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Phase change materials (PCM) for cooling applications in buildings: A review

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A B S T R A C T

Cooling demand in the building sector is growing rapidly; thermal energy storage systems using phase change materials (PCM) can be a very useful way to improve the building thermal performance. The right use of PCM in the envelope can minimize peak cooling loads, allow the use of smaller HVAC technical equipment for cooling, and has the capability to keep the indoor temperature within the comfort range due to smaller indoor temperature fluctuations. This article presents an overview of different PCM applications in buildings for reducing cooling loads under different climate conditions, and the factors affecting the successful and the effective use of the PCM. Many drawbacks have been found in PCM applications, mainly the intense impact of summer weather conditions over the PCM performance, which prohibits its complete solidification during night, and thus, limiting its effectiveness during the day. Proposed solutions are reviewed in this article. Finally, a topology diagram is presented to summarize the steps leading to an effective use of PCM in building applications.

Contents

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Nomenclature

Cp	Specific heat (J/kg K)
E_{daily}	Average daily cooling load (kW)
Hf	Latent heat of fusion (J/kg)
kl	Thermal conductivity at liquid state (W/m K)
ks	Thermal conductivity at solid state (W/m K)
Q_{cool}	Cooling load (kW)
Tm	Melting temperature (°C)
Ts	Solidification temperature (°C)
ρ_{PCM}	Density of PCM (kg/m^3)

Acronyms

AC	Air conditioning
ACH	Air change per hour
AHU	Air handling unit
ASEAN	Association of Southeast Asian Nations
CC	Cooled-ceiling
COP	Coefficient of performance
DRSS	Distributed responsive system of skins
E	Energy storage effectiveness
E*	Modified energy storage effectiveness
EIA	Ecodesign impact accounting (study)
EJ	Exajoules
HTF	Heat transfer fluid
HVAC	Heating, ventilating, and air conditioning
LHS	Latent heat storage
LHTES	Latent heat thermal energy storage
Mtoe	Million tonnes of oil equivalent
MVS	Mechanical ventilation system
PCM	Phase change materials
RT	Rubitherm GmbH
SEER	Seasonal energy efficiency ratio
SIP	Structural insulation panels
SPP	Simple payback period
SSPCM	Shape stabilized PCM
TES	Thermal energy storage
VDSF	Ventilated double skin facade
VF	Ventilated facade
WHS	Water heat storage

1. Introduction

An ever-increasing world population combined with a large increasing in energy demand has led to an important environmental crisis that already shows its clear beginning. The primary energy production, according to the International Energy Agency (IEA), has increased 49% and CO_2 emissions 43% over the past 20 years [1]. Research findings have specified that buildings account for almost 41% of the world's energy consumption, which constitutes 30% of the annual greenhouse gas emissions [2]. It is expected that the energy demand in the building sector will rise by about 50% in 2050, and the space cooling demand will triple between 2010 and 2050. Hence, the building envelope should be optimized in order to minimize cooling loads in hot climates. In highly efficient-energy applications for cooling, the energy savings potential is estimated to be between 10% and 40% [3]. In the European Union (EU), the building sector is the main energy consumer and constitutes about 40% of the total energy usage; considerable parts of this energy usage are directly related to the heating and cooling of buildings [4]. In 2010, according to the EIA forecasts, the space cooling demand in the EU reached 220 TWh, and it is expected to increase to 305 TWh (+38%) in 2020 and 379 TWh (+72%) in 2030 [5].

Another study conducted by the European Technology Platform on Renewable Heating and Cooling (RHC) [6] showed that the cooling demand in the EU is expected to rise in both residential and service sectors as shown in Fig. 1.

Additionally, in 2006 the building sector in the USA accounts for 38.9% of the total primary energy consumption; 18% for commercial buildings while 20.9% for residential buildings [7]. In 2009–2010, the energy consumption of residential building in Australia was around 25% of total energy consumptions [8]. Present predictions show that the energy use by nations with rising economies (Middle East, Southeast Asia, South America and Africa) will increase to an average annual rate of 3.2% and will exceed by 2020 that for the developed countries (Western Europe, Japan, North America, New Zealand and Australia) at an average growing rate of 1.1% [9]. According to IEA [10], the cooling demand is expected to increase swiftly in areas where urbanization is promptly growing as shown in Fig. 2.

Since the energy consumption of heating and air conditioning systems is still rising with the increasing demand for thermal comfort, therefore there is large potential to ameliorate the building energy efficiency in the areas of heating and cooling technologies.

One of the interesting ways to reduce the energy demands is the use of thermal energy storage (TES). Depending on environmental circumstances, TES materials can absorb heat, store it and release it; improving the gap between energy supply and energy consumption [11]. The energy can be stored by TES materials in three ways namely sensible heat, latent heat or chemical reactions. The latent heat thermal energy storage (LHTES) is an attractive way and has taken much attention over the last decades for heating and cooling purposes in buildings. In residential buildings, a large variety of studies proved that the application of thermal mass in well-insulated structures provides cooling and heating energy savings between 5 and 30% [12].

Recently, Phase change materials (PCM), that utilize the principle of LHTES, have received a great interest and forms a promising technology. PCM have a large thermal energy storage capacity in a temperature range near to their switch point and present a nearly isothermal behavior during the charging and discharging process [13]. The right use of PCM can minimize the peak heating and cooling loads, and has the capability to keep the indoor temperature within the comfort range due to smaller temperature fluctuations. Consequently, reduce the dimensions and energy consumption of the corresponding technical equipment. The main advantage of the use of PCM is that it enhances the thermal storage potential with a minimum change of the existing building design [12].

Many studies have investigated the use of PCM in buildings and showed that PCM can remarkably improve the building energy performance. But a lot of difficulties were encountered especially concerning the efficient use of PCM and its practical application.

Al-Saadi and Zhai [14], Baetens et al. [15], Cabeza et al. [16], Khudhair and Farid [17], Kuznik et al. [18] and others, have conducted several reviews on the use of PCM in buildings for thermal energy storage and indoor climate comfort purposes, clearly

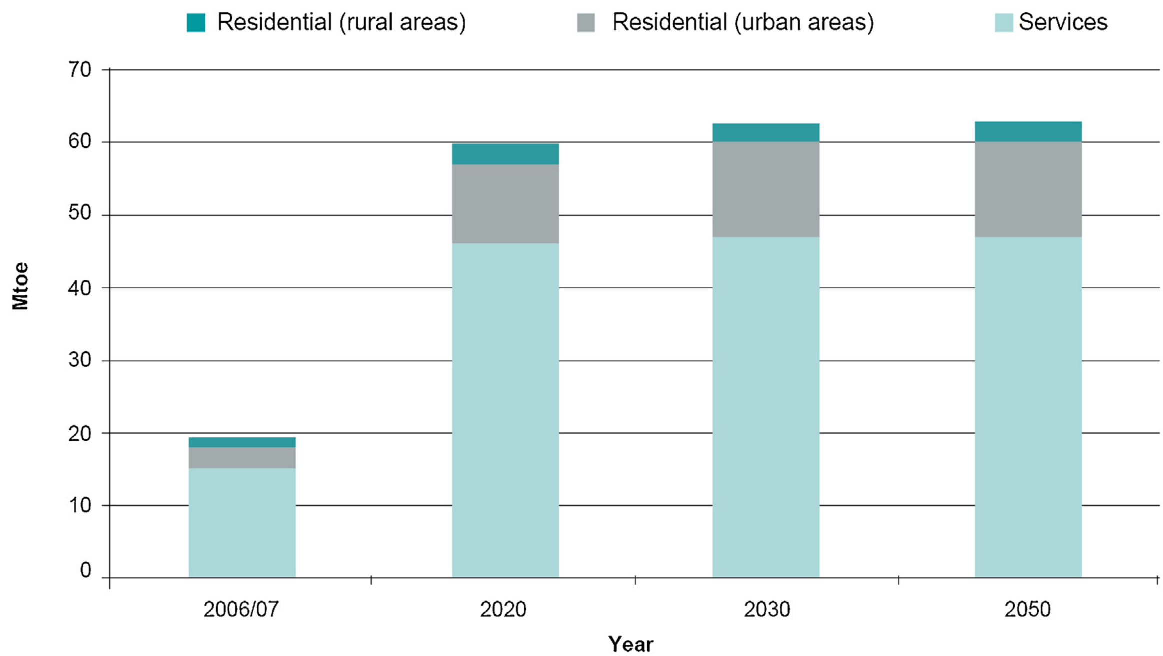


Fig. 1. Predicted evolution of cooling demand in EU for residential and service sectors [6].

showing that the interest for PCM is increasing worldwide. It has been also proved by several authors that PCM provide energy benefits in the heating period while limited benefits were found during the cooling season.

This study presents an overview of different PCM applications in buildings for reducing mainly the cooling loads under different climate conditions. The difficulties related to the material selection and the factors affecting the successful and the effective use of the PCM are also discussed.

2. Phase change materials (PCM)

2.1. General

PCM can be used to store energy or to control the temperature swings within a specific range. Therefore, applications for heating and cooling in buildings are expected to have great potential for PCM use. When the temperature rises, PCM absorb heat in an endothermic process and changes phase from solid to liquid. As the temperature drops, PCM release heat in an exothermic process, and return to its solid phase.

Certain types of PCM do not satisfy the desired criteria for an appropriate storage medium. The PCM to be used for thermal energy storage purposes should meet desirable thermo-physical, kinetic and chemical requirements shown in Table 1 [7].

2.2. PCM classification

A considerable number of PCM is available in any desired temperature range. According to their chemical composition, PCM can be categorized as organic compounds, inorganic compounds and eutectic mixtures. Each group has its typical range of melting temperature and its range of melting enthalpy. The paraffin waxes, salt hydrates, fatty acids and eutectic organic/non-organic compounds are the most used since last 30 years. The relationship between the melting enthalpy (kJ/l) and the temperature of PCM is shown in Fig. 3. These characteristics are considered very important especially for their application in building envelopes (i.e. PCM incorporated into finish materials, thermal insulation or structural components) [12].

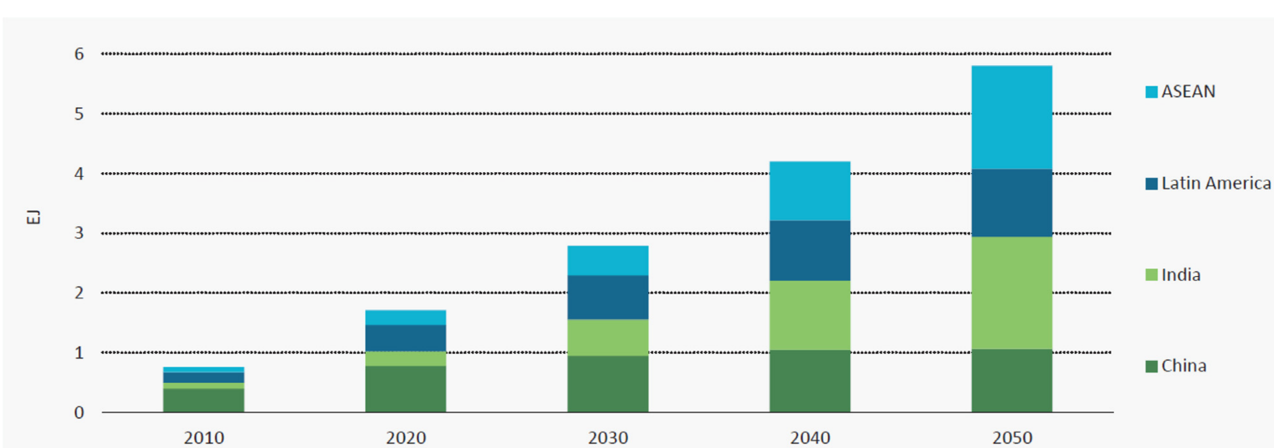


Fig. 2. Predicted evolution of cooling demand (Exa-joule "EJ") in four different regions [10].

Table 1
Thermo-physical, kinetic, chemical, economic and environmental requirements of PCM [7].

Thermo-physical Requirements	Kinetic Requirements	Chemical Requirements	Economic and environmental requirements
- Appropriate melting temperature in the required operating temperature range. - High latent heat of fusion. - High specific heat. - High thermal conductivity of solid and liquid phases. - High density. - Congruent melting of the PCM. - cycling stability. - Small vapor pressure. - Small volume changes. - Little or no sub-cooling during freezing. - no segregation.	- High nucleation rate in order to avoid super cooling of the liquid phase. - High rate of crystallization to satisfy demands of heat recovery from the storage system.	- Long term chemical stability of the PCM. - No degradation after freeze/melt cycles. - Complete reversible freeze/melt cycle. - No corrosiveness. - non-flammable, Non-toxic and non-explosive materials for safety.	- Low price and cost effective. - availability - Nonpolluting. - Low environmental impact. - Good recyclability. - Low embodied energy. - Facility of separation from other materials.

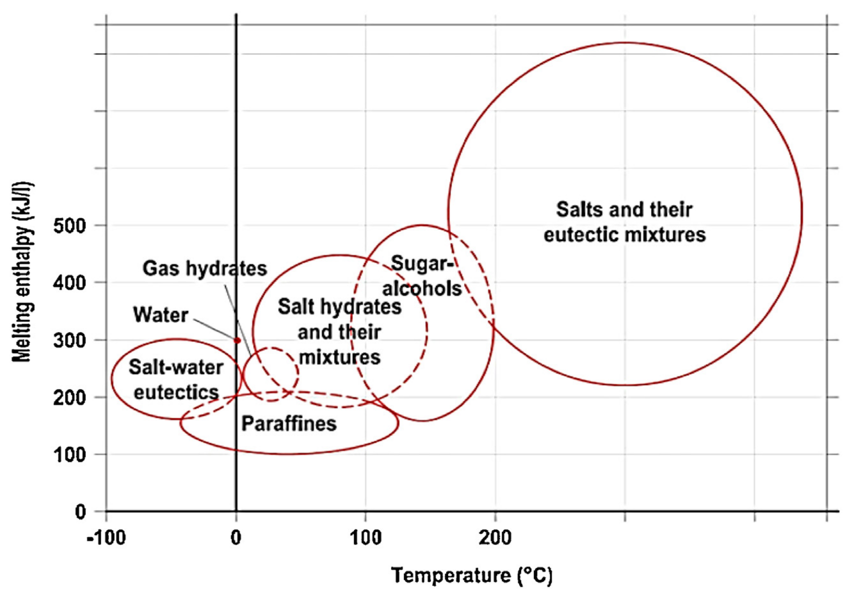


Fig. 3. Relationship between PCM melting enthalpy and temperature for the different groups of PCM [15].

For a specific application, PCM for thermal energy storage in buildings do not meet all the above stated requirements and performance properties. Each material has its own specific poor characteristics, which can be enhanced by proposing different solutions. For example, using metallic fins can increase the thermal conductivity of PCM, introducing a nucleating agent may suppress super-cooling and the use of suitable PCM thickness can prevent incongruent melting [7]. A classification of PCM is given Fig. 4.

2.2.1. *Organic materials*

Organic phase change materials are paraffin and non-paraffin, the latter including fatty acids, ester, alcohols, glycols, etc. . . They have some characteristics making them beneficial to latent heat

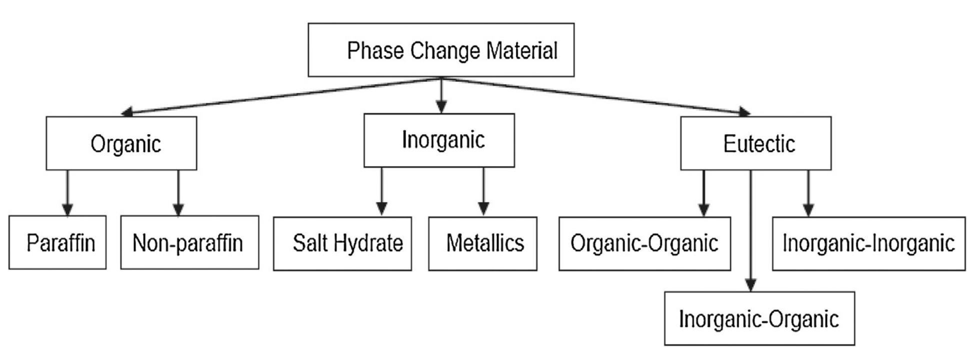


Fig. 4. PCM classification [19].

Table 2
PCM used for cooling applications.

Name of PCM	Melting point (°C)	Latent heat (KJ/Kg)	Reference
Emerest 2325 (butyl stearate + butyl palmitate 49/48)	17–21	138–140	[24]
Hexadecane	18	236	[26]
Heptadecane	18	214	[26]
KF, $4H_2O$	18.5	231	[24]
Butyl stearate	19	140	[29]
Paraffin C16–C18	20–22	152	[32]
Paraffin RT20	20–22	172	[34]
Paraffin FMC	20–23	130	[33]
Dimethyl sebacate	21	120–135	[32]
Eutectic E21	21	150	[34]
Capric-lauric 45/55	21	143	[27]
Salt hydrates Na_2SO_4,$10H_2O$	21	198	[33]
ClimSel C 21	21	122	[34]
Octadecane	22	244	[26]
Capric-palmitate 75.2/24.8	22.1	153	[30]
Paraffin RT25	24	164	[33]
$CaCl_2{\cdot}6H_2O$	24–29	192	[31]
45% $Ca(NO_3)_2\text{-}6H_2O$ + 55% $Zn(NO_3)_2\text{-}6H_2O$	25	130	[32]
66.6% $CaCl_2\text{-}6H_2O$ + 33.3% $MgCl_2\text{-}6H_2O$	25	127	[32]
$Mn(NO_3)_2$,$6H_2O$	25.8	125.9	[28]
Paraffin R27	26–28	179	[32]
SP27	27	180	[33]
Eutectic E23	29	155	[34]

storage in buildings. Generally, organic PCM are available in large temperature range, they are chemically stable, non-corrosive and non-toxic, they freeze with little or without super cooling, they present no segregation, and they have a high latent heat of fusion and good nucleation rate. However, Most of the organic PCM are not stable in higher temperatures due to covalent bonds [7]. Also, their density is low (usually less than 103 kg/m^3), which is below the density of inorganic materials such as water and salt hydrates.

Paraffin are available in a large range of melting points from about 20 °C up to 70 °C, however they have a low thermal conductivity (about 0.2 W/(m K)) limiting their applications [17]. During the freezing cycle, when high heat transfer rates are desired, Paraffin presents a problem. Moreover, they have a large volume change during the phase change [20]. In addition, they are available from many manufacturers but they are expensive comparing to salt hydrates. Paraffin wax is the most used commercial organic PCM.

Fatty acids that are generally presented by the chemical formula CH3 (CH2) 2nCOOH, have similar characteristics to paraffin and they are stable at cycling. The combination of different fatty acids to get melting temperatures ranges of 20–30 °C with a precision of ± 0.5 °C can be promising [7].

2.2.2. Inorganic materials

Inorganic materials are salt hydrates and metallic. They have respectively good thermal conductivity and high latent heat of fusion; they are not expensive and non-flammable. Their main drawback is compatibility with metals, since in some combinations of PCM with metals corrosion can be developed [7]. They require containment; hence, they are inadequate for impregnation into porous building materials.

The most attractive and important TES materials are salt Hydrates, due to their relative high storage density of about 240 kJ/kg, their small volume change during phase transition, and their relative high thermal conductivity of about 0.5W/(m K). Salt hydrates have some disadvantages such as super-cooling, segregation, and corrosion [7]. Concerning Metallic PCMs, they are not within the desired temperature range for building applications.

2.2.3. Eutectics

Eutectics are a mixture of proportions of many solids, in order to get more desired properties mainly a higher latent heat and a more specific melting point. They almost melt and solidify without segregation, preventing the separation of components. Eutectics are divided into 3 groups according to their consisting materials: organic–organic, inorganic–organic and inorganic–inorganic eutectics.

3. PCM for cooling applications

Recently, it has been noticed that the cooling demand of the building sector is increasing rapidly, especially in developing countries, due to: 1) the high need of comfort of building occupants, 2) the rise of the internal heat gains of buildings, 3) the impact of urban heat island felt in overcrowded cities and 4) the reduced cost of cooling equipment [21–23]. Thus Passive or efficient-energy solutions for space cooling have received much attention.

In space cooling, the objective is to keep a space cold, more precisely to avoid the temperature increasing above a certain level, which can be carried out in three ways: the reduction of heat input, the reduction of temperature fluctuations, and the improvement of heat rejection [7].

To meet the cooling requirements, PCM can be installed into the building in passive or active systems. Passive systems do not use active mechanical equipment and no additional energy is required i.e. the heat is charged or discharged only due to temperature fluctuations when the air temperature rises or falls beyond the PCM melting point and only natural ventilation provides cold from outside. Passive applications are easily implemented and can be integrated into the building envelope (walls, roofs, and floors).

On the contrary, Active systems need the help of mechanical equipment to achieve the PCM thermal energy charging or discharging. In this case PCM can be installed in storage units, in HVAC systems or it can be used as heat-cold storage tank in solar cooling technique.

Different PCM cooling system classifications have been suggested in different studies [24,25]. In the current study the PCM cooling systems are divided into five categories: free cooling, solar cooling, air conditioning systems, evaporative and radiative cooling and PCM in building envelope. Active and passive cooling systems could be found together or each alone in these categories. A number of PCM used for cooling applications is listed in Table 2.

