] performed a numerical analysis of an integrated double skin façade (DSF) and PCM blind system using ABSYS Workbench FLUENT software. The study was based on comparing the temperature and velocity fields of a DSF with PCM blinds and another with conventional aluminum blinds. Results showed that the average air temperature and the outlet temperature from the DSF experienced a reduction due to the improvement of the convective heat transfer between the cavity air and blades caused by the PCM. PCM blind was proven to be capable of absorbing a large amount of cavity heat in excess, thus contributing in effective thermal management for minimizing DSF's overheating effect.

### *3.2 Cooling active methods*

Active applications for cooling in buildings are categorized as: Free cooling, active solar façade, ventilated Trombe wall, thermally activated building structures with PCM (PCM-TABS), AC systems, solar cooling, evaporative and radiative systems, geocooling, and ice storage.

#### *3.2.1 Free cooling*

Panchabikesan et al. [73] prepared a modified free cooling unit that permits the usage of spherical macro-encapsulated PCMs within a cylindrical tank in Bangalore's (India) moderate temperature climate. The new design, incorporating the installation of a direct evaporative unit (DEU), allowed a faster rate of heat transfer and a reduction in total charging duration. It was shown that compared to a conventional free cooling system, that the combination of DEU with PCM free cooling system allows the complete solidification of PCM at a faster rate indicating the improvement in thermal efficiency of the storage unit.

#### *3.2.2 Ventilated Trombe walls and active solar facades*

Fiorito et al. [74] investigated the thermal performance of a Trombe wall for five different climatic zones in Australia. It was shown that in hot climates, the integration of PCM in the inner or the outer layer of the Trombe wall both are beneficial in reducing the variability of the superficial temperatures. Further, in all climates there were shifts in heat fluxes by the PCM-TES. Zalewski et al. [75] also studied the impact of solar wall system on energy-efficient buildings, and observed that a time lag occurred between heat gained and heat rejected as a supply to the room, thus presenting the capability of PCM in shifting heat fluxes.

#### *3.2.3 TABS with PCM*

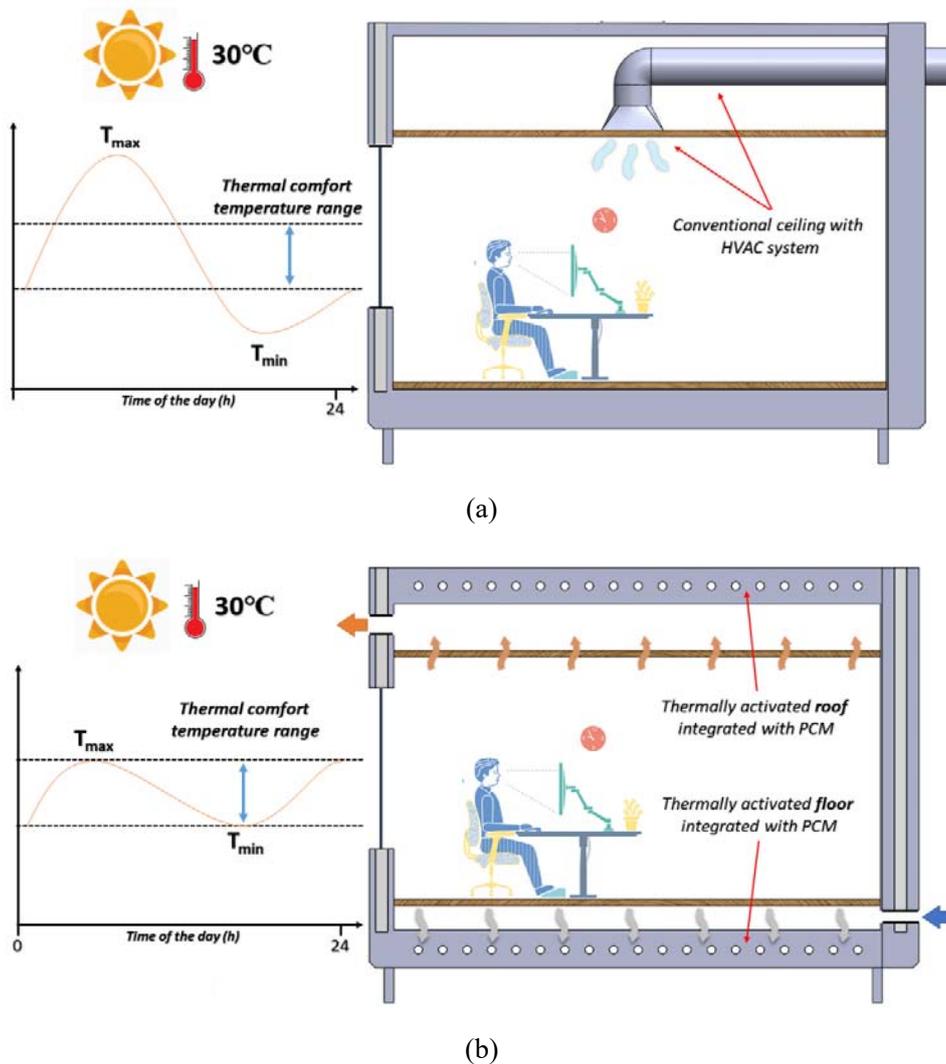
Thermally activated building structures (TABS) can offer a high performance efficiency if incorporated with PCMs to act as a sustainable thermal energy storage system that permits the continuous functioning of TABS all over day and night.

A simulation study by Bojic et al. [76] on high-rise buildings of Hong Kong showed that reducing the walls thermal capacity can increase the cooling energy demand by 60%. However, increasing the thermal mass, by adding PCM for instance, enhances the building's thermal performance. Indeed, the absence of large ambient fluctuations between day and night consequently diminishes the effect of PCM. Thus, adapting thermally activated building systems are more efficient. For a building to be thermally activated, a liquid (usually water) is used as the heat transfer fluid that flows through a net of pipes that are integrated in the ceiling, roof, walls or floor, or any combination of building structure partition. For cooling purposes, ground water serving as natural cold source or absorption/compression chillers as artificial cold sources. **Figure 11** illustrates the differences between buildings integrated with conventional HVAC system, and TABS integrated with PCM in its structure

partitions [77]. It is demonstrated how TABS with PCM are able to reduce indoor temperature fluctuations and thus maintaining thermal comfort all over the day if the system was installed optimally.

Lehmann et al. [78] prepared a simulation study on a thermally activated building structure located in central Europe. The main results proved that the hydronic circuit typology has a significant impact on the system energy efficiency, where separate zone return pipes configuration compared to common zone return pipes is capable of saving 20-30% of heating and cooling demands. The control strategy also has a great impact, where electricity demand for pumps can be reduced by 50% for the case of pulse width modulation control compared to continuous pumping. A study by Koschenz and Lehmann [79] on thermally activated ceiling panel with PCM serving as thermal energy storage included simulations, calculations, and laboratory tests. It is depicted that using microencapsulated heptadecane paraffin PCM (25% by weight) within the activated panels can reduce its thickness to mere 5 cm and is capable of maintaining thermal comfort in standard office buildings.

On the other hand, a study by Pomianowski et al. [80] on the thermal performance of a hollow concrete deck, with microencapsulated PCM and a thermally activated building system, showed that the cooling capacity of TABS can be reduced when PCM concrete is involved in decks.



**Figure 11** Schematic showing the difference between (a) conventional HVAC cooled office and (b) an office integrated with TABS and PCM.