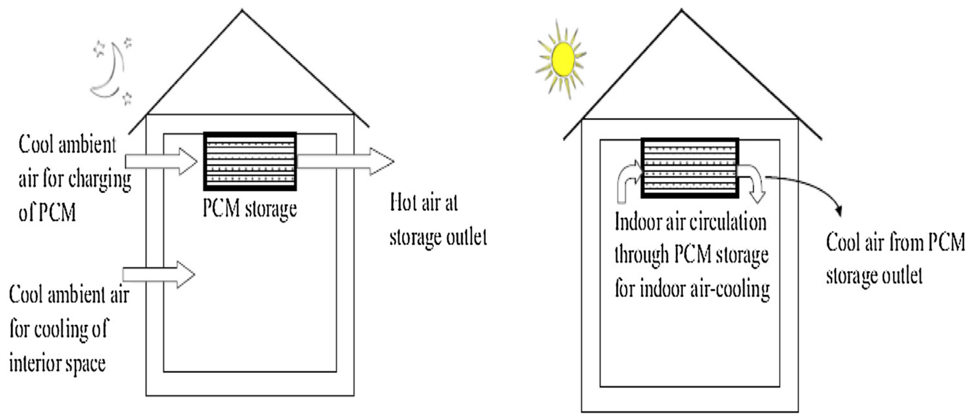


Fig. 5. Principal function of PCM "free cooling system"[25].

3.1. Free cooling

In free cooling technique, a separate storage unit is utilized in order to provide the cold into the room whenever it is required by circulating room air through the storage unit. The difference between the natural night ventilation and free cooling is that fans or other mechanical equipment (extra power) are used to charge or discharge the heat from the storage unit which improves the cooling potential, unlike the night ventilation where building envelope such as walls are used for thermal storage. The effectiveness of PCM-based free cooling application depends on the diurnal temperature range that should be between 12 °C and 15 °C [35]. If the air temperature swing between day and night is relatively small, then other parameters should be accurately considered in the design of free cooling system coupled with PCM i.e. selection of an appropriate PCM with suitable encapsulation [36].

The principle of a free cooling system with PCM, shown in Fig. 5, consists of two operation modes:

- Solidification of PCM: occurs at night when the ambient temperature is lower than the indoor temperature. The outdoor cool air flows across the storage unit, by means of a fan, absorbing heat from PCM, which leads to the beginning of solidification process, which lasts until the outdoor temperature became nearly equal to the PCM solidification temperature.
- Melting of PCM: occurs during the day when the indoor temperature increases above the comfort range. Hot air of the room passes through the storage unit and the heat is absorbed by the solid PCM which leads to the beginning of melting process. Consequently, the room air temperature is reduced and the cooled air is delivered to the interior of the building.

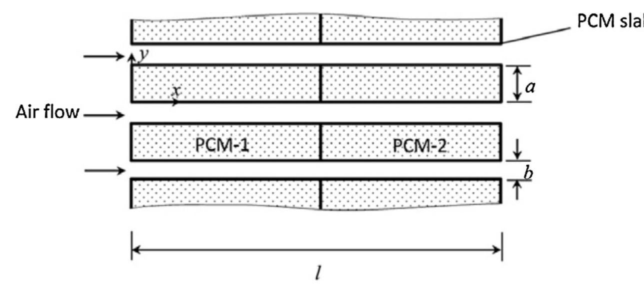


Fig. 6. Schematic diagram of the TES unit. [37].

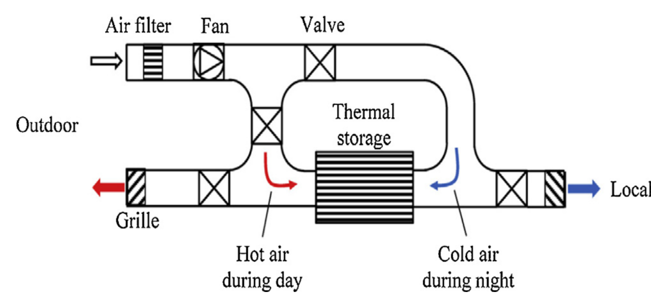


Fig. 7. Installation of thermal storage for free cooling [38].

Many Parameters affect the thermal performance of a free cooling system during charging and discharging such as the air flow rate, the outlet air temperature and the inlet air temperature of the storage unit, in addition to the thermo-physical properties and encapsulation thickness of PCM, which all affect the melting and the solidification processes. Moreover, PCM melting temperature

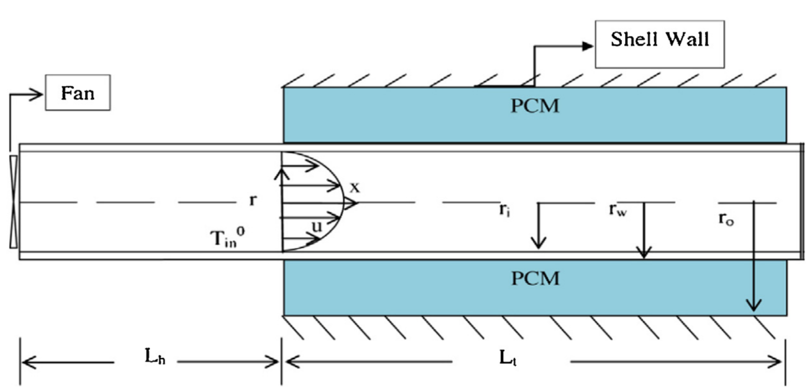


Fig. 8. Schematic diagram of LHS System for air cooling through cylindrical tube [39].

is an important factor in the design of a free cooling system. The cooled air temperature in the room after the discharging of PCM should be within the comfort range (23–27 °C), therefore the PCM melting temperature should be taken between 19 °C and 24 °C [34].

It is found that commercially available PCM having melting point between 20 °C and 27 °C, are often used in the application of free cooling system. In addition, Most of the studies have used paraffin as PCM in the storage unit since they do not react with the encapsulated material (no leakage) and without sub cooling in contrast to salt hydrates which are rarely used.

Many Studies had discussed the efficiency of free cooling system in alleviating the building cooling loads during hot periods. An experimental installation was designed by Zalba et al. [36] to investigate the performance of PCM in free cooling system. The principal parameters affecting the melting and solidification processes were discussed. They concluded that the designed installation is technically and economically beneficial, considering further enhancements such as increasing the heat transfer coefficient and the use of more appropriate PCM. Mosaffa et al. [37] studied numerically, using heat capacity method, the performance of multiple PCM TES unit for free cooling shown in Fig. 6. They investigated the impact of some parameters mainly the thickness and the length of PCM slabs, and the thickness of air channels using energy based optimization method. Another optimization method, based on energy storage effectiveness, was proposed by same authors [38] to enhance the performance of multiple PCM free cooling system (Fig. 7). They concluded that the suggested method is not appropriate for free cooling system optimization, but the model may be advantageous to design an optimum free cooling system at different climates. Anisur et al. [39] aimed to validate experimentally a previous analytical work concerning a shell LHS system (Fig. 8); they concluded that this method is beneficial to design an air cooling system forecasting different parameters.

Rouault et al. [40] investigated numerically the effect of the geometry (shapes and arrangements), of rectangular tubes filled with PCM (Fig. 9), on the LHTES unit performance. They finally suggested a future design support system principally considering the PCM solidification stage. Osterman et al. [41] examined numerically, using Fluent software, and experimentally the performance of a proposed TES system (Fig. 11) on a yearly basis, and they discussed its viability for space cooling and space heating. They concluded that the maximum quantity of cold is accumulated in August and July, due to larger diurnal temperature fluctuations. Darzi et al. [42] investigated the influence of PCM plate thickness, inlet air temperature and mass flow rate on the efficiency of plate PCM storage unit (Fig. 10). They found a linear relation between the PCM-plates thickness and the duration of melting process. Lazaro et al. [43] tested experimentally two prototypes of PCM-air heat exchangers. They concluded that, for free cooling applications, the design of heat exchangers is more important than improving PCM thermal conductivity.

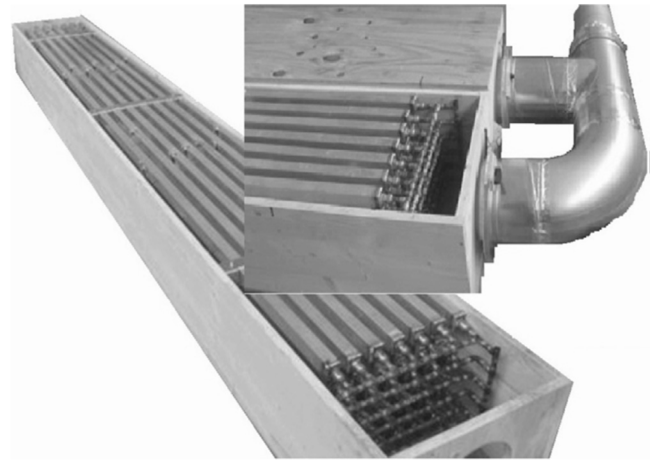
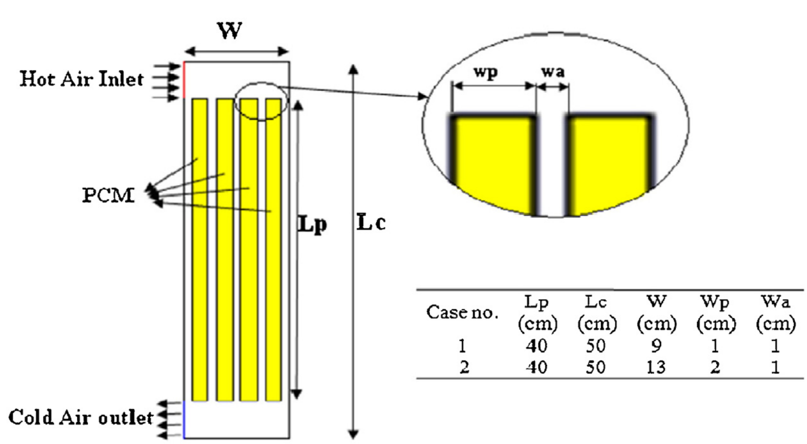


Fig. 9. An energy storage unit and its airline connection [40].

Tan and Zhao [44] investigated the performance of PCM storage unit (Fig. 12) integrated in thermoelectric system using a mathematical model, and then validated it experimentally. They also recommended a guideline on the design of the combined system. They concluded that the selection of TEM depends significantly on three factors namely the COP, cost and cooling power. Yanbing et al. [45] investigated the performance of night Ventilation with PCM (NVP) storage system. They found that the NVP system is efficient and can decrease the room energy consumption. Takeda et al. [46] investigated the potential of a PCM packed bed storage unit (positioned in the building ventilation system) in decreasing the ventilation load for different Japanese climates. They found that during discharging procedure, the outlet air temperature is always constant and in the range of phase change temperature. The use of PCM storage unit can decrease the building ventilation load up to 62% in the different considered Japanese cities. Waqas and Kumar [47] investigated experimentally the performance of free cooling system in hot and dry climate; the storage unit is shown in Fig. 13. They found that a complete solidification of PCM can be achieved in short period when the air flow rate is higher and the outdoor temperatures are lower at night. Moreover, the potential of free cooling principle was also investigated using other different systems: two cylindrical LHTES filled with PCM spheres [48] as shown in Fig. 14, cold storage com-



Case no.	Lp (cm)	Lc (cm)	W (cm)	Wp (cm)	Wa (cm)
1	40	50	9	1	1
2	40	50	13	2	1

Fig. 10. Schematic diagram of heat exchanger with plate-type PCM [42].

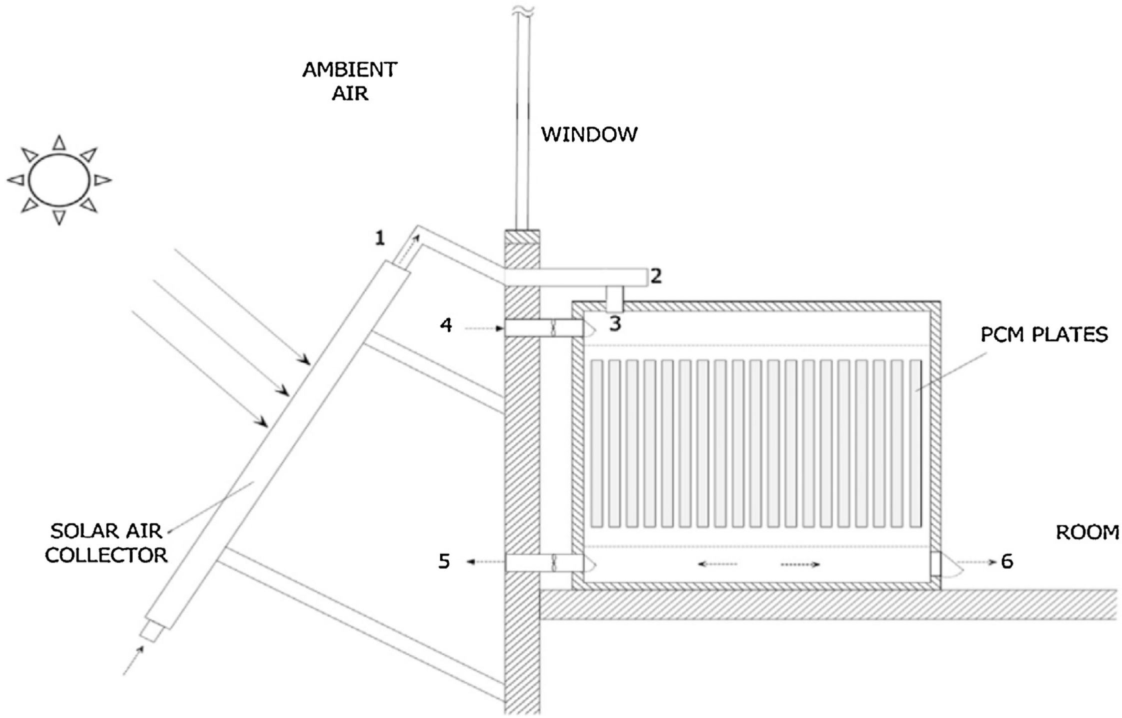


Fig. 11. Conceptual design of a storage unit [41].

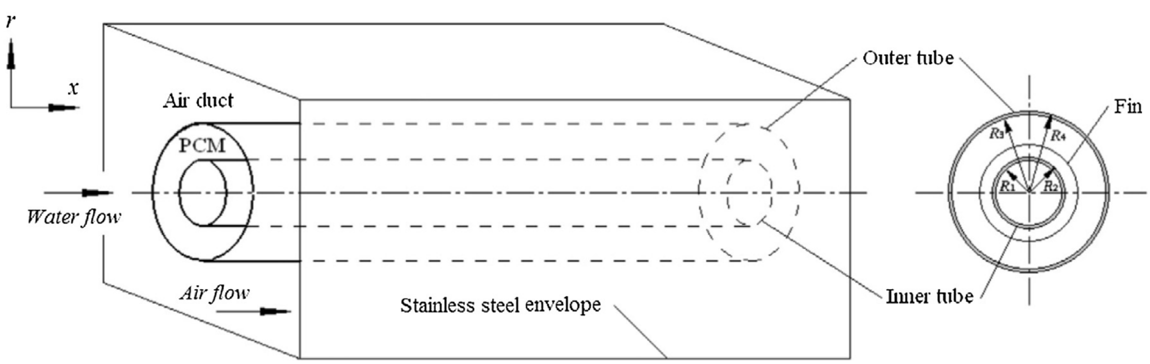


Fig. 12. Schematic diagram and cross-section of the PCM heat storage unit [44].

posed of a metal box [49] built in a ceiling board, with aluminum fins in order to increase its thermal power, heat pipes embedded in PCM [50], PCM packed bed storage [51] integrated under the floor as shown in Fig. 15 and a bulk PCM tank with a finned-pipe heat exchanger [52] (TRNSYS component type 842) as shown in Fig. 16. The free cooling system applications are summarized in Table 3.

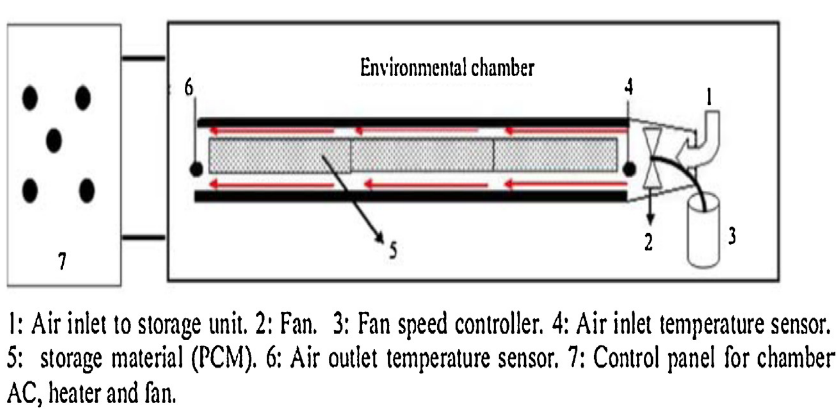


Fig. 13. The experimental PCM storage unit [47].

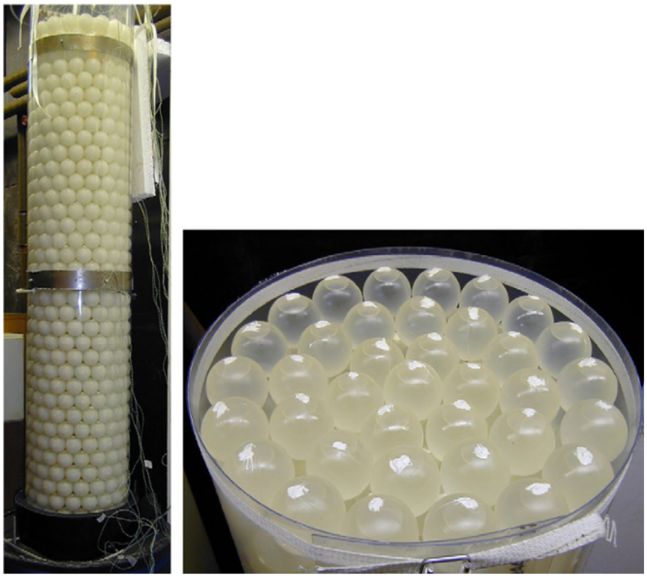


Fig. 14. Cylindrical LHES filled with PCM spheres [48].

It could be noticed that the main component in the free cooling system is the PCM storage unit; moreover, suitable PCM with appropriate melting temperature should be carefully selected. PCM free cooling system technology is not yet commercialized and its initial cost is higher by about 10% than a traditional air-conditioner; keeping this cost competitive with other traditional cooling technologies requires more PCM commercialization [33]. However, it was shown that PCM solidification during the limited period at night is slow due to the low thermal conductivity of PCM; heat transfer improvements are needed. It is also found that free cooling systems are investigated numerically in many studies, and barely any free cooling system was applied in experimental real case for building [25]. Also, the majority of studies investigated the PCM free cooling performance in summer conditions in European climates, however there is a need to evaluate the potential of PCM free cooling system for the desert climate with high diurnal temperature ranges [25].

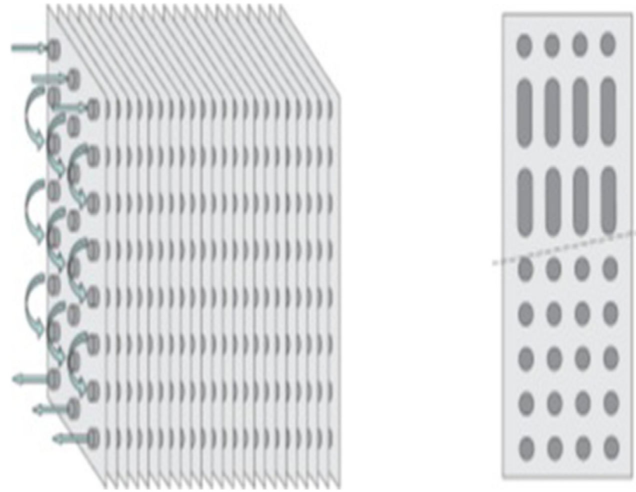


Fig. 16. Heat exchanger considered in TRNSYS [52].

3.2. Solar cooling systems with PCM

Solar cooling systems including adsorption and absorption cooling have been examined in the last few years, and it can be considered as alternatives to traditional air conditioning systems. Moreover, solar powered absorption cooling system can realize summer comfort conditions in buildings at low primary energy consumption. Solar cooling systems can reduce the cooling needs in buildings under hot climate [53]; they can also decrease the peak demand for electricity and consequently reduce the environmental pollution.

The use of PCM with solar absorption cooling, help significantly to meet cooling demand when the solar energy is not available.

Helm et al. [54] examined a solar-driven absorption cooling system coupled with PCM and a dry air cooler instead of a traditional wet cooling tower as shown in Fig. 17. They concluded that by integrating PCM in heat rejection circuit of the chiller, a quantity of required power could be shifted to the off-peak hours with minor rise in total electric consumption of the absorption cooling system. A novel concept for a solar cooling system including dry cooler with PCM had been investigated [55] in order to improve the system

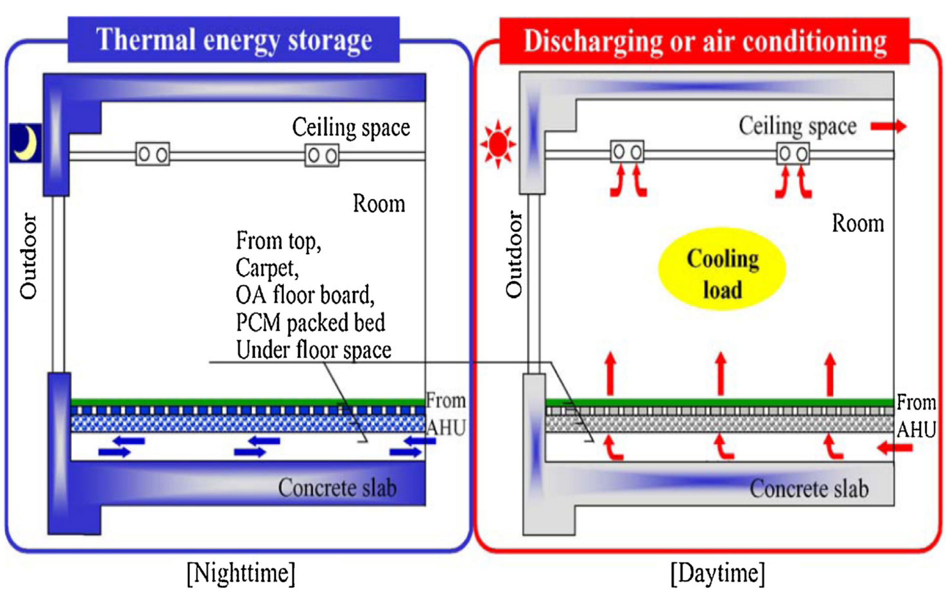


Fig. 15. Concept of the PCM system packed bed storage integrated under the floor [51].