### 3.2.5 Air conditioning systems

A solar-driven air conditioning system with integrated PCM cold storage is modeled using TRNSYS software by Allouche et al. [81]. The simulations were performed for satisfying the cooling demand of a 140 m<sup>3</sup> space in Tunis, Tunisia. The model comprises four main subsystems presented as: solar loop, ejector cycle, PCM cold storage, and air-conditioned space. It was found that the application of a relatively small hot storage tank (700 l) led to the highest solar fraction (92%). Results without cold storage indicated that the comfort temperature was exceeded during more than 26% of the time; however, with cold storage of high indoor temperatures periods diminished significantly. The authors concluded that applying latent heat storage with PCM, as low temperature thermal energy storage, is highly recommended for ejector solar cooling, where more stability is given to the AC system with the improvement of COP and solar thermal ratio values could reach up to 100% with the contribution of PCM.

Pop et al. [82] provided a numerical study for the energy efficiency of a fresh air-cooling system equipped with a PCM- TES in a virtual office building under various climatic conditions. After evaluating the PCM energy efficiency in fresh AC system, savings of 7% to 41% in electric energy consumption can be achieved based on particular local conditions leading to reduction in carbon impact.

### 3.2.6 Evaporative and radiative systems

Wang et al. [83] proposed a hybrid system utilizing a microencapsulated PCM-slurry storage tank, for cold storage, in combination with a cooled ceiling and an evaporative cooling system. Results show that the lowest and highest cooling energy storages respectively for Hong Kong (10%) and Urumqi (80%). The authors recommended their hybrid system for dry weather climatic conditions having high diurnal temperature difference.

Another hybrid system formed of microencapsulated PCM-slurry storage tank in combination with a nocturnal sky radiator was investigated by Zhang and Niu [84] for the determination of its cooling performance in buildings under various climate conditions in five cities in China. Results inferred that 77% and 62% energy savings were achieved in Lanzhou and Urumqi respectively, where as Hong Kong had the weakest savings.

### 3.2.7 Geocooling

The application of PCM in assisting geocooling systems for cooling commercial buildings was the topic discussed by McKenna et al. [85]. The research included a numerical approach using TRNSYS software for modeling the system. Geocooling alone was capable of meeting the cooling demand for 84% of a four-month cooling season; however this percentage increases to 99% when using TES with the system. Compared to a system based on a reference ground-source heat pump (GSHP), the authors stated that with more advanced TES control strategies, electricity savings of 24% to 45% could be achieved by combining geocooling with TES in a small lightweight commercial building.

## 3.3 Summary

Finally, to summarize all reviewed applications for the systems that are classified as active or passive, a schematic showing the classification of the applications for cooling systems utilizing PCMs in buildings are illustrated in **Figure 12**. Then, a summary for the literature on the use of phase change materials in buildings for cooling applications are summarized in **Erreur ! Source du renvoi introuvable.** Further, the used PCM types, thermophysical properties, incorporation methods, and applications are summarized in **Erreur ! Source du renvoi introuvable.**