Table 3
PCM in active free cooling system applications.

Ref/Type[a]	Location/climate	Used PCM properties	Heatexchanger	Results
[36] E	Laboratory experiment- Spain	- encapsulated PCM RT25 - $Tm = 25\,^{\circ}C$ - m_{total} PCM = 3 kg	flat plate heat exchanger	Main parameters affecting solidification and melting processes: - Thickness of PCM encapsulation, - air flow, - inlet air temperature - interaction between temperature and thickness
[37] E,S	Tabriz, Iran	- $CaCl_2.6H_2O$, $Tm = 29\,^{\circ}C$ - Paraffin C18, - $Tm = 27.5\,^{\circ}C$ - RT25, $Tm = 26.6\,^{\circ}C$	Parallel rectangular air channels separated by PCM slabs	COP = 7 realized by: - combination of RT25& $CaCl_2.6H_2O$ - air channel thickness = 3.2 mm - PCM slab length = 1.3 m and thickness = 10 mm
[38] E,S	Eindhoven, south of Netherlands	- Climsel C24, $Tm = 24\,^{\circ}C$ - $KF4H_2O$, $Tm = 18.5\,^{\circ}C$	Layers of flat PCM slabs with HTF channels in between	- COP = 7.63 & $Q_{cool} = 4.38$ kW - Air channel thickness = 3.2 mm, length = 1.3 mm, slab thickness = 9 mm & maximum flow rate ~1200 $m^3/h \rightarrow T_{outlet} < 20\,^{\circ}C$ for 8 h & power consumption = 4.6 kW h - Air flow rate < 700 $m^3/h \rightarrow$ optimum $E^* = 0.66 \rightarrow COP < 5.76$ & $Q_{cool} = 2.96$ kW - Air channel thickness $\searrow\searrow \rightarrow E^* = 0.54 \rightarrow COP = 6.22$ & power consumption = 5.8 kWh.
[39] E	Kuala Lumpur, Malaysia	- Heptadecane - $Tm = 22.33\,^{\circ}C$	shell and tube LHS filled with PCM	- $T_{inletair} \nearrow\nearrow \rightarrow$ Better (COP). - $T_{inletair} = 34.5\,^{\circ}C$, tube inner radius = 5.35 mm and 1 mm thickness $\rightarrow COP = 4.16$
[40] E,S	–	- RT28HC paraffin - $Tm = 28\,^{\circ}C$	bundle of rectangular tubes filled with PCM	- Vertical flat plates marginally more effective than horizontal ones. - Improvement of heat exchange between tubes & air are required.
[41] E,S	Ljubljana, Slovenia	- paraffin RT22HC - m_{PCM} in the plate = 1003 g	30CSM Plates filled with PCM & Air gap between plates = 0.8 cm.	- Reduction of annual energy consumption = 142 kWh. - In July and August: complete TES cycles & stored energy rises. - TES cost = 2 × cost of a conventional system. - TES cost in the operation period is lower.
[42] S	different indoor temperature conditions	- PCM salt SP22A17 - $Tm = 22–24\,^{\circ}C$	PCM plates type storage	- Mass flow rate $\nearrow\nearrow \rightarrow$ cooling power $\nearrow\nearrow$ - Stefan number $\nearrow\nearrow \rightarrow$ cooling power & T_{outlet} $\nearrow\nearrow$ - Lower mass flow rate & lower Stefan number $\rightarrow$ more efficient heat exchanger.
[43] E	Zaragoza, Spain	- inorganic PCM: Ks = 0.7 w/m k - Stored energy = 31.584 kJ - organic PCM: Ks = 0.16 w/m k - Stored energy = 24.395 kJ	2 prototypes: - aluminum pouches filled with inorganic PCM - aluminum panels filled with organic PCM	- Lower Ks and lower stored energy $\rightarrow$ cooling power $\nearrow\nearrow$ & shorter melting period - Prototype 2 more practical for free-cooling.
[44] E,S	Denver, Colorado, USA	- organic paraffin RT22 - $Tm = 19–23\,^{\circ}C$(main peak = $22\,^{\circ}C$) - m_{total} PCM = 15.4 kg.	Shell and tube PCM storage unit incorporated in thermoelectric cooling system	- PCM integration $\rightarrow$ COP $\nearrow\nearrow$ from 0.5 to 0.78 - determining PCM volume depends on system accumulated heat dissipation. - Necessity to evaluate the weather condition to ensure fully discharging of PCM at night.
[45] E,S	Beijing-China	- 2000 capsules containing fatty acid - $Tm = 22\,^{\circ}C–26\,^{\circ}C$, - m_{total} PCM = 150 kg.	PCM Packed Bed Storage (NVP)	- NVP reduces the room temperature and increase thermal comfort level. - during day, PCM discharged 300 w cold to the room - $COP_{overall}$ (Qdis/P fan) = 80.

Table 3 (*Continued*)

Ref/Type[a]	Location/climate	Used PCM properties	Heatexchanger	Results
[46] E,S	8 Japanese cities	- PCM granules (65% ceramic and 35% paraffinic hydrocarbon), - Tm = 22.5–25 °C - m_{total} PCM bed = 4.59 kg	PCM packed bed fixed vertically in a supply air duct.	- Selection of PCM depends on climatic data particularly on the diurnal temperature variation. - Significant reduction in ventilation load in all cities, especially in Kyoto by about 62.8%.
[47] E	Islamabad-Pakistan/dry and hot climate	- SP29 encapsulated in containers of galvanized steel - Tm = 27–29 °C - m_{total} PCM = 13 kg	PCM storage unit: open air circuit type (flat plate heat exchanger)	- decreasing $T_{charging}$ from 22 °C to 20 °C → 33% less time required to fully solidify the PCM - increasing $T_{charging}$ from 22 °C to 24 °C → 52% more time required to fully solidify the PCM. - Increasing air flow rate from 4 m^3/h to 5 m^3/h → 16% reduction of solidification time period. - Tm of PCM affects the storage unit performance more than the air flow rates.
[48] E,S	Ljubljana- Slovenia/latitude = 46 °C	- RT20 paraffin - Tm = 20 °C	2 cylindrical LHTES units filled with PCM spheres, integrated into MVS	- Optimum PCM mass in both LHTES units: 6.75 kg/m^2 (heavyweight bldg.) and 13.5 kg/m^2 (lightweight bldg.) - mechanical ventilation size is reduced - more favorable temperatures are provided.
[49] E	Lab scale experiment Ljubljana-Slovenia	- RT 20 paraffin - Tm = 22 °C - m_{total} PCM = 3.6 kg	metal box with external and internal fins filled with PCM	- $T_{outletair}$ (when airflow = 1.5 m s^{-1}) < $T_{outletair}$ (when airflow = 2.4 m s^{-1}). - proper selection of PCM type depends on local climate conditions. - Inlet air temperature = 26 °C and airflow = 1.5 m s^{-1} → greater air cooling time by the buffer compared to other regimes
[50] E,S	Typical UK summer conditions	- Salt hydrate (Na_2SO_4,$10H_2O$) - Tm = 21 °C.	heat pipes embedded in PCM storage unit	- ΔT = Tm − $T_{charging}$ ↗↗ → Better solidification: - higher air flow rates (→full solidification) - free cooling → prevents overheating in summer, and reduces CO_2 emissions. - ΔT between air and PCM˜15 °C → PCM melting and solidification in practical time (7 ± 10 h). - Heat transfer <40 W when temperature difference is 5 °C (more reasonable) and flow rates 0.18 m^3/s.
[51] E,S	Japan	PCM granules with diameter of some micrometers containing paraffin.	PCM packed bed storage	Each night, 89% of daily Qcool is stored using 30 mm thick packed bed of granular PCM.
[52] S	Stockholm/Swedish climate excessive overheating in summer	- Commercially available salt based PCM - Tm˜17 °C (close to the average summer temperature in Stockholm)	bulk PCM tank with a finned-pipe in an aluminum based heat exchanger	- Active free cooling keep the room temperature within indoor comfort range. - 75% of the cooling demands are met at half of electricity consumption. - free cooling is an economically and environmentally proper solution for a passive building.

[a] E: experimental, S: simulation.

efficiency. The operating costs and maintenance for the new developed system are lower, compared to the wet cooling tower. On hot days, PCM support the dry cooler to assure a low cooling water return temperature to the absorption chiller. At the University of Lleida, Gil et al. [56–58] developed a TES system for solar cooling application shown in Fig. 18 (pilot plant at the laboratory), in order to be used later in real installation for cooling purposes on the roof of a building in Seville [58]. The storage tank implemented in real solar cooling installation is shown in Fig. 19. In the experiment, a dry cooler was used to remove heat instead of the absorption chiller and an electrical boiler was used to provide heat instead of the solar collector. They also tested two PCM storage tanks (shell-and-tubes heat exchanger) one with fins and the other without fins [57]. They concluded that in the design of a real PCM storage tank, the dead PCM volumes must be avoided.

Belmonte et al. [59] investigated the performance and the feasibility of an alternative solar cooling system where the open wet tower is replaced by a dry cooler combined with PCM TES system (Fig. 20). Then, conventional and alternative configurations were simulated and compared for different climate conditions. They concluded that the conventional system is more efficient, at all locations, in terms of chiller's COP and produced cooling energy, but in terms of overall system COP, the system efficiency is improved by 50% in the alternative configuration. Furthermore, Agyenim et al. [60] designed a tube heat exchanger with PCM in order to improve the COP of LiBr/H_2O absorption cooling system. It has been found

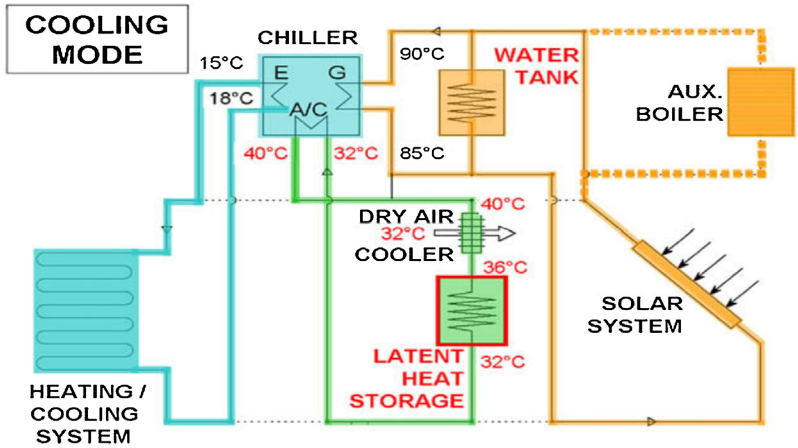


Fig. 17. Solar heating and cooling system with absorption chiller and latent heat storage in cooling mode [54].

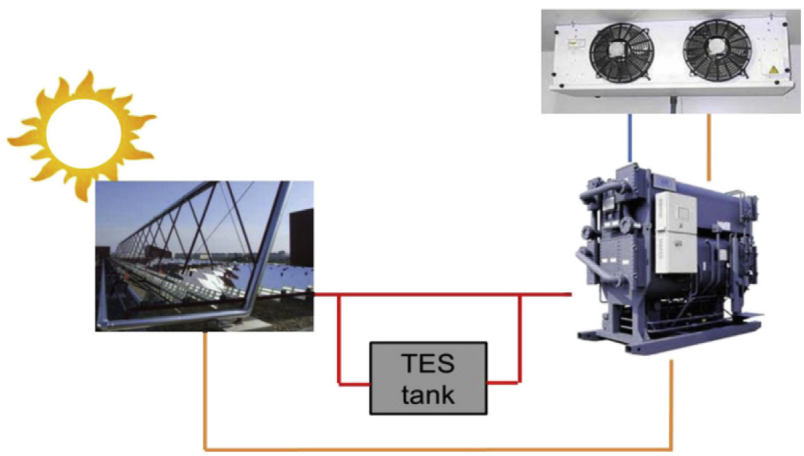


Fig. 18. Location of PCM storage tank in the solar cooling application [58].

that the chosen PCM was appropriate to improve the COP of the solar cooling system. The solar cooling systems combined with PCM applications are summarized in Table 4.

3.3. PCM-air conditioning systems

Air conditioning systems control several changes such as weather conditions, residential, commercial and industrial activities. Thus during the day, the electrical consumption varies considerably and reaches peak values. Integrating PCM in AC system could significantly reduce the cooling load, where AC with smaller power size could be used. Fang et al. [61] tested the performance of an AC system incorporated with PCM spherical capsules packed bed. They investigated different parameters mainly the cool storage rate and capacity, the condensation and the evaporation pressures of the refrigeration system, the COP of the

Fig. 19. Storage tank implemented in a real solar cooling installation at the University of Sevilla (Spain) [58].

Table 4
PCM combined with solar cooling system applications.

Ref/Type[a]	Location/climate	Used PCM properties	PCM-solar system	Results
[54] E	Munich, Germany	- calcium chloride hexahydrate ($CaCl_2$,$6H_2O$) - Tm = 27–29 °C	- PCM & dry air cooler in solar-driven absorption system - PCM support heat rejection of absorption chiller	- PCM instead of conventional WHS → Volumetric storage density 10 times higher. - Reduction of over-sizing of the solar collector
[55] E,S	8 European climatic conditions	- Calcium chloride hexahydrate - Tm = 29 °C	- PCM with dry re-cooled sorption chiller - LHS module with inner heat exchanger containing 1 m^3 of PCM	- In situ measurement → positive effect on SEER for cooling by 11.4. - Simulation → efficiency ↗↗ up to 64% compared to system with only dry re-cooling(without PCM)
[58] E	Lleida & Seville, Spain	- PCM: Hydroquinone - Tm = 166 °C–173 °C	PCM storage tank with absorption chiller and Fresnel collectors	- Tank with fins → shorter melting/solidification time, PCM conductivity↗↗, heat transfer rates↗↗, energy stored faster - fins → money & time investment↗↗, PCM quantity & stored energy ↘↘ → rejection of using fins in real applications.
[59] S	52 provinces of Spain	- hydrated salts. - Tm = 30 °C	PCM in the heat rejection loops of absorption chillers	Alternative system with PCM TES: - In temperate & humid summers → COPsys improved by one unit. - Reduction of total cooling energy in evaporator (21–38%) - worsening of mean performance coefficient of chiller (between 7 & 13%).
[60] E	Cardiff, Wales.	- Erythritol - Tm = 117.7 °C	PCM at the hot side of absorption chiller with solar collector	Erythritol suitable for the application, provide ˜4.4 h of cooling at peak load

[a] E: experimental, S: simulation.

system, the inlet and outlet coolant temperatures during charging and discharging periods and others. They concluded that the AC system incorporated with PCM showed better performances. Fig. 21 shows their investigated experimental system. Chaiyat [62] installed a PCM bed in the return duct of an AC system (Fig. 22) in order to reduce the air temperature that enters the evaporating coil and thus improving the cooling efficiency of the AC.

A tube-in-tank off-peak PCM storage system shown in Fig. 23, incorporated in a domestic chiller, was modelled and simulated by Bruno et al. [63] using ε-NTU technique (effectiveness-number of transfer units) to determine the instantaneous heat transfer. Zhao and Tan [64] aimed to increase the cooling COP of a conventional

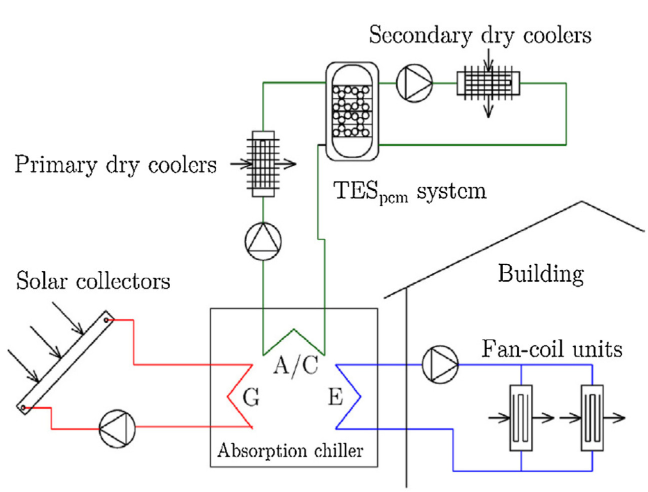


Fig. 20. Solar cooling system with dry coolers and a TES PCM [59].

AC by integrating a shell-and-tube PCM thermal storage unit that uses water (for charging loop) and air (for discharging loop) as a HTF. Fig. 24 shows the AC integrated with PCM and a cross-section of PCM thermal storage unit. They investigated the impact of HTF mass flow rate, inlet temperature and fin height on PCM system performance. Results showed that optimization should be carried out, depending on the cooling load profile, in order to design HTF mass flow rate and fin height. The air-conditioning systems combined with PCM applications are summarized in Table 5.

3.4. Evaporative and radiative cooling systems

Direct Evaporative cooling strategy is a way to cool the air by evaporation of water. More precisely, evaporation of water allows the absorption of the heat and thus the air is cooled. After evaporation, the water vapor transfers the absorbed heat to the air as latent heat. Thus the humidification of air occurs and the total enthalpy of air barely changes. The cooled and the humidified air are therefore used for cooling purposes in building especially under dry and hot climates. Indirect evaporative cooling is more suitable for humid climates, due to the humidity added to the air by separating air and water. The evaporative cooling system is investigated in the Darmstadt house (2009) [66]. Other attractive cooling strategy is the night radiative cooling (losing heat by thermal radiation), suggested by the Technical University of Madrid in 2007 and used by Rodriguez-Ubinas et al. [67,66] in the Darmstadt house (2007). Moreover, Zhang and Niu [68] investigated a hybrid system (Fig. 25) which is a combination of a nocturnal radiative cooling coupled with microencapsulated PCM slurry storage tank (Tm = 18 °C) in order to evaluate its cooling performance in buildings. The investigations were carried out under different climatic conditions in five cities in China (from north to south: Urumqi, Beijing, Lanzhou,

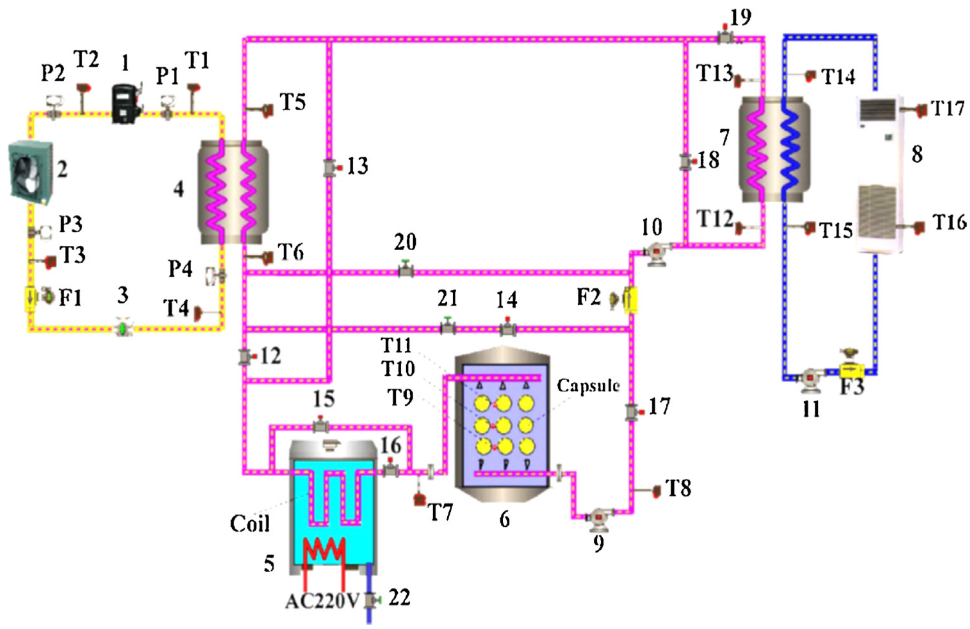


Fig. 21. Schematic diagram of the AC experimental system with PCM [61].

Shanghai and Hong Kong). The results showed that the energy savings in Lanzhou and Urumqi are up to 77% and 62% for low-rise buildings respectively, and Hong Kong under hot and humid climate showed the weakest performance. Authors recommended using this hybrid system in cities where the temperature is low at night and the weather is dry (north and central China).

Ansuini et al. [69] developed radiant floor panels with granulated PCM showed in Fig. 26 (Ts = 24 °C and Tm = 29 °C) with incorporated pipes for heating and cooling. The primary results showed that the PCM panels could be useful in summer but their performance was unhelpful in winter. The increased resistance between pipes and the melted granulated PCM is the cause of the bad performance of PCM panels during the heating season. With the aim to decrease the thermal resistance of granulated PCM, a special steel matrix (act as thermal diffuser) was designed to optimize the internal structure of the radiant floor. A numerical simulation was carried out after this optimization in winter, mid-season and summer season. It was concluded that in summer season, the quantity of cooling water to keep the temperature in comfort range was reduced by 25%, however in winter season there is no effect. In the mid-season, the floor temperature peak was reduced by about 3.5 °C. This system is effectively beneficial to maintain the room temperature comfortable without any extra energy source.