**Table 3** Summary of literature for PCM cooling and heating applications for buildings.

Test methodology	Prototype/software	Climate	Used PCM	Application	PCM-LHTES technique/system	Key results	Ref.
Experimental	15 m <sup>2</sup> office cubicle	Laboratory in Oslo, Norway	Bio-PCM Q23 M51	Cooling	Suspended ceiling and ceiling plates	- Significant cooling effect for ceiling PCM exposed to occupants. - Variation of outdoor thermal environment effect is minimized effectively by the PCM	[68]
Numerical	Bedroom	Coastal Yantai, China	-	Cooling	External bedroom envelope equipped with PCM	- As T <sub>m</sub> is increased, variation of return air temperature is reduced when the equivalent envelope temperature is high.	[67]
Experimental	30 × 30 × 3 cm <sup>3</sup> mPCM honeycomb wallboard	Taiwan (artificial summer)	Paraffin based micro-capsulated PCM	Cooling	mPCM incorporated into 8-mm core cell aluminum honeycomb plate	- Thermal protection periods of 4 h, 4.7 h, and 4.7 h for cases 1-3, respectively. - Heat releasing periods: 2.8h, 3.3h, and 3.8h for cases 1-3, respectively.	[66]
Experimental	Two identical small-scale test houses (1.83 × 1.83 × 1.52 m <sup>3</sup> )	DOE region 4, U.S. central part	Paraffin-based PCM	Cooling	Paraffin PCM mixed with cellulose insulation in wall cavities	- average peak heat fluxes were time delayed by about 1.5 h - 26.6% hourly peak heat flux reduction and an average cost savings of 3 cents/m <sup>2</sup> for all walls.	[52]
Experimental and Numerical	Test cubicle of 2 m side/ TRNSYS 15	Cukurova, Turkey/ Ljubljana, Slovenia	Fatty acid mPCM	Cooling	Composite walls of concrete and concrete with mPCM embedded with 0.12 m total thickness	- Inside surface of the test cabin is colder by 5 °C than the reference panel.	[86]
Experimental and Numerical	Prototype room (1.7 × 1.7 × 2.2 m <sup>3</sup> ) with a window on west wall (0.6 × 0.8 m <sup>2</sup> ) / TRNSYS software	Tianjin, China	Paraffin/expanded perlite SSPCM	Cooling	Shape stabilizes PCM wallboards (PCMW) incorporated to the internal surface of the walls and roof of tested prototype	- PCMW improves thermal comfort, smoothens indoor temperature fluctuation, and increase the building energy efficiency. - Numerical model is validated with a confidence level > 95%. - Numerically, for 4000 m <sup>2</sup> office, cooling load reduction of 22.16%, 5.84 years payback period, and a lifespan > 20 years is achieved. - Optimum PCMW: have a phase change temperature range of 25-26 °C and thickness 10 mm. - For a cooling set point of 22 °C, the highest annual wall heat gain reduction was achieved.	[63]
Experimental and Numerical	Natural exposure test (NET) building / COMSOL Multiphysics	Charleston, South Carolina, USA (Hot humid climate)	Paraffin, n-heptadecane (C <sub>17</sub> H <sub>36</sub> )	Cooling	Incorporation of shape stabilized nano-PCM in gypsum wallboard	- No reduction in heat gains for the cases of 22 and 23.3 °C set points. - Potential of electrical consumption reduction is illustrated by the nano-PCM wallboard.	[64]

Numerical	Finite volume solver with SIMPLE scheme calculation method	Shanghai city ( <i>Hot climate</i> )	6 RUBITHER M RT-line PCM	Cooling	PCM layer incorporated into concrete wall	<ul style="list-style-type: none"> <li>- Heat transfer rate and average inner surface temperature are reduced by using PCM.</li> <li>- The optimum PCM type, thickness, and position are RT42 with 20 mm thickness, placed outside.</li> <li>- Heat transfer reduction of 34.9% was achieved,</li> </ul>	[42]
Experimental and Numerical	Cubical enclosure with concrete roof ( $1.5 \times 1.5 \times 0.15 \text{ m}^3$ ) having cylindrical holes ( $d = 0.1414 \text{ m}$ , and $h = 0.075 \text{ m}$ )	Kuwait ( <i>hot summer climate</i> )	Paraffin-based PCMs A28, A32, and A38	Cooling	PCM filled in cylindrical holes of a concrete roof	<ul style="list-style-type: none"> <li>- Significant reduction in heat gain with larger PCM holes diameter.</li> <li>- Reduction in heat flux at the indoor surface between 9 and 17.26% depending on the selected PCM, working hours and operating months.</li> </ul>	[69]
Numerical	EnergyPlus®	Nancy, France	-	Cooling	Bio-based composite wall with PCM	<ul style="list-style-type: none"> <li>- Best performance in terms of reducing stratification effects was in the case of heavy weight wall with PCM compared to lightweight</li> </ul>	[87]
Experimental	Solar chimney ( $2 \times 1 \times 0.2 \text{ m}^3$ ) with a bottom air inlet and top outlet (both 1m wide and 0.2m high)	Laboratory environment ( <i>different heat fluxes through solar simulator</i> )	RT42 paraffin wax	Cooling	PCM enhanced container (with fins) adapted to a solar chimney	<ul style="list-style-type: none"> <li>- For three different solar heat fluxes (700, 600, and 500 W/m<sup>2</sup>), the best thermal efficiency was for 500 W/m<sup>2</sup> while the minimum outlet temperature was for 700 W/m<sup>2</sup>.</li> <li>- Air flow rates were 0.04 kg/s, 0.039 kg/s and 0.037 kg/s for 700 W/m<sup>2</sup>, 600 W/m<sup>2</sup>, and 500 W/m<sup>2</sup>, respectively.</li> </ul>	[61]