Wang et al. [70] proposed a hybrid system consisting of cooled ceiling, microencapsulated PCM slurry storage (hexadecane C16H34 particles and pure water, Tm = 18.1 °C) and evaporative

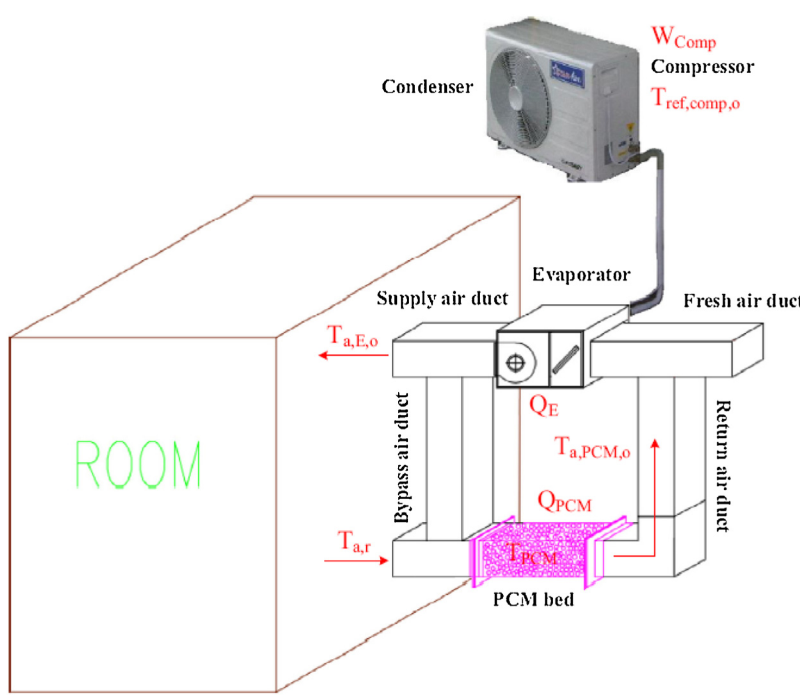


Fig. 22. Prototype of the air-conditioner integrated with the PCM bed [62].

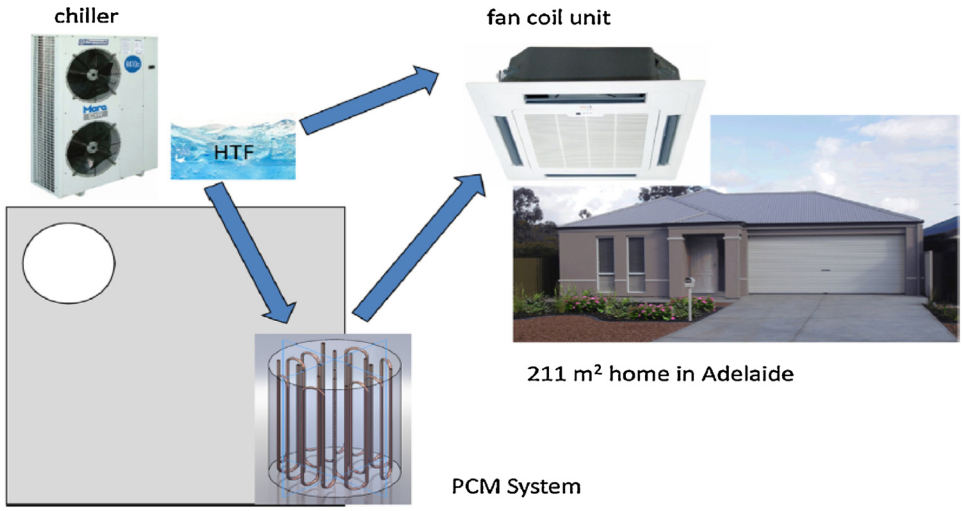


Fig. 23. Schematic diagram of domestic cooling system with PCM storage unit [63].

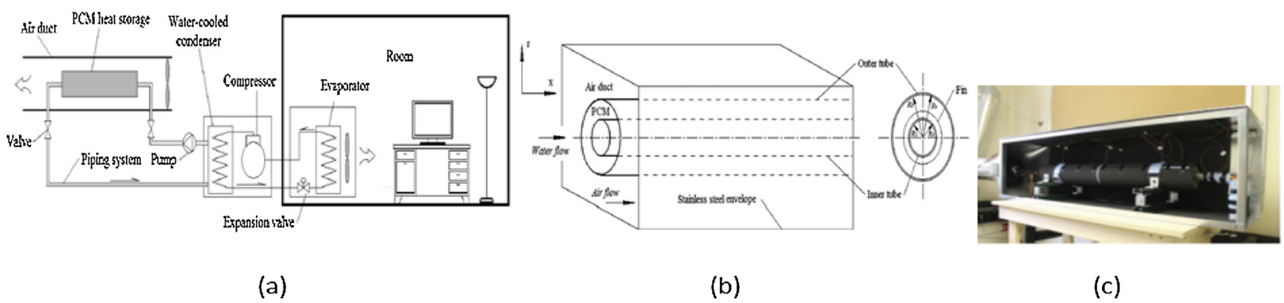


Fig. 24. (a) Schematic diagram of AC integrated with PCM thermal storage, (b) cross-section of the PCM thermal storage unit, (c) photo of PCM thermal storage unit during heat charging process [64].

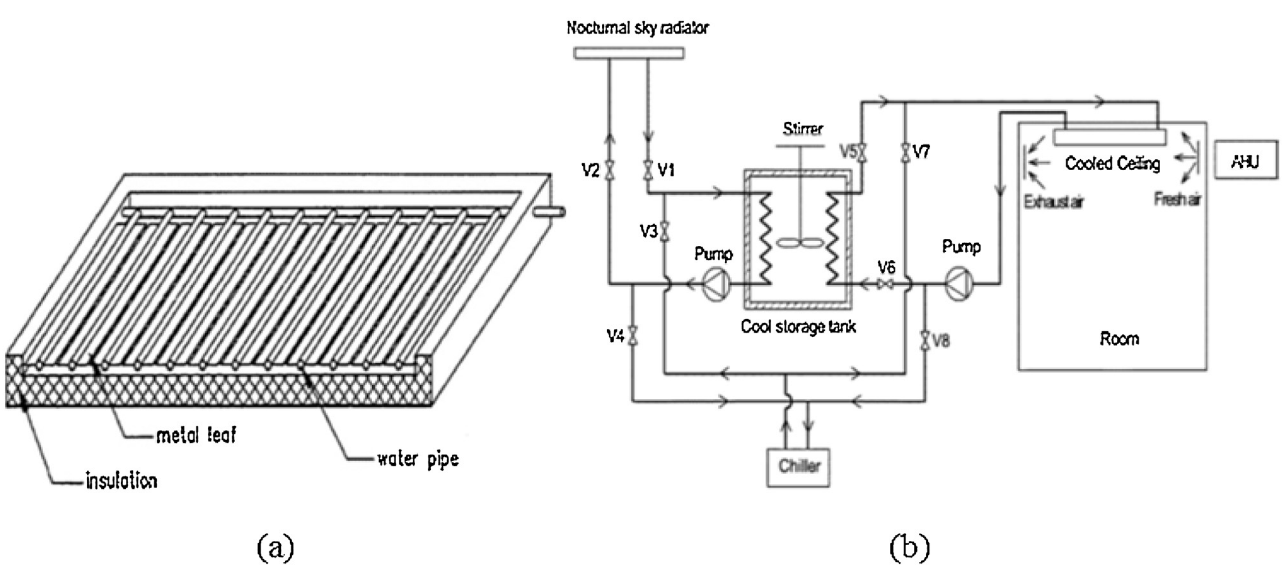


Fig. 25. (a) Construction of the nocturnal sky radiator, (b) schematic diagram of the hybrid system [68].

cooling technique shown in Fig. 27. They evaluated the system in five cities in China under different climatic conditions. The cooling energy produced by the evaporative cooling system is stored by the MPCM slurry storage. The results showed that energy savings reached 80% under northwestern Chinese climate (Urumqi), about 10% under southeastern Chinese climate (Hong Kong) and between these two values for the other three cities (Shanghai, Beijing, Lanzhou). This hybrid system is suitable for cities under dry climate with high diurnal temperature difference.

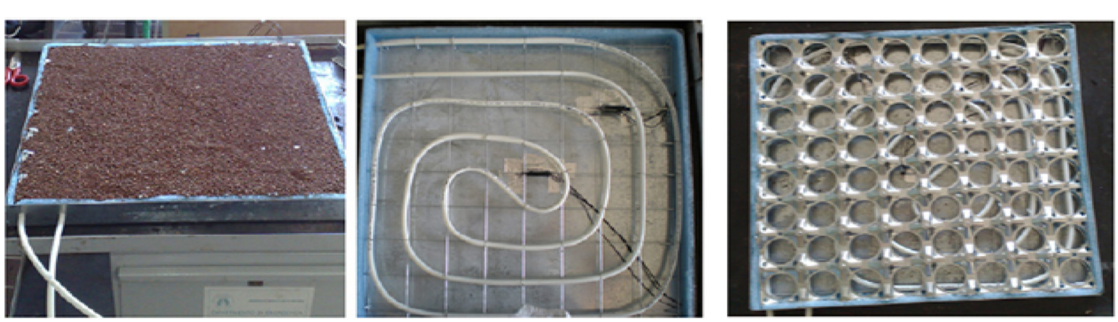
3.5. PCM in building envelope

The previous sections presented PCM used as a separate storage unit installed with other mechanical equipment which were

Table 5
PCM-air conditioning system applications.

Ref./Type[a]	Location/climate	Used PCM	PCM-AC system	Results
[61] E	Lab experiment in China	Water used as PCM (183 spherical capsules)	cold storage AC system with spherical PCM capsules packed bed, consisting of refrigeration & charging and discharging circulation systems	- In case of charging: cold storage rate ↘↘ from 12.3 kW to 2.2 kW & cold storage capacity = 59.7 MJ - In case of discharging: cold discharge rate ↘↘ from 8.5 kW to 3.4 kW & cold storage capacity = 45 MJ - Outlet air temperatures remained between 20.7 °C & 24.4 °C.
[62] E,S	Chiang Mai, Thailand	- RT20 - Tm˜19–22 °C	- PCM in group of plastic balls kept in packed bed with thickness 40 cm.	- Use of packed ball bed of PCM → significant reduction in energy consumption of air-conditioner for air cooling. - Electrical power of PCM-air conditioner system could be saved˜9%. - The payback period of PCM˜4.12 y. - PCM ball integrated with air-conditioner seemed beneficial & highly effective.
[63] S	Adelaide, Australia/semi Mediterranean climate	- Hf = 220 kJ/kg, ρ= 1200 kg/m^3, ks = 1.5 W/m K & kl = 1.2 W/m K - Different Tm = 0,4,7,10 °C	PCM thermal storage unit coupled to chiller with an inverter driven scroll compressor	- 85% of energy consumption for cooling shifted to off-peak period. - Tm & Ts ↗↗ → energy consumption ↘↘ - PCM with Tm = 4 °C → possibility to attain an energy saving for cooling. - PCM with Tm = 10 °C → energy savings˜13.5% - Energy usage ↗↗ with a more efficient PCM storage system. - Optimal charging during coldest time at night → energy consumption ↘↘ - kl ↗↗ → amount of discharging at daytime ↗↗ & significant load shifting
[64] E,S	Laramie, Wyoming, USA	- PCM RT22 - Tm = 19–23 °C (main peak: 22) - m_{total} PCM˜6.3 kg	- AC integrated with shell-and-tube PCM thermal storage system - Function of PCM: heat sink to the AC during day cooling period.	- In heat charging process: T_{inlet} HTF (water), mass flow rate & fin height ↗↗ → PCM heat charging rate ↗↗ & total charging time is shorter. - In heat charging process: HTF (air) mass flow rate ↘↘ → save fan energy consumption. - Effectiveness of PCM storage system > 0.5. - PCM storage system instead of conventional cooling tower for a water-cooled AC → COP ↗↗ by 25.6%.
[65] S	Nagoya-Japan	PCM mixtures of paraffin waxes	Air distribution system (AC) equipped with a PCM storage tank for peak shaving	- In Nagoya, 400 kg of PCM for 73.8 m^2 of room surface (5.4 kg/m^2) are optimum values to maintain a constant room temperature without the need of cold source operation. - Appropriate PCM melting temperature was about 19 °C.

[a] E: experimental, S: simulation.



(a) (b) (c)

Fig. 26. (a) Metal container with pipes and supporting metal net, (b) specimen filled with the granular PCM (c) optimized specimen with the steel matrix [69].

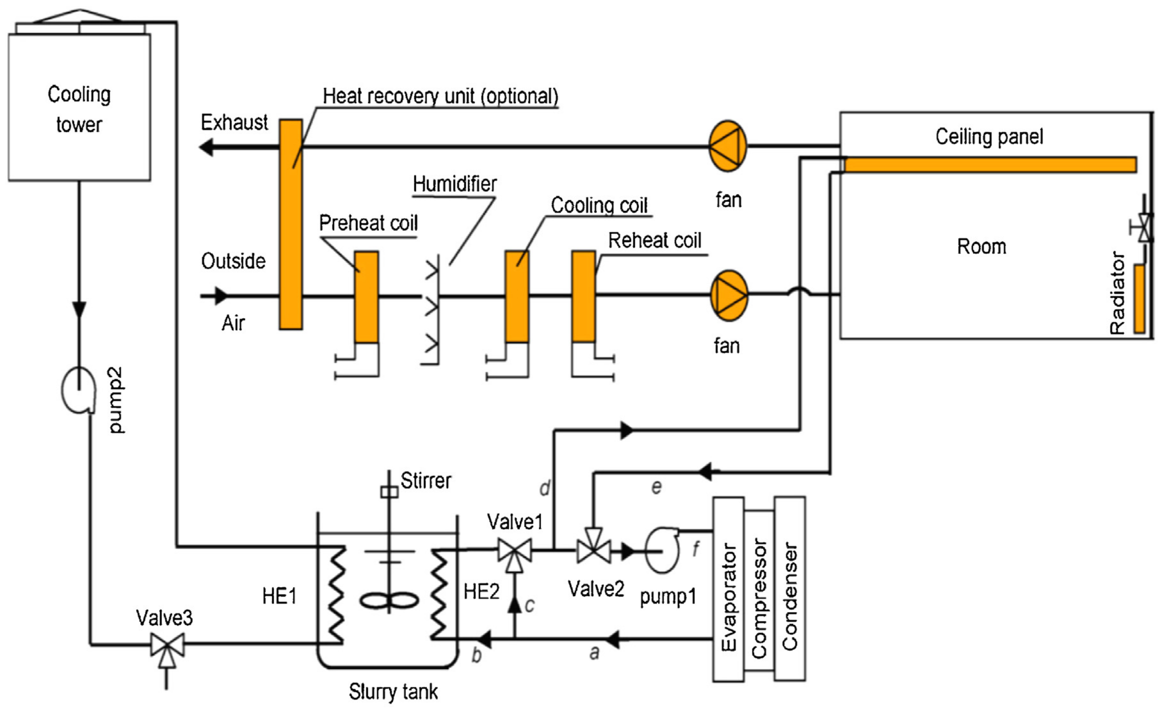


Fig. 27. Schematic diagram of the hybrid system [70].

considered mostly as active systems. The installation of such systems needs a specific place in the building, which is considered an important disadvantage for the designers and users. As a solution for this drawback, PCM can be integrated into building envelopes i.e. walls, roofs, and floors as part of building structure or as building component and can be installed whether in passive or active system. The PCM integration into the building envelopes has attracted a great interest in the last 10 years.

3.5.1. PCM passive system applications in the building envelope

Some authors [7,66] classified passive system applications in the building envelope into two main categories:

- PCM "integrated" into building materials: when they are incorporated to a building construction material such as plaster with microencapsulated paraffin, gypsum plasterboards with microencapsulated paraffin, concrete with microencapsulated paraffin, panels with shape-stabilized paraffin [7], and blending PCM with thermal insulations. The main benefit of PCM-enhanced insulation is their capability to reduce and shift significantly the peak hour thermal loads of the building envelopes [12]. The team of Germany (2009), in a group work [67], have used microencapsulated PCM integrated into drywall panels as the interior finishing of a German house for cooling periods. These panels contain Micronal microscopic polymer spheres filled with paraffin wax developed by BASF Company. The selected PCM (Tm = 26 °C) starts to absorb heat when the room temperature rises above PCM melting temperature, reducing overheating, where excess heat is stored in the walls. At night the heat is discharged, since the air temperature drops below the PCM switch temperature thanks to night ventilation. As a result, a more regular space temperature is provided, since temperature peaks are cut off, and thus the need of a mechanical conditioning system is minimized [66].

- PCM as "component": the main difference between building components equipped with PCM and PCM integrated into building materials is that a component can be manufactured before the building being constructed and have a particular design. Blinds with integrated PCM are considered as an example for PCM component. In fact, solar gains through windows are considered one of the major sources of heat input into a building. Thus to avoid direct solar radiation, blinds equipped with PCM (Fig. 28) can be used, it can be fixed inside the building or outside in front of the window. Integration of PCM into the internal blinds can reduce and delay the temperature rise of the blinds, and then the heat release into the room is delayed. The notion of internal blinds with integrated PCM is shown in Fig. 29. The company ZAE Bayern and Warema (project "Innovative PCM-technology") [7], have tested a room under realistic conditions to investigate the reduction and the delay of the temperature rise of the blinds by integrating PCM. Compared to the conventional blinds, the room air temperature was around 2 K less; the temperature rise of the blinds decreased approximately 10 K, and was delayed by about 3 h. The numerical simulation showed that the operative temperature of the room decreased approximately 3 K and the thermal comfort in the room improved largely.

Suspended ceilings with PCM are considered as an example for PCM component; salt hydrates are used and are encapsulated in plastic containers, in bags or in metal containers. The company Dörken sells a full range of PCM under the brand name DELTA®COOL

Fig. 28. Internal blinds with integrated PCM [7].

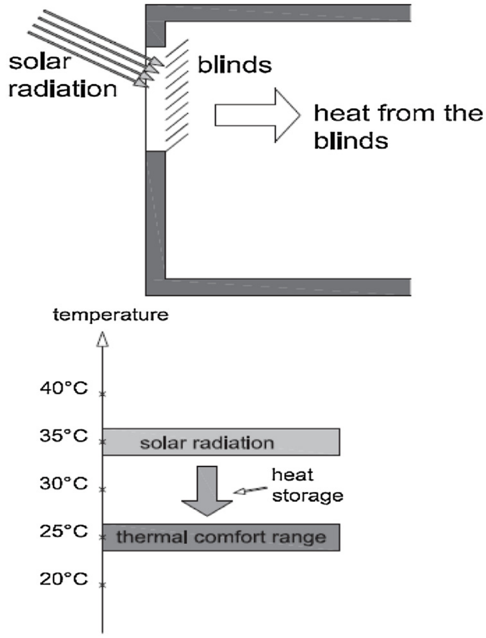


Fig. 29. Internal blinds absorb solar radiation in order to cool the space by reducing the solar heat input [7].

system and it can be installed in ceilings or floors [7]. A system was designed by Ontario team [66] using the commercial PCM product DELTA-COOL 24 shown in Fig. 30 which consists of salt hydrates encapsulated in 15 mm polypropylene panels with a melting temperature of 24 °C, and a solidification temperature of 22 °C. A gross area of 62.1 m^2 of PCM panels was installed; each panel had a heat storage capacity of 62.6 kWh, with a melt enthalpy of 158 kJ/ kg. The team used "DRSS" concept to develop a house envelope, where exterior shades are one of the basic components that respond to the change of external conditions. The shades change their angles between perpendicular and parallel to the sun's rays as required, keeping the indoor temperature comfort. During the day, when cool is needed, the shades eliminate undesirable solar gains by preventing the solar radiation to reach the glazing, PCM remove the excess heat and then reduce the cooling peak. During the night, the PCM release the stored heat into the cool night air due to the activation of an air force night ventilation system.

Moreover, Kalnæs and Jelle [71] presented many examples of integration of phase change materials for passive systems, exploring possible areas and materials where PCM can be usefully incorporated. And they divided these examples to five different

Fig. 30. Delta Cool 24, upper face of PCM panel [7].

Fig. 31. PCM enhanced gypsum board [12].

categories according to the location of integration of PCM: in walls, floors, roofs, windows/shutters, concrete, thermal insulation materials and furniture. Moreover, Pomianowski et al. [72] presented various construction materials of the building (gypsum and wallboards, concrete, bricks) which were blended or combined with PCM in passive systems. Zhue et al. [73] presented an extensive list of PCM passive systems investigated experimentally with important results. Different possibilities of the use of PCM and their application in the American Solar Decathlon, including the descriptions of the systems and the factors that affect their performance, as well as results of simulations and experimentation were presented by Rodriguez-Ubinas et al. [66]. Soares et al. [74] also explored PCM application in passive systems, and investigated the effect of these systems on the energy performance of buildings. Some examples of passive system applications are presented in the following, according to the location of PCM integration:

- PCM in wall/wallboard: installation of PCM wallboards in the inner side of the building envelope is the most general and suitable solution for implementing PCM into buildings. Fig. 31 shows PCM gypsum board. During the last years, many studies (numerical/simulation, experimental or both) investigated a large variety of this type of materials. Scalat et al. [75] believed that the human comfort can be maintained for longer periods using PCM wallboard, after the heating or cooling system was stopped. Kuznik et al. [76] investigated a renovation project in the south of Lyon-France using PCM wallboards. By testing a room in the same building that was renovated without PCM and then comparing it to the room with PCM, they concluded that the PCM increased the indoor thermal comfort, but it appeared unable to use its latent heat storage capacity for a number of durations due to the incomplete discharge overnight. Athienitis et al. [77] investigated the thermal performance of PCM gypsum board in a direct-gain outdoor test room. The results showed a reduction of the room temperature by a maximum 4 °C during the daytime. Neeper [78] investigated the thermal dynamics of room with fatty acid and paraffin waxes gypsum wallboard. The results showed that the maximum diurnal energy storage is occurred when the melting temperature of PCM was chosen close to the average room temperature.