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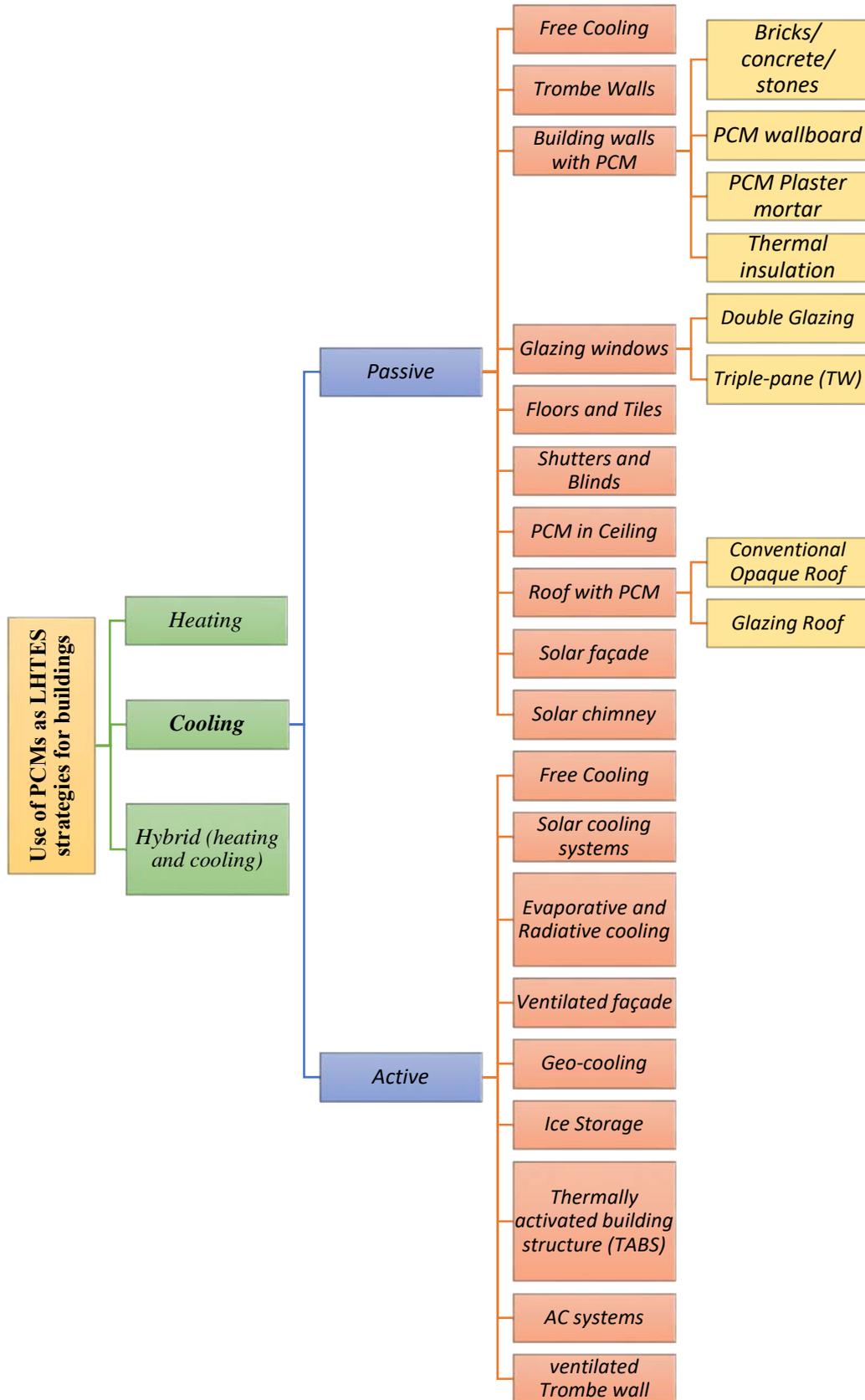
**Table 4** Thermophysical properties of key PCMs used in experimental cooling and heating applications for buildings