- PCM in floors, roofs and ceilings: incorporation of PCM in floors that are in direct contact with solar radiation could be an effective solution for thermal energy storage. Xu et al. [79] investigated the thermal performance of PCM floor system in passive solar buildings. This performance is affected by several factors such as the choice of covering material, thickness of PCM layer, PCM melting temperature, its thermal conductivity and heat of fusion, and the air gap between the PCM and covering material. The results showed that the thickness of PCM should not be greater than

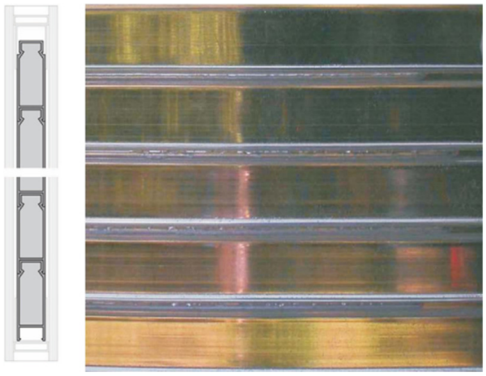


Fig. 32. Illustration of a PCM filled window [71].

20 mm and the heat of fusion and thermal conductivity of PCM should respectively exceed 120 kJ/ kg and 0.5 W/m K.

Incorporation of PCM into roof systems has not gotten too much attention, Pasupathy and Velraj [80] investigated the performance of a double layer of PCM incorporated into roof in Chennai, India. Inorganic eutectic of hydrated salts used as PCM was incorporated into roof panels of a room and then it was compared experimentally to a room without the PCM panel. The results showed that the indoor air temperature swings can be narrowed due to the PCM roof panel, and that this system can be suitable all seasons when the upper PCM layer had a melting temperature 6–7 °C greater than the ambient temperature during summer and the lower PCM layer had a melting temperature close to the indoor temperature. A naturally ventilated roof with a photovoltaic (PV) module with PCM in Oak Ridge, Tennessee was developed by Kośny et al. [81]. Reducing heating loads and cooling loads during winter and summer respectively was the main objective of this system, in winter PCM absorb heat during the day and release it at night while in summer PCM absorbs excess heat. The results showed that heating loads and cooling loads were reduced by 30% and 55% during winter and summer respectively; additionally it was observed that peak daytime roof heat fluxes were reduced by about 90%.

- Windows and shutters: in cold climates great parts of energy are lost due to glazed facades, which increase the need for heating while in warm climates excessive solar heat gain increases the need for cooling, Fig. 32 shows PCM filled window. Ismail et al. [82] investigated a glass window in a hot climate (Brazil) with incorporated PCM. After comparing PCM window with another glass window filled with absorbing gas, it was shown that the amount of heat penetrating into the room was reduced while PCM melts, even though the U-value of windows was increased due to addition of PCM. Goia et al. [83] studied the effect of PCM incorporated into glazing on the thermal comfort in three different seasons. After comparing the PCM prototype to a traditional double glazing, it was shown a significant improvement in thermal comfort conditions during all periods of the year except on cloudy days. Additionally, the authors emphasized the importance of the correct selection of PCM melting temperature. Weinlaeder et al. [84] investigated a solar shading system with integrated salt hydrate PCM having a melting range between 26 °C and 30 °C in office rooms. After comparing rooms with PCM blinds to rooms with traditional blinds, it was shown that the air temperature is lower by about 1–2 K in the PCM blinds room in summer while in winter PCM blinds do not affect the heating power. It was found that the main problem of PCM blinds is their renovation at night. The use of mechanical or natural ventilation was useful to fully regenerate the PCM at night.
- PCM in concrete: the general objective of incorporating PCM in concrete materials is to increase heat storage of heavy construction materials in buildings. A number of studies have been carried out on PCM incorporated into concrete and have shown positive results such as reducing indoor temperatures in warm climates. Entrop et al. [85] investigated experimentally the performance of PCM incorporated into concrete floors. Two rooms with PCM concrete floor as well as two rooms with regular concrete floor were constructed. The results showed that this application leads to decrease the temperature fluctuations in the room. Cabeza et al. [86] presented a similar research, where two identical cubicles made of concrete were tested experimentally. The first one was built of traditional concrete and the other one of new concrete with microencapsulated PCM. The results showed a reduction in temperature fluctuation in the room with PCM. Arce et al. [87] continued the work presented in Ref. [86]. One of the most important obstacles found in Ref. [86] was the strong effect of solar radiation and high outdoor temperature peaks on PCM effectiveness during the summer, which leads to incomplete solidification during the night. The principal aim of this application was to raise the PCM's operation time in order to resolve the PCM cycling problem. Results showed a slight reduction in temperatures. The PCM stayed active for at least 4% more time and the problem of high temperatures was not completely solved. Royon et al. [88] tested the potential of filling hollow concrete floor with paraffin PCM having a melting temperature of 27.5 °C. In summer, the results showed that the temperature was lower in the hollow concrete building which allows using such system as a passive thermal conditioner. Other passive system applications for cooling purposes [89–107] are presented in Table 6.

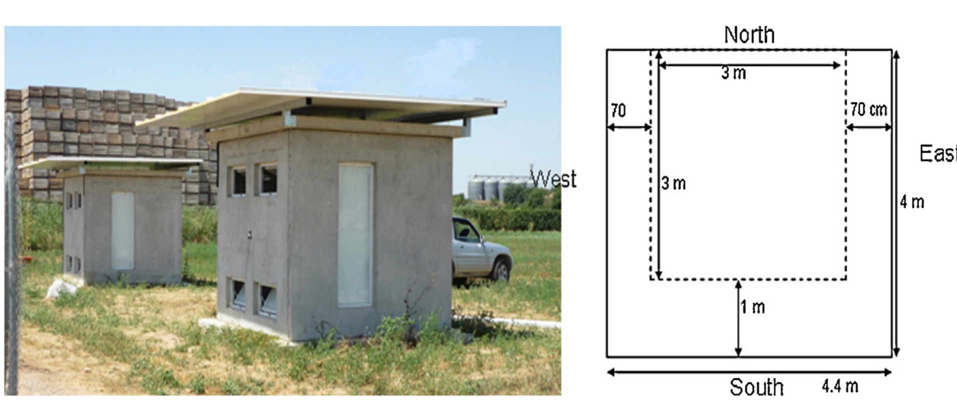


Fig. 33. Concrete cubicles with awnings (outer view and top view) [87].

Table 6
PCM passive system applications in the building envelope for cooling purposes.

Ref./Type[a]	Location/climate	Used PCM properties	Installation/Strategies	Results/Conclusions
[7] S	Austin, USA/humid subtropical (hot summers and mild winters)	- PCM/graphite composite: Tm = 21 °C, Ts = 19 °C - paraffin wax: Tm = 21.7 °C, Ts = 18.7 °C - encapsulated organic material: Tm = 23 °C,Ts = 22 °C - Encapsulated octadecane: Tm = 25.3 °C, Ts = 26.3 °C	- Layer of PCM plasterboard located in 3 different placements with different thicknesses. - Set-point temperature schedule is created (the charging cycle of PCM is controlled).	- Use of Encapsulated octadecane → lowest required cooling loads. - Surface area $\nearrow\nearrow$& thickness of PCM$\searrow\searrow$ → more effective. - Cooling demand depends on charging cycle and peak load varies depending on set point temperature schedule. - Adding natural ventilation does not have an important effect in reducing energy consumption.
[87] E	Lleida-Spain	Microencapsulated PCM (Micronal® from BASF), Tm = 26 °C & Hf = 110 kJ/kg	- PCM integrated into concrete walls Fig. 33 (concrete contain about 5% in weight of PCM). - Awnings added to provide solar protection, reduce high wall temperatures and allow PCM solidification overnight - Two operation modes: free-cooling (windows opened only at night) and open windows (all the time).	- Using awnings → reduction of temperature peak = 6% (3–4 °C), increasing of active hours ~4–10%, & increasing in comfort time ~10–21%. - Delay of peak hours increased 36% in case of free-cooling while in case of open windows it decreased 14% - PCM phase change cycles still incomplete.
[89] E,S	Tianjin-China/warm temperate semi-humid continental with cold winters and hot dry summers	- Capric acid (CA), Tm = 303.35 K. - Capric acid and dodecanol (CADE), Tm = 299.65 K. - Cp and K varies with temperature.	- 2 operation mode: free cooling & opening window at night (natural ventilation) - CA panels on the outside surface of walls and roofs (PCMOW) - CADE panels on the inside surface of walls and roofs (PCMIW) Fig. 34	- Inside surface temperatures of walls and roofs in PCMOW & PCMIW rooms < than that in room without PCM. - Performance of PCMIW is better than PCMOW especially with the condition of natural ventilation. - When PCM room temperature > comfort temperature (26 °C) → active cooling should be operated. - Heat that should be removed (ROH) is lower in case of natural ventilation than the free cooling condition. - Reduction of ROH for PCMIW up to 80%.
[90] S	Kuwait/hot climate	- n-Octadecane, Tm = 27 °C - n-Eicosane, Tm = 37 °C - P116, Tm = 47 °C. - Different geometries of PCM container.	- Roof-PCM system: concrete slab with cone frustum holes filled with PCM Fig. 35. - Reducing heat flow from outdoor to indoor space by absorbing heat gain in the PCM before it reaches the indoor space.	- Significant reduction in heat gains. - heat flux reduction at the indoor space ~39%. - N-Eicosane performed better than other tested PCMs. - Regarding thermal effectiveness → conical geometry is the best as a PCM container.
[91] S	- Shenyang/severe cold - Zhengzhou/cold - Changsha/Hot summer and cold winter - Kunming/mild - Hong Kong/Hot summer and warm winter	octadecane paraffin with different Tm = 23, 24, 25 °C	- PCM board (PCMB) integrated into interior surface of an external wall. - Natural cold source - reducing the utilization of AC system leading to electricity savings.	- PCM phase transition temperatures$\nearrow\nearrow$ → energy savings $\nearrow\nearrow$ - Use of PCMB did not provide economic benefit from reduced AC utilization. - Mean electricity savings ratio = 13.1%. - Optimal Tm > mean outdoor air temperature + 3 °C → acceptable SPP - Colder regions → lower Tm are required - Hotter regions → higher Tm are required
[92] S	Kuwait/hot climate	- n-Octadecane, Tm = 27 °C, - n-Eicosane, Tm = 37 °C, - P116, Tm = 47 °C, - thickness of PCM shutter varied between 0.01 & 0.03 m.	- window shutter filled with PCM - Reducing solar heat gain in building through windows by absorbing it before it reaches indoor space.	- PCM with highest Tm = 47 °C (close to upper temperature limit of windows) → best thermal performance. - P116 shutter → heat gain reduction = 23.29% with thickness = 0.03 m to absorb large quantity of heat during the daytime.
[93] S	Beijing, China	- Different Tm, Hf, K & thickness of SSPCM - Different ACH at night and day.	- SSPCM plates as inner linings of 4 walls & ceiling. - SSPCM plates combined with night ventilation without active AC - Natural ventilation in the day and mechanical ventilation at night.	- Reduction of daily maximum temperature by 2 °C - Indoor comfort improved especially in early summer days. - Optimum values for Tm, Hf, K & thickness of SSPCM are: 26 °C, 160 kJ/kg, 0.5 w/m °C & 20 mm respectively. - ACH at night should be at the highest possible level but ACH at daytime should be controlled. - SSPCM plates useful for free cooling application in summer.

Table 6 (*Continued*)

Ref./Type[a]	Location/climate	Used PCM properties	Installation/Strategies	Results/Conclusions
[94] S	Hong Kong Subtropical (Hot humid summer-short mild winter)	Energain® - PCM wallboard composed of 60% microencapsulated paraffin, Tm = 21.7 °C	5 mm PCM layer wallboard incorporated into external walls in different orientations.	- PCM integrated in eastern & western walls → better performance. - Temperature of interior surface of PCM wall stays above 28 °C > Tm. - Higher Tm of 28 °C–30 °C should be investigated in subtropical Hong Kong climate.
[95] S	London, UK/summer months.	- PCM with different Tm = 23, 25, 27 °C, & with thicknesses of 12, 24, 36, 48 and 60 mm - wide air gaps = 15, 20, 25, 30 and 35 mm	- PCM installed in the inner side of wall construction system Fig. 36. - Integrating PCM with naturally ventilated air gaps in building envelope - Air gap is similar to ventilated façade & provides extra insulation and airflow.	- In terms of annual energy consumption (kWh/m^2): the optimum values for Tm, PCM thickness and air gap width are 25 °C, 48 mm and 25 mm respectively. - Application of PCM in building reduces overheating problems & improves indoor temperature in hot periods. - Effectiveness of PCM becomes higher as temperature rise to year 2080 levels.
[96] E	Lawrence, KS, USA/cooling seasons under full climatic conditions.	- Hydrated salt-based PCM, - Tm range = 18–38 °C, peak Tm = 31.36 °C, starting Tm = 24.79 °C - m_{total} PCM = 1.5 kg/m^2	- PCM contained in thin polymer pouches, arranged in sheets laminated with aluminum foil Fig. 37. - PCM thermal shield (PCMTS) integrated as thin layers at five locations at different depths between insulation boards & wallboard in the west & south walls	- Optimum location of PCMTS is at 1.27 & 2.54 cm from the wallboard in west & south wall respectively. - Peak heat flux reduction is 51.3% for south wall and 29.7% for west wall. - Peak heat flux time delayed by 6.3 h in south wall when PCMTS is next to wallboard & 2.3 h in west wall when PCMTS at 1.27 cm from wallboard. - Daily heat transfer reduction = 27.1% in south wall (PCMTS at 2.54 cm from wallboard) & 3.6% in west wall (PCMTS at 5.08 cm from wallboard).
[97] E,S	Weimar, Germany	Microencapsulated paraffin with diameter = 5 µm, Tm range = 25–28 °C.	Paraffin-modified gypsum plaster (with salt mixture) applied on surrounding walls.	- Peak temperature reduction ˜4 K. - PCM loses its storage capacity if it cannot be discharged at night after sequential hot days hence night ventilation should be used.
[98] S	Three US climate: Minneapolis, MN, Louisville, KY, and Miami, FL	- PCM wallboard containing paraffin with active temperature range of 25 °C to 27.5 °C - Volume fraction of PCM to gypsum is 25%.	PCM composite wallboard integrated in walls and roof in three different locations (exterior, center, and interior) of the multi-layered envelope surfaces	- Optimal PCM location exists depending on resistance values between external boundary conditions & PCM layer. - PCM wallboard in the middle of multilayered wall → best performance. - Use of PCM wallboard shift peak electricity load & decrease energy consumption in summer.
[99] E	Experimental room in China	Capric acid (CA) & lauric acid (LA) mixture, Tm = 20.4 °C & Ts = 19.1 °C.	PCM wallboards integrated in an ordinary wall (26% PCM by weight into gypsum wallboards)	PCM wallboard has high latent heat storage capacity & energy consumption in peak load shifted to off-peak load period.
[100] E	Hong Kong	- Paraffin macro-encapsulated in stainless steel box - k = 21.712 W/m K, Tm = 20.78 °C, - Hf = 147.4 J/g, Ts = 25.09 °C, and Hs = 146.9 J/g.	PCM incorporated in concrete walls in different positions: internally bonded, laminated within and externally bonded Fig. 38.	- PCM in concrete walls regulates indoor temperature. - Effectiveness of PCM highly depends on its placement in concrete walls. - PCM laminated within concrete walls → best temperature control: maximum temperature reduction ˜4 °C. - PCM internally bonded → best humidity control - Reduction of relative humidity providing indoor comfort. - Payback period of PCM application ˜11 years in public house in Hong Kong.
[101] E	Full-scale test rooms/summer conditions (CETHIL-INSA de Lyon, France)	product from DuPont constituted of 60% of microencapsulated PCM with Tm = 22 °C.	PCM integrated in internal partition wall.	- overheating effect ↘↘ - Temperatures of wall surfaces ↘↘ improving thermal comfort conditions by radiative effects.
[102] E	Puigverd de Lleida-Spain	macro encapsulated PCM RT-27 paraffin, Tm = 28 °C & SP-25A8 hydrate salt, Tm = 26 °C	- CSM PCM panels located between perforated bricks and polyurethane in western & southern walls and in roof Fig. 39. - domestic heat pump as a cooling system.	- Peak temperatures reduction = 1 °C, & daily temperature fluctuations were smoothed out. - In case of PCM cubicle (RT27 + PU) → consumption of electricity reduction = 15% & CO_2 emissions reduction˜ 1–1.5 $kg/year/m^2$. - In case of PCM cubicle (SP25 + Alveolar) → energy savings = 17% (2.7 kW h/m^2/year).

Table 6 (*Continued*)

Ref./Type[a]	Location/climate	Used PCM properties	Installation/Strategies	Results/Conclusions
[103] E	Solar house "Magic Box" located in the IES ("Instituto de Energía Solar" of Technical University of Madrid)	- ACUAL 20 PCM: multi-component mixture of hydrocarbons of paraffinic composition with unsaturated additives, dyes and preservatives - Tm = 20 °C & Ts = 13.5 °C	- PCM integrated in floor tiles Fig. 40. - the tile basically consist of 4 pieces of pure clay stoneware 20 mm thick and a metal container (32 mm thick) containing 4.8 l of paraffinic mixture.	- PCM tiles placed in the floor are useful in summer season at night. - Tm↗↗→ the system work more efficiently as a heat sink. - Higher effectiveness can be achieved in the sunny tiles.
[104] S	China	PCM mixture of $Mn(NO_3)_2$,$6H_2O$ and $MnCl_2$,$4H_2O$	- brick wall with Sierpinski carpet filled with PCM. - Thermal response of PCM brick wall is based on the enthalpy-porosity technique.	- Use of PCM in brick walls is useful for thermal comfort. - filling amount of PCM ↗↗→ temperature fluctuations ↘↘ - This model is verified experimentally.
[105] S	Periodic variations of temperatures	Salt PCM held in stasis by a perlite matrix.	- installed within the wall or ceiling insulation. - Delay peak AC request times until the evening. - 3 values of operative temperature were considered.	- With PCM, peak cooling loads reduction = 11–25%. - In case of "insulation only" peak reductions˜ 19–57%
[106] E,S	Warsaw-Poland Marseille-France Cairo-Egypt/summer hot period	Bio-based PCM with properties determined by heat flow meter apparatus (HFMA).	Fiber insulations containing microencapsulated PCM integrated in the southern-oriented wood-framed wall.	Indoor set temperature = 24 °C → peak-hour heat gains ↘↘ for Marseille by 23–37% & 21–25% for Cairo; but no positive effects were observed in Warsaw.
[107] E,S	Chambery-France Catania-Italia	Paraffin (Micronal T23 BASF), Tm = 22 °C & Ts = 28.5 °C.	Wallboards made of aluminum honeycomb matrix contain 60% of micro- encapsulated paraffin installed in the partition walls of an office building.	- In hottest months, PCM average storage efficiency in Chambery and Catania is 50% & 39% respectively - PCM is liquid for approximately 60% of summer time. - PCM utilized only 45% of its latent heat. - Quantity & type of PCM depend on the season that one aim to improve.

[a] E: experimental, S: simulation.

3.5.2. PCM active system applications in the building envelope

In contrast to passive systems for PCM integrated into building materials, PCM active systems lead to a better heat transfer coefficient by replacing the free convection by forced convection. The solidification of PCM actively can be accomplished with a minimum of energy with the help of small fans.

3.5.2.1. Active systems using air as heat transfer fluid.

3.5.2.1.1. Systems integrated into the ceiling. Providing a small fan into suspended ceilings to effectively discharge the absorbed heat, makes it an active system [7]. A two dimensional channel that directs the air flow is built in the ceiling construction. PCM located in this channel can be considered as heat storage. Cold night-air circulates in the channel, cools down the PCM and discharges the stored heat to the outside of the building. During the day, warm air from the room is compelled to move through the PCM, it is cooled and then provided to the room [108]. Fig. 41 shows the general concept for cooling with PCM integrated into the ceiling.

The Swedish company Climator developed a system called "CoolDeck" shown in Fig. 42. This system has been installed as part of a project in the town hall of Stevenage in England. The Cool Deck consists of the PCM C24, a salt hydrate encapsulated in bags with a melting temperature of about 24 °C, a metallic channel to direct the air and a fan [109].

An active thermal storage unit in the ceiling was developed by the Team Germany (2009) [66]. The application is composed of four insulated channels, with polycarbonate profiles filled with salt-hydrate PCM with a melting temperature of 26 °C, the PCM system used is Delta Cool 28 by Dorken [67]. The team equips the channels with ventilation fans, grills, operable flaps, and temperature sensors. Depending on weather conditions, the COP of the system varies from 9 to 15. During the day, in cooling mode, the air in the room circulates through the ceiling and decreases its temperature. The cool air from outside, at night, blows across the ceiling and discharges the PCM.

3.5.2.1.2. Systems integrated into the wall. Since wall systems have been used for a longer time than other applications, the same concept is followed as for the ceiling in a wall construction. The system consists of bags filled with PCM, at the bottom a fan is used in order to transfer the air, openings at the top and the bottom allowing the intake and the exit of air from the room. However, it should be assured that the volume flow rate of air at the exit does not lead to uncomfortable air velocities. An extra intake at the outside of the wall can be used optionally for direct absorption of cold night air [108].

3.5.2.1.3. Systems integrated into the floor. It is possible to integrate the same system as for the ceiling and for wall into the floor. The PCM can be directly located under the floorboards. Fig. 43 shows the general concept for cooling with PCM integrated into the floor. During the day, the warm air from the room is taken away; it is cooled during the melting of PCM and then the cooled air is supplied back to the room providing cooling. At night, cold air circulates under the floor, cooling the PCM and discarding the stored heat [7].

3.5.2.2. Active systems using a liquid as heat transfer fluid. Active systems with air thermal exchange used to reject the stored heat means that the cold night air is used as a cold source. Regarding

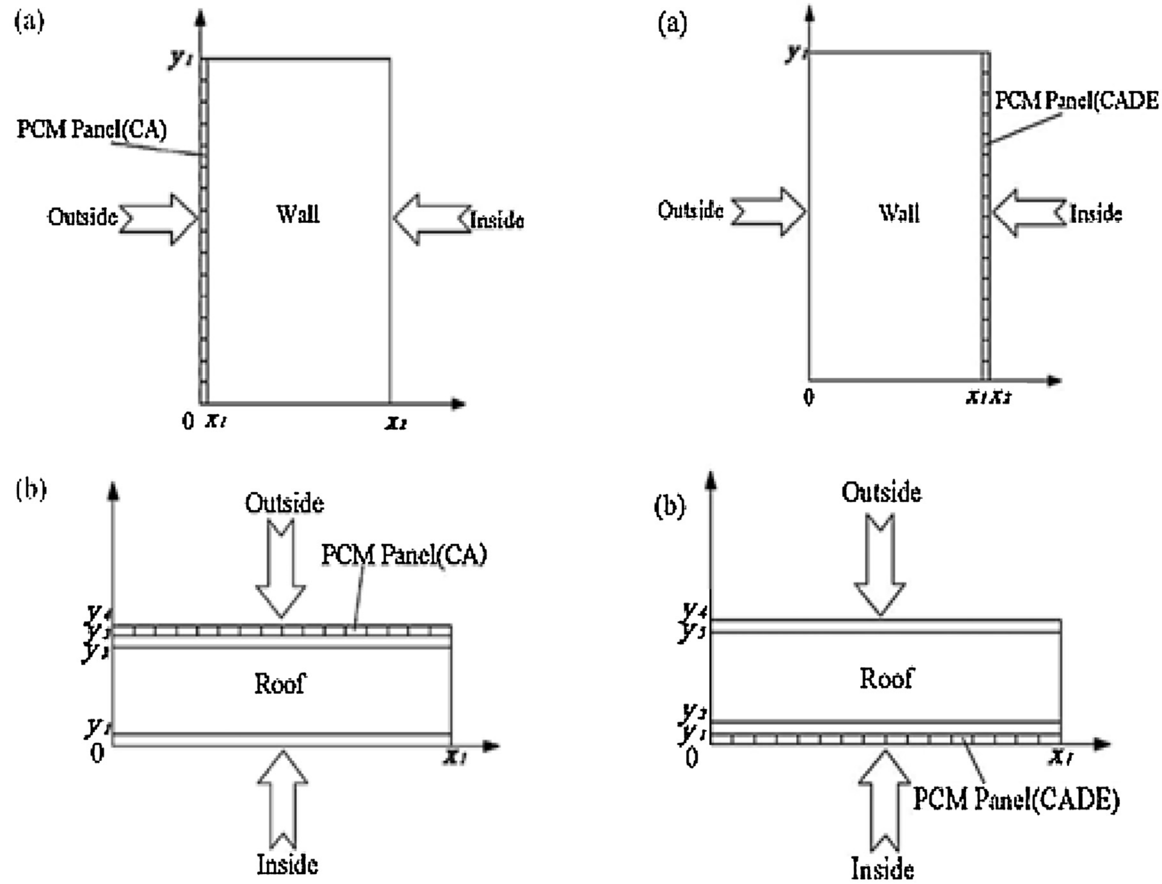


Fig. 34. Schematic of building envelope for PCM-OW(left) and PCM-IW (right) [89].

the energy consumption, it seems a very effective method, but it is not completely trusted that the night-air temperature drops to a temperature low enough to reject all the heat stored during the day [108]. It is possible to integrate systems with liquid-air thermal exchange to solve this problem, and to attach it to a cold source with a liquid heat transfer fluid.

3.5.2.2.1. PCM-plaster with capillary sheets. The capillary sheets can be fixed at the surface of the concrete wall and then cover it by a plaster layer with PCM. Integration of capillary sheets as heat exchanger into the wall is a general approach for the thermal activation of concrete walls [108].

3.5.2.2.2. Cooling ceiling with PCM plasterboard. Panels suspended from the ceiling are an example of this application; a plate for dry construction used as a wall or ceiling element, was developed by the Company ILKATHERM, which is made up of a pure-foam as an insulating layer located between two coatings made of plaster board, metal, plastics, or others [7,108]. In this application, the coating can be PCM plasterboard. The construction and the installation of the PCM plasterboard are shown in Figs. 44 and 45.

Incorporation of PCM in ceiling boards to act as air conditioning systems seems effective to shift peak loads. Kondo and Ibamoto [110] developed a PCM ceiling board with micro capsulated PCM for an office building. At night, the cold air from the AHU flows into the ceiling and cool down the PCM ceiling board. During cooling time, the cool air from the AHU flows immediately into the room. During the peak load time, the warm air from the room circulates through the PCM ceiling board, where it is precooled before returning to the AHU. The results showed a reduction of the peak loads; however an

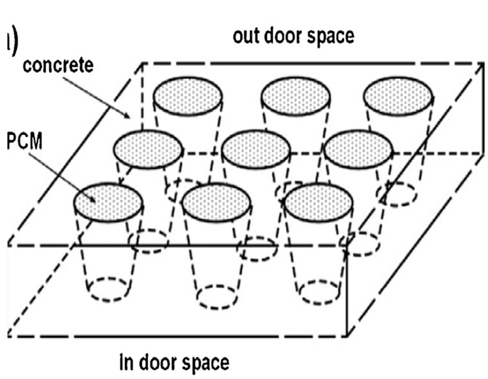


Fig. 35. Schematic of the roof with holes filled with PCM [90].

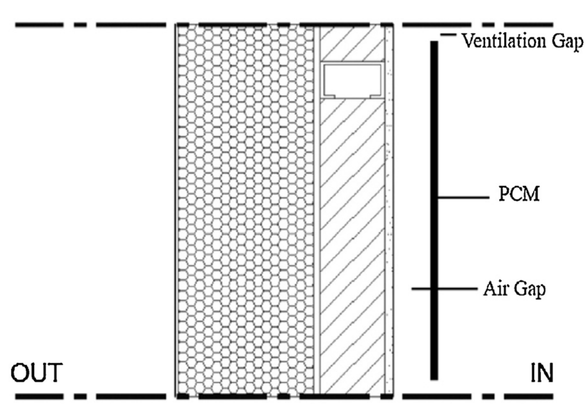


Fig. 36. PCM installation in the wall with ventilation gap [95].

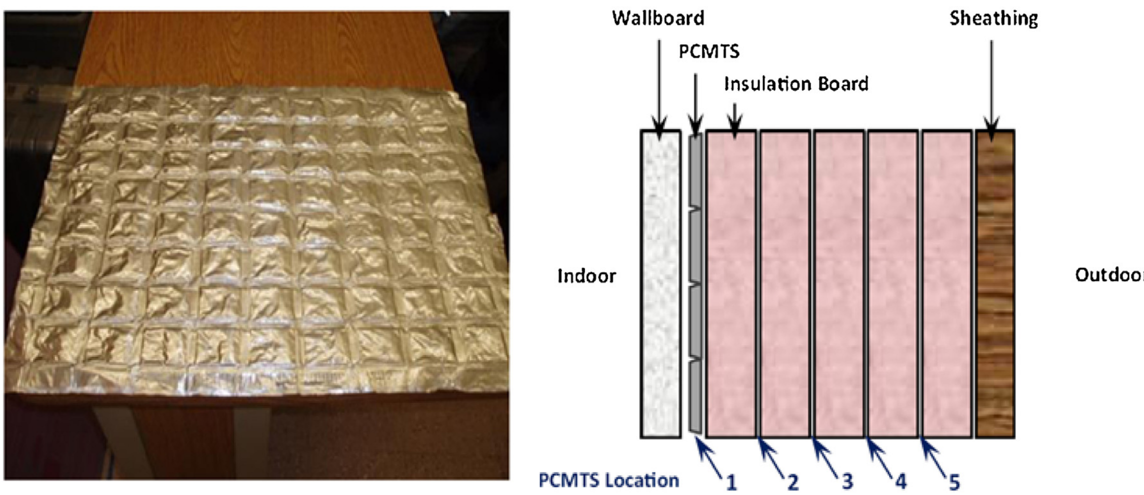


Fig. 37. Sheet of PCM thermal shield PCMTS (left) and wall section showing the PCMTS location (right) [96].

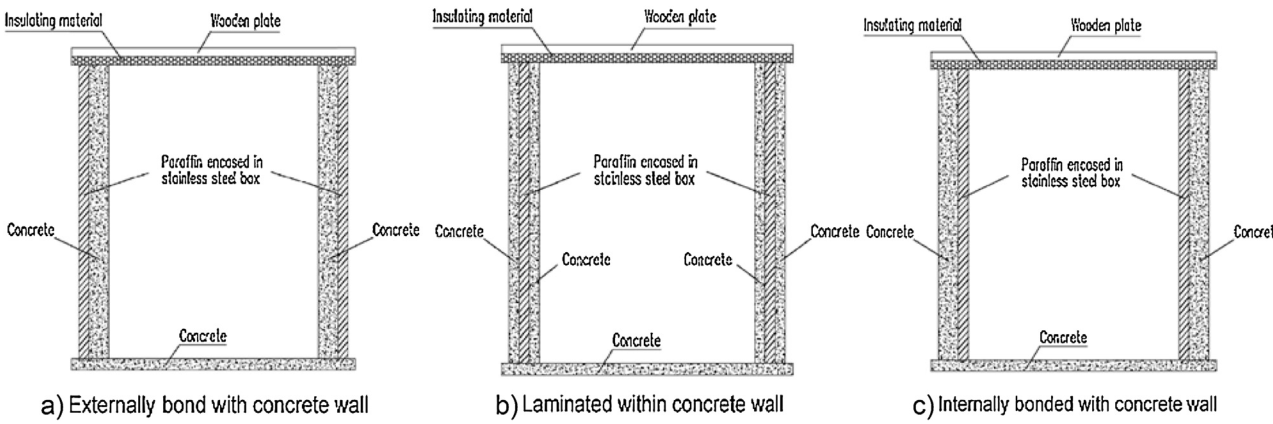


Fig. 38. PCM layer: (a) externally bond with concrete wall, (b) laminated within concrete wall and (c) internally bonded with concrete wall [100].

improvement of ceiling board is needed. Various numerical studies were also achieved on the thermal performance of this system [111,112]. Jin and Zhang [113] investigated an activated floor with two layers of PCM for cooling and heating. Their main objective was to find the optimal melting temperature for each PCM layer. The results showed a reduction of the floor surface temperatures fluctuations. The reduction of the fluctuations is caused not only by the latent heat capacity of PCM, but also by the implementation of additional high resistance of two layers of PCM with low thermal conductivity. Moreover, it was found that the optimal PCM melting temperature for heating and cooling were respectively 38 °C and 18 °C and the energy release during the peak period was increased by 41% and 38% for heating and cooling respectively. Other active system applications are presented in Table 7.

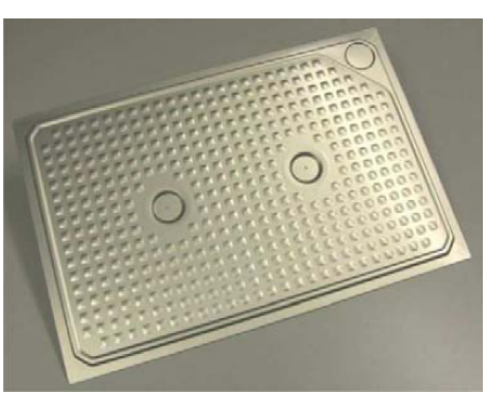


Fig. 39. CSM panel containing PCM [102].

3.5.3. Ventilated facades principle and applications

To reduce the energy demand of a building, the careful design of its façade is considered as the most important method. Ventilated facades (VF) have been recently used in buildings and have attracted great attention of architects and engineers, in order to fit the energy restrictions recommended by the European Directive (2010/31/EU) [114]. PCM can be introduced into the external layer of VF [115] or in its air cavity [116,117]. During cooling season, VF with PCM can act as a free cooling system in order to avoid overheating and therefore minimize the HVAC energy consumption. VF or VDSF are considered as a special kind of envelopes, where in front of an ordinary building façade, a second skin is placed, and conse-

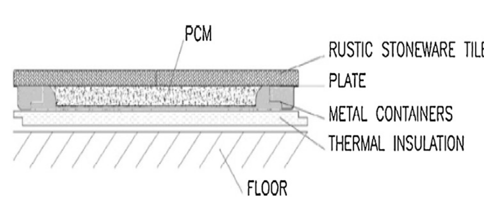


Fig. 40. Schematic of the floor with PCM integrated in tiles [103].

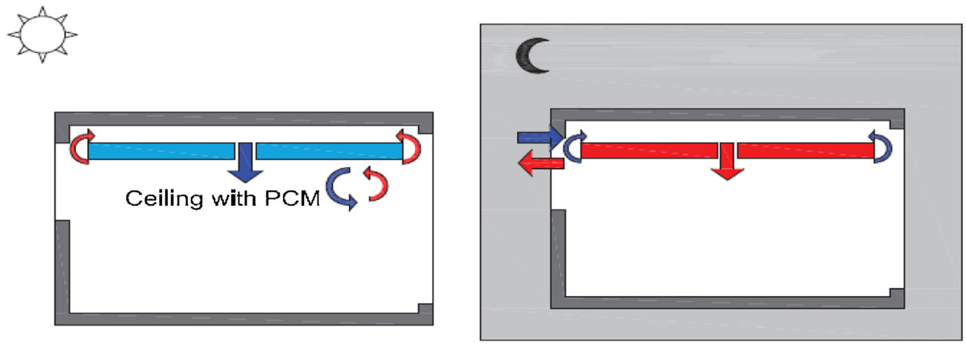


Fig. 41. The general concept for cooling with PCM integrated into the ceiling [108].

Fig. 42. Cool Deck C24 developed by "Climator" [7].

Fig. 44. Installation of ILKATHERM PCM board [108].

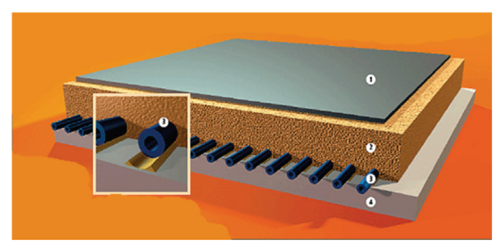


Fig. 45. PCM board from ILKATHERM; 1) sheet metal coating, 2) PU rigid foam, 3) capillary tube mats, 4) Micronal PCM smartboard gypsum construction panel [108].

quently an air cavity (channel) is created. In order to ameliorate the energy or thermal performance of the building, the air in the cavity can be naturally or mechanically ventilated [118]. Ventilated façades (VF) have the potential to ameliorate the energy efficiency of buildings, and it can be used in both new and refurbished buildings.

During the cooling period, the working principle of VF-PCM is to use the low temperatures at night to fully solidify the PCM, while during the day time, supply cold when it is needed by removing heat through melting of PCM. Fig. 46 shows how a ventilated façade works:

- PCM solidification: occurs at night when the outdoor temperature is lower than the PCM phase change temperature, the air from outside enters to the channel leading to PCM solidification. To ensure the full PCM solidification, fans operating under

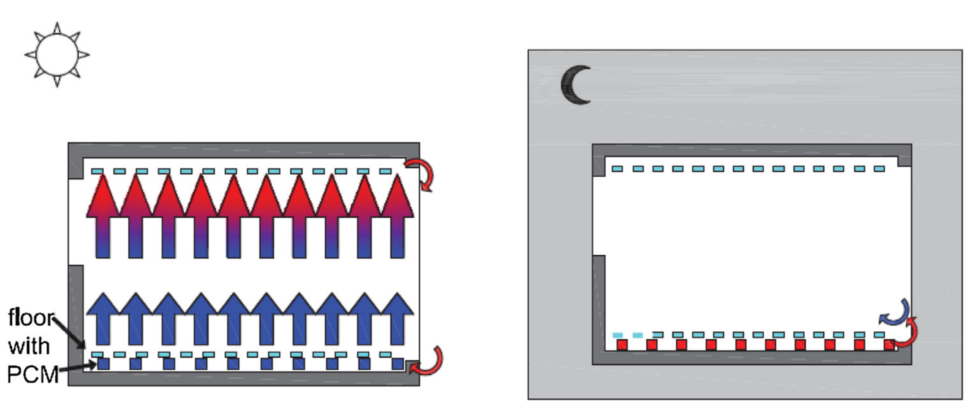


Fig. 43. General concept for cooling with PCM integrated into the floor [7].

Table 7
PCM active system applications in building envelope including active VF.

Ref./Type[a]	Location/climate	Used PCM	Installation/Strategies	Results/conclusions
[26] E,S	Lab scale experiment/Periodic variations of the temperature	Microencapsulated paraffin in gypsum (Heptadecane), Tm = 22 °C & m_{total} PCM = 13.3 kg/m^2	- ceiling panel with PCM incorporated in retrofitted buildings. - thermal storage controlled by an integrated water capillary tube system.	- 5 cm layer of microencapsulated PCM are sufficient to keep the office temperature within the comfort range. - this system can be used in lightweight structures due to its benefits. - Fire resistance could be ensured by micro-encapsulated PCM in gypsum covered in a sheet steel tray.
[117] E	Puigverd de Lleida (Spain)/Continental Mediterranean with severe or mild summer	- macro-encapsulated panels of salt hydrate SP-22, Tm = 22 °C & Ts = 18 °C - 112 PCM panels (1.4 kg of SP-22 each) distributed throughout the facade making 14 air flow channels.	- VF in south wall consisting of 3 fans & Six automatized gates in order to control the operational mode Fig. 47. - the system used as a cold storage unit (an overheating protection) & as a night free cooling application.	- Night free cooling operation mode reduces cooling loads. - Cold storage sequence presents low energy storage efficiency due to significant heat gains through the outer skin. - The system prevents effectively the overheating effect. - Effective use of VF for cooling purposes → weather conditions & cooling demand of final users should be taken into account.
[120] E,S	Madrid Seville	- RT22 in containers, located inside an air chamber. - Tm = 23 °C	- Ventilated facade with fins filled with PCM. - PCM cylinders in hollow core slabs Fig. 49. - increasing contact area between PCM & air. - increasing convective heat transfer coefficient & improving utilization factor.	- PCM located inside mechanically ventilated air layers → convective heat transfer coefficients ↗↗ & control strategies used to match cooling needs of building. - Use of encapsulation shapes such as fins, cylinder and sphere increase convective heat transfer coefficients & improve the use of considerable amounts of PCM.
[121] S	Catania (Southern Italy)/hot Mediterranean climate	Wallboard panels consisting of aluminum honeycomb matrix containing 60% of microencapsulated paraffin	- PCM placed at a certain distance from the partition walls. - Narrow ventilated cavity between PCM wallboards & partition wall Fig. 48. - Fresh air circulates according to suitable control logics.	- Ventilation occurs at night → PCM storage efficiency↗↗. - Average room operative temperature is reduced˜ 0.4 °C & indoor conditions are maintained for longer time in a comfortable range. - At night, heat stored by PCM is rejected to the air flowing into the cavity, rather than being released to room air.
[122] S	Tübingen/Germany	- PCM plates, - Tm = 26–28 °C	- PCM in gypsum boards of top floor ceiling and wall. - Daytime mechanical ventilation with air precooling through a horizontal brine soil heat exchanger. - mechanical night ventilation	- PCM gypsum boards in ceiling and wall was not effective enough to control the room temperature level. - The problem is that during the night, the heat flux for discharging PCM was low with limited air exchange rates.
[123] E	Central Poland/daily ambient temperature oscillates in high range	Gypsum-mortar composite containing˜27% microencapsulated PCM Fig. 50 (Micronal DS-5008X, by BASF), Tm = 22.8 °C	Ceiling in shape of thick board with parallel internal ventilation channels to improve night ventilation system-PCM based heat exchangers located in air ducts.	- Daily fluctuations of air temperature are eliminated & the room temperature within the comfort range. - Entire amount of PCM does not undergo complete melting & solidification. - this study needs some optimization in terms of thickness of channels and distribution of PCM in construction materials. - Numerical modeling & results of simulations of heat transfer in ceiling panel can be found in [124].
[125] S	Linköping, Sweden/Excessive temperatures occur summertime.	- Ttransition = 19 °C - C_{PCM}, solid (T < 17) = 2 kJ/(kg K) - C_{PCM}, liquid (T > 21) = 2 kJ/(kg K) - different m_{total} PCM = 50, 100, 200, 400 kg	- External PCM night cool storage. - PCM air heat exchanger placed in an insulated box on the outside of the wall Fig. 51.	- Indoor temperature reduction˜0.5 °C to 2 °C (depending on PCM amount) in the warmest 10 days of summer season. - PCM cool storage does not provide enough cooling when the indoor temperature > 28 °C. - 22–36% of the degree hours with excessive temperatures could be removed.
[126] S	Hong Kong	- PCM Hexadecane ($C_{16}H_{34}$) - Tm = 18 °C & Hf = 224 kJ/kg	AC system: combination of cooled ceiling (CC) & MPCM slurry storage tank	- Tank with volume = 0.52 m^3 was sufficient to keep the indoor temperature within comfort level. - Electricity demand reduction˜33%. - Annual energy consumption reduction = 1157 kWh.