PCM ingredients	Type	Synthetic/ commercial	Melting temperature	Latent heat	Thermal conductivity	Specific heat	Reference
-	Bio-based PCM Q23M51	Commercial	23 °C	-	0.2 W/m.K	1.97 kJ/kg.K	[68]
85-90% paraffin and 10-15% polymer shell	Paraffin-based PCM	Commercial	37 °C	166.54 kJ/kg	0.13 W/m.K (solid) 0.11 W/m.K (liquid)	3.21 kJ/kg.K (solid) 2.70 kJ/kg.K (liquid)	[66], [88]
Paraffin	Paraffin-based PCM	Commercial	28°C	137.5 kJ/kg	0.2 W/m.K	-	[52]
Perlite ( <i>supporting material</i> ) + Paraffin 8% wt.	Paraffin-based PCM	Synthetic	23.98 °C	67.13 kJ/kg (for melting) 69.06 kJ/kg (for freezing)	-	-	[63]
Expanded graphite nanosheets + 92% wt. Paraffin, n- heptadecane (C <sub>17</sub> H <sub>36</sub> )	Paraffin-based nano PCM	Synthetic	21.1 °C	26.9 kJ/kg (for melting) 26.8 kJ/kg (for freezing)	0.41 W/m.K (solid) 0.427 W/m.K (liquid)	2.312 kJ/kg.K (solid) 2.236 kJ/kg.K (liquid)	[64]
Paraffin	RUBITHERM RT-line	Commercial	31, 35, 42, 47, 50 and 55°C	160-170 kJ/kg	0.2 W/m.K	2 kJ/kg.K	[42]
Paraffin	Paraffin-based PCM A28 PCM A32 PCM A38	Commercial	28°C 32°C 39°C	230 kJ/kg 215 kJ/kg 190 kJ/kg	0.21 W/m.K 0.21 W/m.K 0.22 W/m.K	2.22 kJ/kg.K 2.2 kJ/kg.K 2.22 kJ/kg.K	[69]
-	-	-	27-29 °C	205 kJ/kg	0.21 W/m.K	2.23 kJ/kg.K	[14]
-	RT22	Commercial	22 °C	200 kJ/kg	0.2 W/m.K	2 kJ/kg.K	[57]
80% methyl methacrylate + 20% methacrylic acid	Organic MEPCM	Synthesized	23.68 °C	170 kJ/kg	-	-	[89]
Salt-hydrate	SP22	Commercial	22 °C	170 kJ/kg	0.6 W/m.K	2 kJ/kg.K	[90]

61% polypropylene BB412E + 39% RT82	Polymer PCM SS-RT82	Synthesized	86 °C	82.8 kJ/kg	-	-	[59]
Paraffin	RT43	Commercial	38-43 °C	174 kJ/kg	0.2 W/m.K	2 kJ/kg.K	[60]
Paraffin	C20	Commercial	44-46 °C	189 kJ/kg	0.21 W/m.K	2.1 kJ/kg.K	[91]
Paraffin	RT50	Commercial	45-51 °C	160 kJ/kg	0.2 W/m.K	2 kJ/kg.K	[92]
-	-	-	46.3 °C	-	0.1 W/m.K (solid) 0.17 W/m.K (liquid)	1.7 kJ/kg.K (solid) 1.9 kJ/kg.K (liquid)	[93]
	Bio-PCM Q23	Commercial	25.5 °C	70 kJ/kg	0.157 W/m.K	0.837 kJ/kg.K	[94]
Capric acid	organic	-	32 °C	152.7 kJ/kg	0.372 W/m.K (solid) 0.141 W/m.K (liquid)	0.475 kJ/kg.K	[95]
Zinc nitrate hexahydrate	organic	-	36 °C	147 kJ/kg	0.464 W/m.K	1.34 kJ/kg.K (solid) 2.26 kJ/kg.K (liquid)	[95]
15% HDPE + 15%EG + 70% paraffin wax	GH20 SSPCM	Commercial	20.93 °C	61.44 kJ/kg	-	2.52 kJ/kg.K	[96]
Paraffin	MG29	Commercial	27-29 °C	205 kJ/kg	0.21W/m.K	2.23 kJ/kg.K	[97]
Paraffin wax	RT42	Commercial	38-43 °C	174 kJ/kg	0.2 W/m.K	1.8 kJ/kg.K (solid) 2.4 kJ/kg.K (liquid)	[61]
Hexadecane paraffin	organic	Synthetic	18 °C	236 kJ/kg	0.17 W/m.K	1.65 kJ/kg.K (solid) 2.1 kJ/kg.K (liquid)	[79]
Heptadecane paraffin	organic	Synthetic	22 °C	214 kJ/kg	-	-	[79]

Octadecane paraffin	organic	Synthetic	28 °C	244 kJ/kg	0.26 W/m.K	1.75 kJ/kg.K (solid) 2.1 kJ/kg.K (liquid)	[79]
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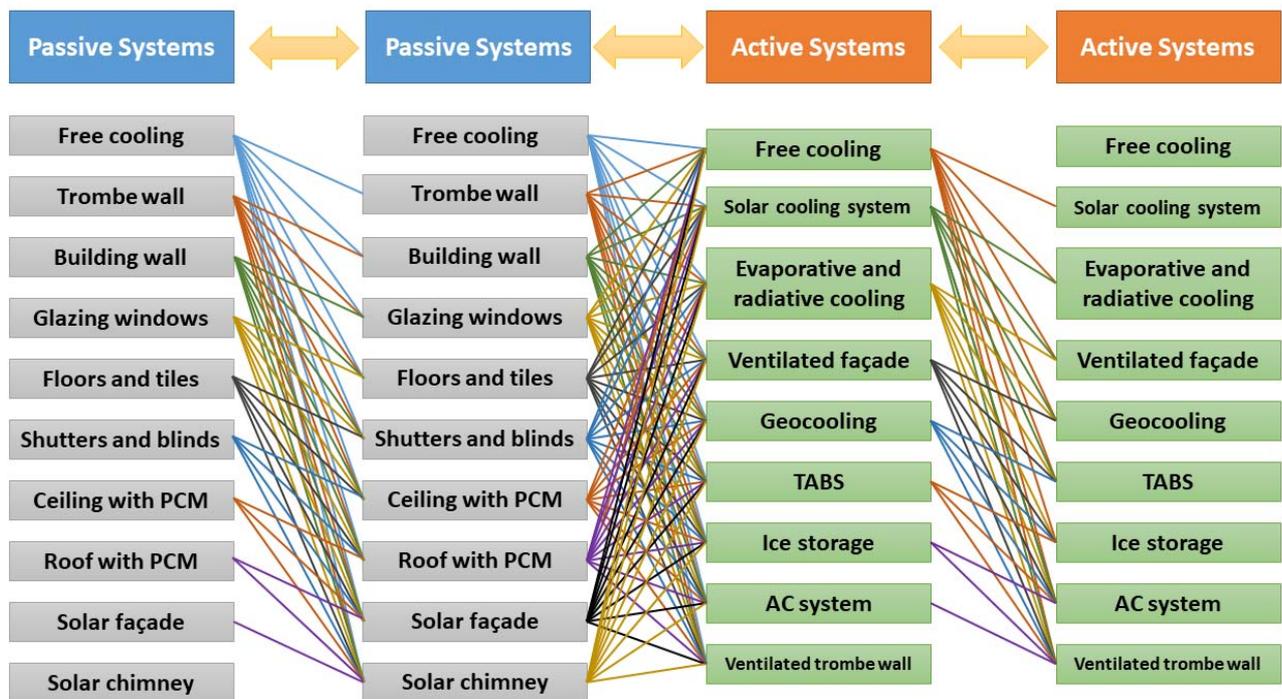