[a] E: experimental, S: simulation.

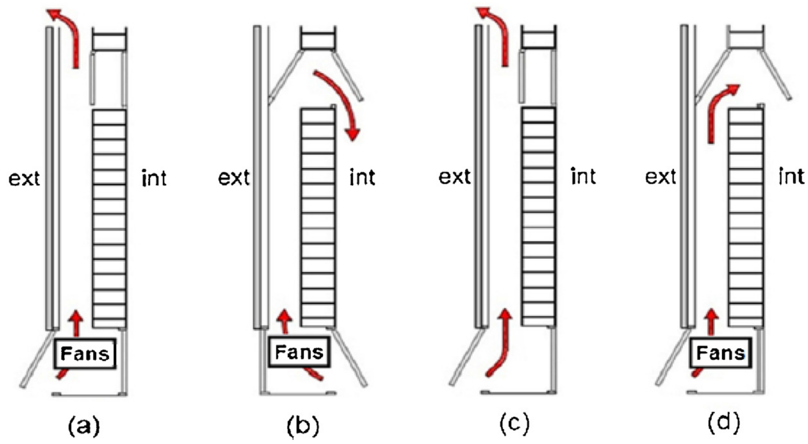


Fig. 46. Modes of operation of VF. (a) Solidification process, (b) melting process, (c) overheating prevention, and (d) free cooling [116].

various power rates can be used (mechanical ventilation instead of natural ventilation) increasing the convective heat exchange.
- PCM melting: during the day, PCM absorbs heat from the indoor air to provide cooling effect.
- Overheating prevention: after the PCM melting, due to the buoyancy forces, the air flows from outdoors to outdoors preventing the overheating in the air channel by natural convection.
- Free cooling: occurs at night when the outdoor temperature is lower than the indoor set point temperature.

Ventilated facades with PCM were studied by many authors during heating period (winter season) [115,119]. However, de Gracia et al. [116] investigated experimentally the efficiency of PCM-VDSF in different cities under Mediterranean-continental climates in order to reduce cooling energy consumption; the used PCM is SP-22 with melting temperature of 21.5 °C and solidification temperature of 18 °C, 112 PCM panels were incorporated in the south wall and the air channel thickness was 15 cm furthermore, natural or mechanical ventilation conditions were tested and three fans were used in the system in case of mechanical ventilation. They concluded that three possible benefits can be offered by the VDSF: free cooling, cold storage, and solar radiation protection. Free cooling can be provided for cities under “warm temperate” and “snow” main climates where the temperature swings are considered as high. The cold storage effectiveness depends highly on heat gains and the solar irradiance. The cooling supply during the day provided by the cold storage [116] strategy was about 12 MJ/day; while it reaches 150 MJ/day in case of free cooling. Further, in order to optimize the charging process, a control strategy based on artificial intelligence algorithms can be used. Other VF system applications [117,120] are presented in Table 7.

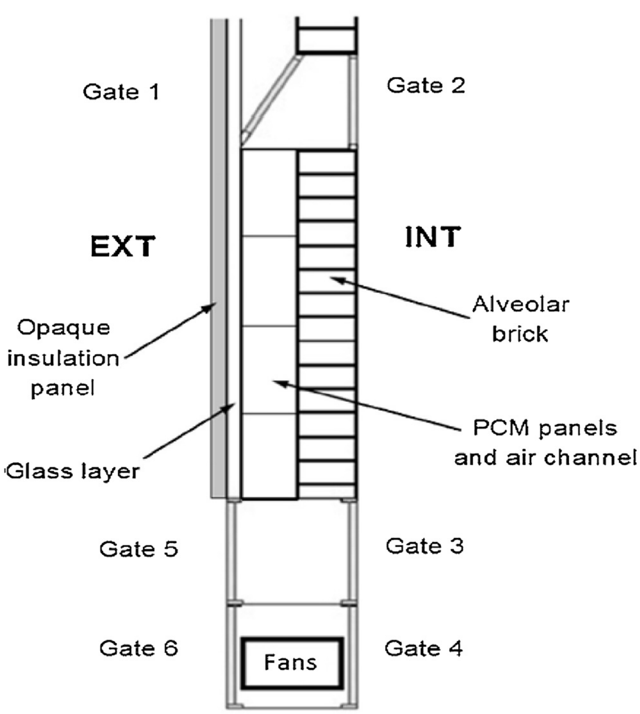


Fig. 47. Ventilated façade with the distribution of fans and automatized gates [117].

4. Discussion

In building applications, PCM can be incorporated in passive or active systems. Passive systems do not require additional energy, are easy to install with integrated low consumption devices. They depend completely on the outdoor temperature and the variable weather conditions. Thereby if night temperatures do not drop considerably below the PCM phase change temperature, the PCM will not fully solidify which hinders the pursuit of its operation. In addition, among day-night cycles the heat transfer between the air and the wall limits the maximum capacity of storage which restricts the application of passive systems [46]. Furthermore, the required rate of heat exchange between the air and the PCM is not always attained. During summer season, Schossig et al. [127] proposed to increase air-change rate at night; even though natural ventilation could provide cold from outside but it may be insufficient; thus mechanical ventilation must be applied, which is considered as an active system, leading to a better heat transfer coefficient. Improving the heat transfer rates using electrical fans requires adding their energy consumption in the economic study. Active systems seem to be more efficient than the passive ones, the charge/discharge process is fully controlled and its execution depends on several parameters besides the outdoor temperature, moreover the thermal energy storage can be obtained when it is required. On the other hand, active applications are regarded as complicated and complex systems requiring mechanical elements such as pumps and fans, in addition to a control system. In terms of the use of PCM for building applications, PCM integrated materials and PCM components are more and more easily implemented. Recently, PCM mats and boards have become available in the market which facilitates the integration of latent heat storage in lightweight construction. Originally, PCM boards were used only in passive systems, but later on it was used also for active applications [67,66]. For space heating, the solar direct gain is the most significant strategy and the appropriate

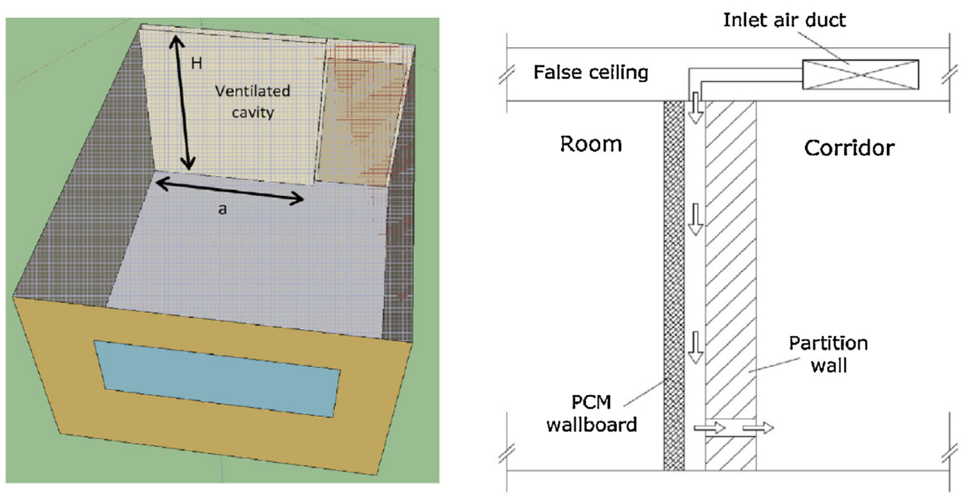


Fig. 48. Location and operation of the ventilated cavity [121].

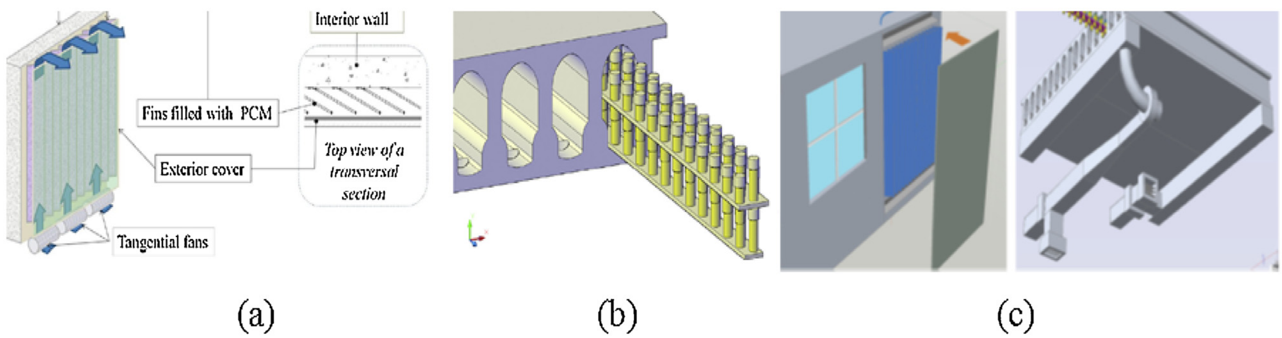


Fig. 49. (a) Ventilated façade with fins filled with PCM, (b) PCM cylinders in hollow cores, (c) position of VF and hollow cores [120].

selection of the finishing material characteristics is very important in this case. Rodriguez-Ubinas et al. [66] used this strategy for the PCM floor application; however this application is affected essentially by the type and the color of chosen floor finishing material since the PCM is not immediately subjected to solar radiation [66]. The heat transfer rate is reduced and delayed when the PCM is not directly in contact with solar radiation, neither with the room air. For space cooling, night ventilation and solar protection are the most important strategies. Night ventilation is advantageous in regions with large temperature swings between day and night; it can improve thermal comfort conditions and it can be achieved through window or door openings, ceiling fans and others [128]. Cooling strategies and PCM applications with active and passive systems are summarized in the synthetic diagram shown in Fig. 52.

4.1. Factors affecting PCM selection

It is clear that the integration of PCM in buildings leads to an increase in their thermal energy storage which subsequently minimizes the indoor temperature fluctuation, providing indoor thermal comfort and therefore reducing the energy consumption. Osterman et al. [24] confirmed that the use of PCM highly improves the energy performance of buildings in summer season. The efficiency of PCM strongly depends on several factors: 1) outdoor climatic conditions, 2) type of PCM, its melting temperature range and its thermo-physical properties, 3) PCM encapsulation method, 4) quantity of PCM (effective volume and PCM layer thickness), 5) location and installation of PCM in the building, 6) purpose of PCM application; 7) way of PCM is charged/discharged (active or passive systems), 8) characteristics and orientation of the building, 9) real life conditions including heating and cooling set points, air infiltration rates, internal gains from occupancy (i.e. people (person/m^2), metabolic rate (Writing, seating, standing Cooking, cleaning... (W/person)), Lighting (W/m^2) and Electric equipment (W/m^2)) schedules), 10) solar gains, 11) orientation and reflectivity of the surfaces (solar absorbance coefficient (α)), 12) and finally investment cost and tariff structure should be taken into account.

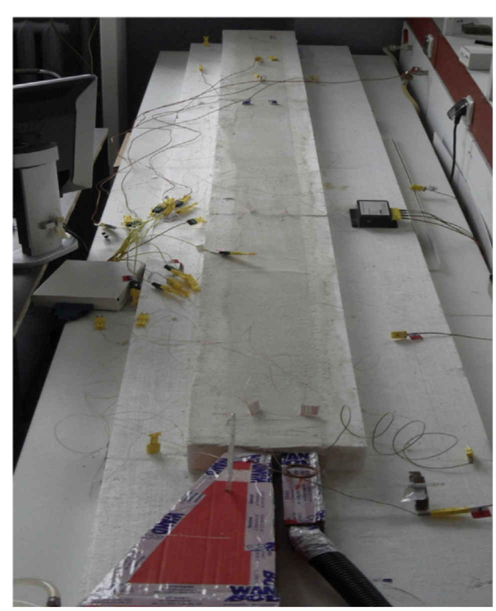


Fig. 50. Ceiling panel made of gypsum-PCM composite [123].

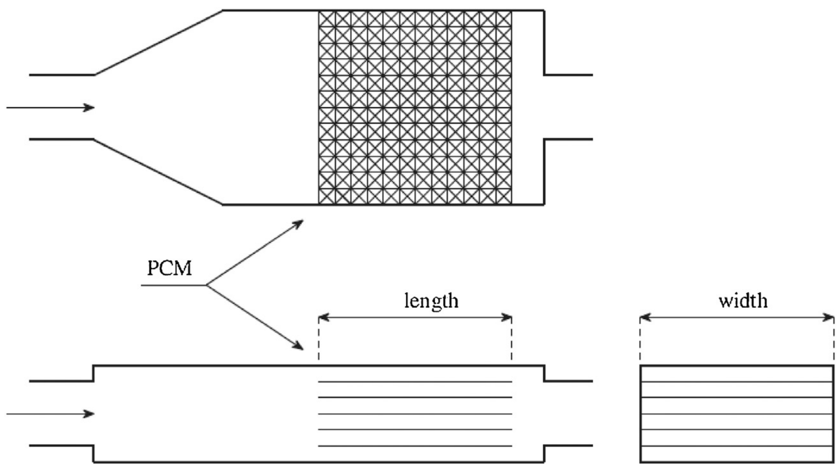


Fig. 51. Schematic of PCM heat exchanger placed in an insulated box on the outside wall [125].

The aim of this section is to investigate the possibility to find an optimum solution (appropriate PCM configuration) for each climate and application, in order to reduce cooling demands in hot/warm climates. It was found that the combination of building energy simulation tools and optimization tools can lead to optimize the design of buildings and HVAC systems [129–132]. Moreover, both mass of PCM and typology of PCM must be carefully designed.

4.2. Climatic conditions

As it was formerly stated, climatic conditions are one of the main factors affecting the efficiency of PCM in building applications, since the system performance is principally influenced by the outdoor weather conditions. The climate of a specified location is influenced by its latitude; terrain, ice or snow lids, and altitude, in addition to close water bodies. It can be defined as the average weather over a long period and it is categorized according to the average and the typical ranges of temperature and precipitation. Cooling and heating needs for buildings in each climatic zone can be determined according to the climatic zone conditions, and other conditions such as the kind use of building (residential, or non-residential) and internal gains from occupancy.

One of the most popular climate classification systems is Köppen-Geiger, Fig. 53, it divides the main climate in five zones namely, A: equatorial, B: arid, C: warm temperate, D: snow and E: polar. Furthermore, it determines the level of precipitation W: desert, S: steppe, f: fully humid, s: summer dry, w: winter dry, m: monsoonal. Lastly, it gives details about temperature as h: hot arid, k: cold arid, a: hot summer, b: warm summer, c: cool summer, d: extremely continental, F: polar frost. For example in Seville-Spain, the climate is considered as Csa: a Mediterranean climate with dry hot summer and mild winter while in Paris-France the climate is Cfb: Marine west coastal with warm summer, mild winter and rain all the year. In general, each climate zone has clearly different construction and design requirements. Table 8 shows cooling and heating requirements for each climate condition.

Many studies were conducted in order to investigate the performance of PCM under different climates [116,135–138]. It can be observed that the integrated PCM does not give the same advantages for all Mediterranean climates during all months of cooling season, the PCM wallboards appearing more suitable for semi-arid climate than for hot/subtropical Mediterranean climates [137]. However, Soares et al. [135] concluded that the total energy savings due to the integration of PCM-drywalls are more significant for the warmer climates, it reaches 62% and 42% for Coimbra (Csb-Mediterranean climate with dry warm summer and mild winter) and Seville (Csa-Mediterranean climate with dry hot summer and mild winter) respectively. Moreover, it is observed that PCM-drywalls reduce the heating energy demand not only the cooling energy demand in warmer climates. For colder climates in Warsaw (Dfb-Moist continental with warm summer and cold winter) and Kiruna (Dfc- Subarctic with cool summer and severe winter), PCM-drywalls can reduce the heating energy demand significantly but are not attractive in terms of total energy savings due to the increase in summer cooling loads. Finally, it was shown that the optimization of PCM-drywalls incorporation is very important and can be achieved in an annual evaluation basis instead of in a seasonal basis. Furthermore, Alam et al. [136] investigated the effect of PCM in Australian cities under different climates; they concluded that PCM can reduce the energy consumption of buildings in cities under cold, mild and warm temperate climates. However, the

Table 8
Usual cooling & heating strategies as a function of the climate conditions [134].

climates	Cooling & heating requirements
Hot humid summer/warm winter	- Design strategies that reduce cooling energy consumption. - Orientate the building to take advantage of cooling breezes. - Shading all windows & walls. - Use low solar heat gain coefficient glazing. - Encourage natural air flow. - Use ceiling fans & other mechanical cooling equipment.
Warm and humid summer/mild winter	- Auxiliary heating is not necessary. - Ceiling fans & high energy rated cooling appliances are required.
Hot dry summer/Warm winter	- Evaporative cooling & passive solar heating are required
Hot dry summer/Cool winter	- Evaporative cooling, ceiling fans. & night cooling - Passive & active solar heating.
warm temperate climates	- No auxiliary heating or cooling is required - Just may include ceiling fans.
Cool temperate climates	- Cooling is unnecessary. - Significant level of passive/active solar heating strongly desirable if available. - Other heating systems are also needed.

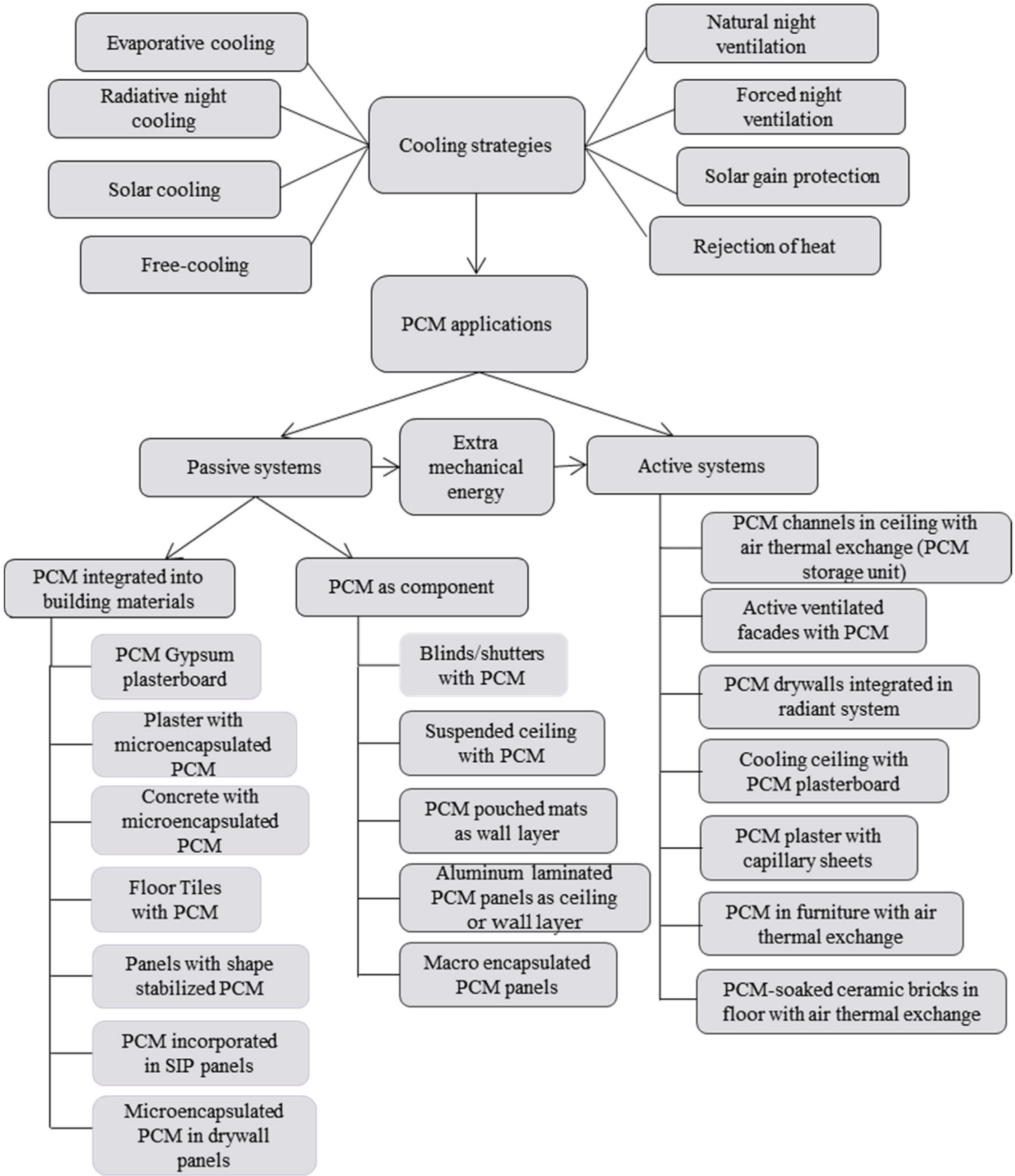


Fig. 52. A synthetic diagram of PCM cooling applications.

integration of PCM in buildings under hot and humid climate has very limited impact on the energy consumption. Aranda-Usón et al. [138] considered five different climatic zones in Spain to evaluate three different commercial PCM installed on tiles. They concluded that PCM can minimize the total energy consumption and the environmental impacts. Moreover, the effective performance of PCM is heavily influenced by the climate conditions and the type of PCM introduced. Borderon et al. [139] investigated a PCM/air ventilation system storing latent heat in order to improve summer comfort conditions in four French cities (Lyon, Nice, Carpentras and Trappes) under different climates, where Carpentras is the warmest climate and Trappes is the coldest one. It was shown that the performance of the system is mainly affected by the daily amplitude of the exterior air temperature. In addition, the diurnal temperature range, which is the amplitude of the outdoor air temperature swing, is a critical factor of the applicability of PCM to reduce cooling loads [140]. Thus, when the diurnal temperature range is between 12 °C and 15 °C the free cooling system with incorporated PCM can be applied showing an effective performance [35].