**Figure 12** Schematic for heating and hybrid applications of PCM–TES in buildings as discussed in the current review article.

### 3.4 Future Application Trends

Studies covered through the context emphasizes on the potential of PCM applications in enhancing buildings thermal performance. However, further studies are required to overcome complicated behavior and vague unanswered questions with respect to PCMs. Passive applications require testing under real climatic weather conditions in different climates. Simulations are valuable but not sufficient to obtain the overall perspective of PCM behavior. Active systems such as TABS are proved to be complex and their control is challenging. Romani et al. [98] proved that with the great potential of TABS in building energy consumption reduction, modeling is essential and simulations are not sufficient owing to the complexity of studying the system and controlling it.

Furthermore, active and passive systems present in this review are studied separately. There are nearly no studies on cooling systems that combines two or more systems at the same time to investigate the possible outcomes that may enhance building thermal performance and be a keyway toward attaining net zero energy building with PCM. Possible combinations of systems might include: Passive-passive, active-active, or active-passive combined systems. **Figure 13** illustrates all the possible combinations that need further study in the near future in the case of two combinations, knowing that every addition of a new system to the combinations opens further options that are endless.



**Figure 13** Possible combinations of active-passive, passive-passive, and active-active systems for study.

#### 4. Conclusions and Recommendations

The current work presented a review on recent research work in the scientific community regarding the usage of phase change materials as latent heat thermal energy storage strategies applied to buildings: commercial and residential. Three application aspects were presented: heating applications in buildings, cooling applications in buildings, and hybrid applications in buildings. Presented literature was classified into two categories in each studied aspect: passive and active systems. The reviewed articles were presented and their thermal performance analyses was included. A summary of the used PCMs in each applications aspect with their respective thermophysical properties and encapsulation techniques are presented. It was shown that:

- PCM do serve as thermal buffers that permits residential thermal comfort in winter cold climates through peak shifting and temperature swing reduction.
- PCMs are proved to be efficient for energy consumption reduction cooling applications such as HVAC in the active category and ceilings in the passive one.
- Numerical simulations encountered plenty of assumptions and the need of real scale prototypes arises especially with the complexity in controlling the cooling demand which is affected by various parameters: solar irradiation, heat gains, and infiltration.
- The range of PCM melting temperature for cooling applications lies in the thermal comfort range of 20-28°C in the case when thermal comfort and stratification effect reduction is targeted. This range increases to 30 – 50 °C if energy storage (e.g. storage tanks) is the target.
- The main drawback in using PCM–TES for cooling is the incomplete solidification of PCM at night.
- Various commercialized PCMs are manufactured from organic compounds such as paraffin, however less concern in bio-based, inorganic, and eutectic mixtures is triggered.
- Novel applications in cooling systems are numerically analyzed with a large number of assumptions that reduces the accuracy of the results.
- The majority of the studies covered the investigation of specified single application which is either a passive or an active system. The combination of two different applications can give wide variety of possible tests that require investigation. The possible combinations and their respective enhanced performances can trigger a successful attempt toward sustainability and converting conventional buildings to net zero energy buildings.
- Active systems seem to be more complicated than passive systems in terms of implementation, control, and thermal performance analysis. Their optimization requires the corporation of simulation, numerical, and experimental inspection.

Special focus must be given to optimization studies dealing with PCM thermophysical, geometrical, and mechanical properties. Economic analysis which is not observed in some literature plays an important role in commercializing the studied systems and optimizing their use.

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