From the above literatures, it is obvious that the effective performance of PCM is extremely related to climate conditions; therefore it is important to choose a suitable PCM melting temperature that it is strongly conditioned by the surrounding climate.

4.3. Melting temperature of PCM

The most significant criterion for PCM selection is the required melting temperature, it is considered as the greatest influent parameter. It is very important to select the right type of PCM because, for a specific climate conditions, if the melting temperature is too low, it is difficult to maintain the indoor air temperature at a comfortable level during the night; furthermore, if the

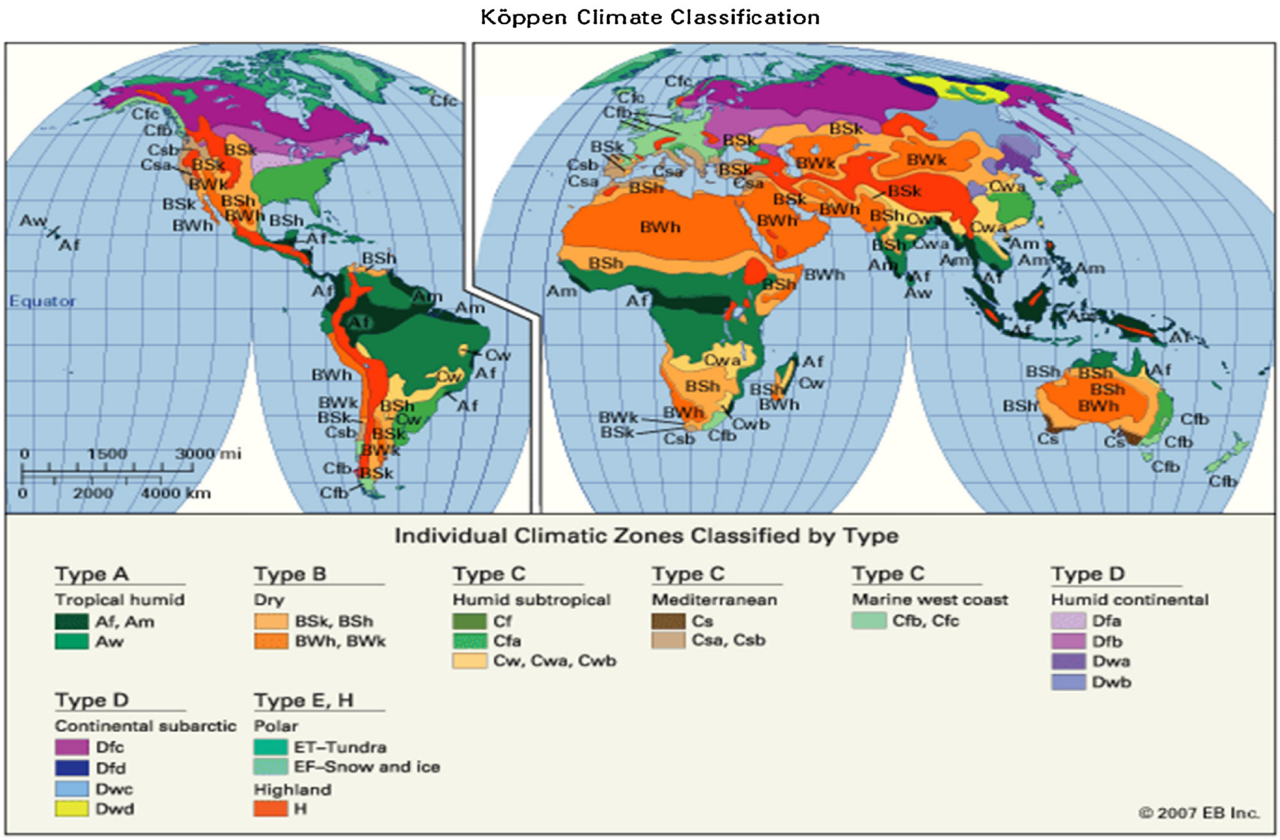


Fig. 53. Climate classification according to the Köppen–Geiger [133].

melting temperature is too high, the quantity of solar radiation heat stored by the PCM will be reduced in the daytime [141]. Additionally, the selection of a low melting temperature leads to insufficient use of PCM in the hottest months. On the other hand, a melting temperature too high could lead to a marginal feasibility during the intermediate seasons. Most of the PCM that can be applied in buildings have melting points between 18 °C and 28 °C, close to the human comfort temperature range. A phase change temperature outside of the operating temperature range of the storage could make the application totally useless. Partial solidification and melting of PCM can lead to insufficient thermal storage [11].

The selection of different melting temperatures depends on the main purpose of the application, which could be to save heating energy or to prevent overheating [127]. The PCM that has a good performance in the heating periods will have an insignificant impact or no effect at all in cooling periods and vice versa. Barreneche et al. [142] created a new database (software CES Selector) that helps selecting the most suitable PCM depending on the application, using data collected by Cabeza et al. [16]. They found that, for cooling applications in buildings, PCM should have been melting temperatures up to 21 °C. Moreover, PCM used to control the indoor comfort temperature, should have a temperature range between 20 and 30 °C and this PCM are commonly used in passive systems. Furthermore, for domestic hot water application, PCM should have temperature range between 29 °C and 60 °C. Other authors reported that in the air conditioning applications PCM that melt below 15 °C are used to store coldness, while for absorption refrigeration, the used PCM melt above 90 °C and all other PCM that melt between 15 °C and 90 °C can be used for solar heating applications [11]. Heim and Clarke [143] showed that the optimal PCM solidification temperature is 2 °C above the heating set point for the room. Peippo et al. [144] indicates that the optimal diurnal heat storage happens with a PCM melting temperature of 1–3 °C above the average room temperature. Moreover, Neeper [78] tested the thermal performance of fatty acids and paraffin waxes gypsum wallboard; they found that, with a PCM melting temperature near to the average comfort room temperature, the maximum diurnal energy storage can be occurred. Additionally, for wallboard installed on external wall, the optimum value of the melting temperature depends on the outdoor temperature and the thermal resistance of the wall. Ascione et al. [137] analyzed the monthly energy improvement that can be achieved in different cities under various climates by changing the melting temperature in the range 26–29 °C. They found that the most appropriate melting temperature for Ankara under semi-arid climate is 29 °C leading to significant cooling energy savings in the cooling season. Otherwise, for Seville climate that has the hottest European summer, although the phase change is considerably activated, the PCM is not able to take full advantage of its storage potential. Therefore, it can be shown that it is not possible to determine an optimal melting temperature for the whole cooling period where the worst results for each melting temperature were found in August, most likely because of the incomplete solidification of PCM. Finally, it was reported that, for the Mediterranean climate the optimal range of melting temperature in the winter period is between 18 °C and 22 °C, while, in summer, appropriate melting temperature range is between 25 and 30 °C. Aranda-Usón et al. [138] have analyzed three commercial PCM with melting temperatures selected within the comfort range (21–24 °C). They concluded that salt hydrates PCM with a melting temperature of 21 °C can reduce the total energy consumption in the five different climate severities in Spain. Moreover, simulations have been carried out by Alam et al. [136], using BioPCM with six different melting ranges from 20PCM (18–22 °C) to 25PCM (23–27 °C) in order to find the optimum PCM melting range for each climatic zone. They concluded that an optimum PCM melting range that leads to the lowest energy consumption in every month of the year

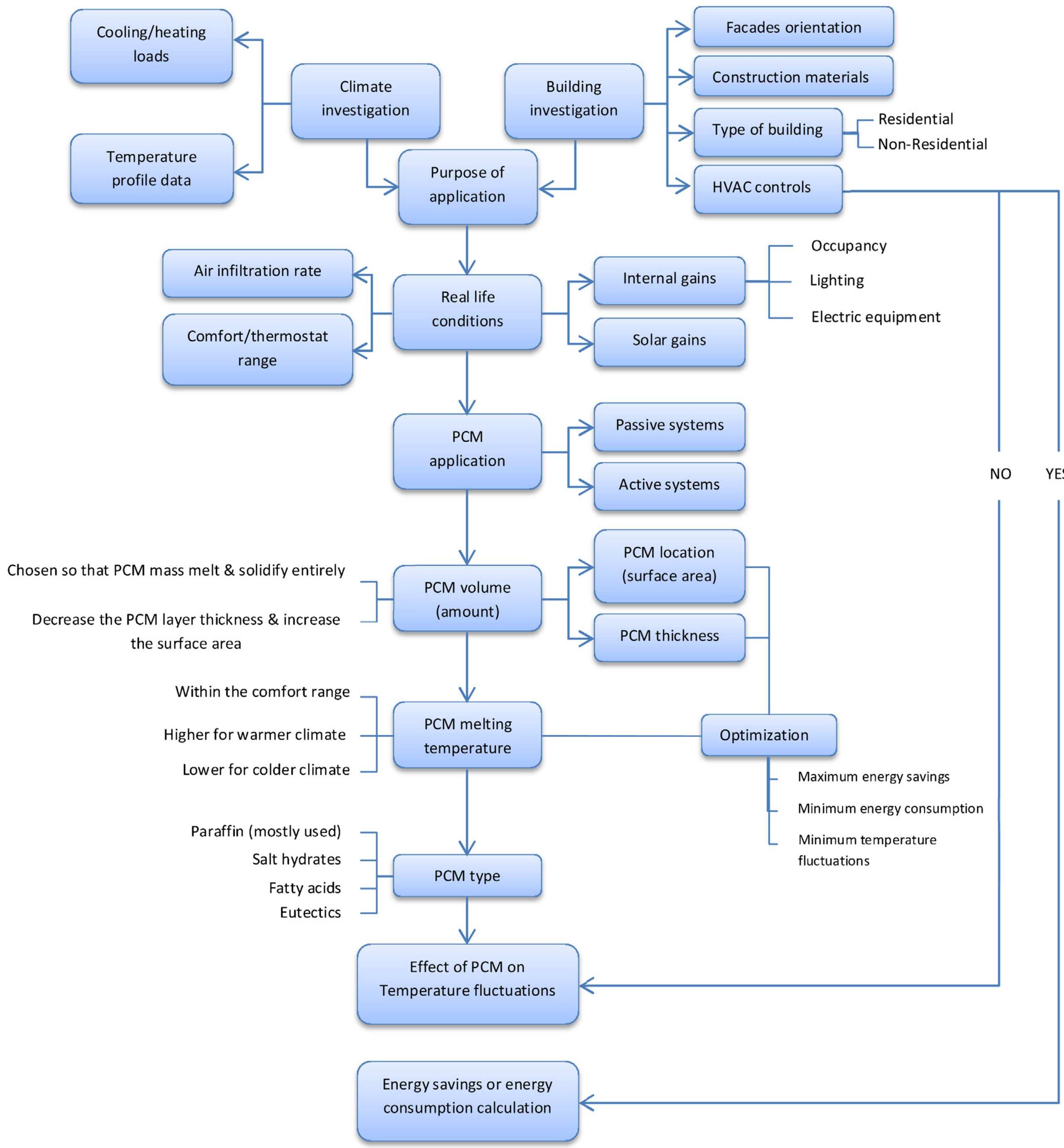


Fig. 54. A typology diagram of PCM in building applications.

can't be unique, and PCM with melting point outside the comfort or thermostat range cannot be effective and lead to decrease energy savings. Furthermore, it was found that PCM with higher melting point were more efficient during summer as well as in warm temperate climate areas, while PCM with lower melting point were most efficient during winter and perform better in cold temperate climate area. Other simulations [145] showed that a phase change temperature of 22 °C, which is the mid-point of the chosen comfort range (20–24 °C), was the best for the studied case. In commercial buildings, peak temperatures can be reduced by about 3–4 °C, and day hours where the temperature is above 24 °C can be reduced by 80%. Moreover, Fiorito [146] found that for a considered climatic zone, the PCM melting point should be selected in order to be compatible with the average maximum outdoor temperatures. Accordingly, for a free cooling system design, the PCM melting temperature is considered as a decisive factor [48], and it should be taken between 19 °C and 24 °C [34,45] which intersect the range of the human comfort 23–27 °C in summer conditions. Waqas and Kumar [147] have found that the performance of free cooling system in hot dry climates is better with a PCM melting temperature selected within the comfort range of the hottest month. In order to find the optimal PCM melting temperature, a new method was presented by Jiang et al. [148] for a passive solar house. They found that the optimal PCM melting point depends on the minimal limit of the indoor thermal comfort band, and its value, in China under different climates, should be taken from 1.1 °C to 3.3 °C greater than the minimum thermal comfort range. Soares et al. [135] investigated the impact of six different melting temperatures; they found that the optimum PCM melting temperature is higher for the warmer climates (between 22 and 26 °C), and lower for colder climates (between 18 and 24 °C). For better PCM performance, Farid [149] suggested to utilize in the same storage unit, more than one PCM with various melting temperatures. In order to get an effective performance all the time under different weather conditions, two layers of PCM with different melting temperature incorporated into the rooftop of the building were used [80]. Moreover, systems with different PCM having different melting temperatures are considered as an important future research, and should be developed in order to improve the building performance in both cooling and heating seasons.

From the above literatures, it can be concluded that there are different criteria to select an appropriate melting temperature whether for heating or cooling applications or both. Knowing that, the same phase change material does not provide the same advantages referring to both heating and cooling energy demands, and none of the PCM is equally effective over the year. The selection of melting temperature should be based reasonably on local thermostat set points along with the climatic conditions. Some authors agree that high PCM melting temperatures seemed more effective for warmer climates, while low PCM melting temperature could be more efficient in colder climates, and others emphasized on the importance of selecting PCM melting temperature within the comfort range. To choose the most suitable PCM melting temperature for an application under considered climatic zone, the optimization method by testing different melting temperatures seemed the most appropriate.

4.4. Location of application: effect of PCM surface area and thickness

In the previous section, the effectiveness of PCM was investigated in terms of selecting a suitable PCM melting temperature for a considered application. In this part, the effect of position, surface area and thickness of PCM integrated in building on energy savings will be investigated. As mentioned previously, PCM can be incorporated into wallboards, roof, underfloor, concrete, plaster, furniture, and insulation of buildings, glazing and others [66,17,150,18,15,151]. The location of PCM, essentially in passive systems, depends on its objective and functioning [11], unlike the PCM storage units that have more options and liberty in terms of their location. Passive PCM application at the floor seems to be the best location for the heating periods; this is due to the fact that in the floor it is possible to benefit from each of the indoor air temperature and direct solar gains via the glazing. However, PCM drywalls (plasterboards, wallboards or gypsum boards) seemed more appropriate as passive systems for cooling purposes. Knowing that, night ventilation together with PCM is a very effective strategy that leads to decrease the cooling demand of buildings. Ingenious solutions [106] for reducing the cooling demand of buildings such as ventilated facade with fins filled with PCM and PCM cylinders in hollow core slabs, were created in order to increase the convective heat transfer coefficient. Therefore they allow the use of large quantities of PCM, and improve the utilization factor of cold stored. Ceilings present considerable areas for passive heat transfer and have less risk of spillage of the macro-encapsulated PCM by drilling; however, they have lower convective heat transfer coefficients compared to walls and floor. Moreover, it was found that a PCM layer incorporated in the roof structure seemed inappropriate to improve the building energy performances [80], actually rooftop temperature increases when the PCM becomes liquid. For the purpose of reducing cooling demand and improving thermal comfort, Ascione et al. [137] installed gypsum wallboard PCM on the inner faces of the external building envelope. The results showed that the application of the PCM plaster on the whole vertical envelope leads to the highest energy savings in different climatic zones. In addition, it has been found that the cooling demand is reduced with the increment of the thickness of PCM plaster; however, authors investigated until a maximum thickness of 3 cm of PCM plaster because additional increment of PCM thickness cannot provide considerable improvements of the indoor temperature. Soares et al. [135] replaced the inner plasterboard layers of the exterior walls, partition wall and roof by a PCM-drywall layer. In all studied cases, they found that the optimum thickness of the PCM-drywalls was equal to 4 cm. Moreover, in terms of surfaces solar absorbance, lower values ($\alpha = 0.3$) are better for warmer climates while higher values ($\alpha = 0.9$) are better for colder climates. Alam et al. [136] investigated energy savings for different locations of PCM (east wall, North wall, West wall, South wall, North wall and roof, West wall and roof, South wall and roof, east wall and roof, all walls, all walls and roof) where the thickness of PCM layer was calculated by dividing the PCM volume by the surface area of the applied location. For a specified amount of PCM, it was shown that energy savings and therefore effectiveness of PCM increase with the decrease of the thickness of PCM layer and the increase of surface area until an optimum level.

During a phase change daily cycle, the PCM volume must be chosen so that PCM mass could be melted and solidified entirely. During the cooling season, if the PCM volume is very high, the solidification process time may be longer than the time of low temperatures at night. Similarly, in winter, if the PCM volume is very high, the PCM cannot be completely melted because the sunshine time could be shorter than the time required for the heat penetration in the PCM. Furthermore, increasing the surface area of the applied location of PCM, leads to an increase of the heat transfer rate between this area and the PCM. At a constant PCM volume, the thickness of PCM layer is thinner when the surface area increases. Therefore, melting and solidification processes become more effective.

The total energy exchanged due to the enthalpy content in the PCM (i.e. the overall latent heat storage capability) can be calculated using Eq. (1) [138]:

$$E_{latent} = n \times m \times H_f \tag{1}$$

where m is the mass of the PCM, n is the number of phase changes that occur during a specified period of time and H_f is the PCM latent heat.

For a better evaluation of the impact of PCM position and thickness, Konstantinidou and Novoselac [7] calculated the total amount of PCM necessary to absorb the surplus heat for cooling periods. The average daily cooling load E_{daily} was determined. Therefore, the diurnal energy stored in the PCM is given by Eq. (2):

$$E_{daily} = m_{cp} \times H_f \tag{2}$$

where m_{cp} is the specific mass of PCM and H_f is the latent enthalpy of the material.

Therefore, the required mass of PCM is calculated and subsequently the required PCM volume is given by Eq. (3):

$$PCMVolume = m(PCM)/\rho(PCM) \tag{3}$$

4.3. HVAC controls

According to the indoor microclimate, two types of study can be carried out:

- Without including the HVAC system (naturally ventilated building): to find out the effect of PCM on the temperature fluctuations in the considered indoor space, where the temperature is free-running, and the potential of PCM in reducing peaks. In this case the hourly temperature data must be given.

- Including the HVAC system (air-conditioned building): to calculate the energy consumptions, and thus the energy savings. In this case, the indoor temperature is controlled and a schedule of set points must be made.

5. Conclusion

A review of PCM applications for cooling purposes, and factors affecting the effectiveness of PCM were discussed in this article. Many experimental and modeling-simulation studies have been presented, showing the effect of PCM on the buildings thermal performance. The use of PCM in buildings seems to be very beneficial; PCM can decrease energy consumption, shift the peak loads of cooling energy demand, decrease temperature fluctuations providing a thermally comfortable environment, and reduce the electricity consumption. Free cooling applications are effective when the diurnal temperature variations are large (up to 15 °C). When HVAC system is used, PCM act as a cold storage unit, shifting the peak loads to low electricity rate periods. Integrating PCM in the building envelope prevents the rise of the indoor temperature improving the thermal comfort. However, many drawbacks have been found in PCM applications, mainly the non-use of considerable portions of employed PCM due to the low convective heat transfer coefficients, incomplete solidification of PCM at night and the limited contact area between the air and PCM.

Several solutions have been proposed, such as the use of proper control strategy, forced ventilation to increase the convective heat transfer, and adequate design of the heat exchangers. Moreover, using fins, cylinders, and spheres to encapsulate the PCM could improve the use of considerable amounts of PCM and increase the convective heat transfer coefficients. Paraffin was mostly used in cooling applications; however, salt hydrates and fatty acids were used in some cases. Selecting the most suitable PCM for a specific climate and a specific application was discussed. The melting temperature is the most influential parameter, some authors approve that high PCM melting temperatures seemed more effective for warmer climates, while low PCM melting temperature could be more efficient in colder climates, and others emphasized on the importance of selecting PCM melting temperature within the comfort range then an optimization method by testing different melting temperatures is required. Moreover, systems with different PCM having different melting temperatures are considered as an important future research, and should be developed in order to improve the building performance in both cooling and heating seasons. Moreover, for a specified amount of PCM, it was shown that energy savings and therefore effectiveness of PCM increase with the decrease of the thickness of PCM layer and the increase of surface area until a certain optimum level. The selection of an appropriate amount of PCM needed for thermal storage still requires also further research. A general topology diagram summarizing the PCM application in buildings is presented in Fig. 54.

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