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A review on the air-PCM-TES application for free cooling and heating in the buildings

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ABSTRACT

Thermal energy storage (TES) technologies incorporating phase change materials (PCM) are proving viable option for achieving energy efficiency economically in the buildings. This paper reviews the application of air-PCM-TES studies and technologies for the free cooling and heating of buildings. TES in general and air-PCM-TES in particular are discussed in this review. An extensive investigation on air-PCM-TES systems has been undertaken through passive and active methods and the advantages and disadvantages for each, are detailed. The thermal performances of these systems have been investigated through experimental and numerical approaches and listed in this paper. Passive methods e.g. use of PCMs in the building envelope present difficulty of exchanging a high rate of heat and therefore unsuitable for extreme climate. Therefore, active methods are adopted for extreme climates to meet the demand. Overall, when the right method is applied, air-PCM-TES systems have shown to be effectively providing free cooling and heating of the buildings through auxiliary sources.

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1. Introduction and background

Research findings have indicated that buildings account for 40% of the world's energy consumption and contributing up to 30% of the annual greenhouse gas emissions [1]. The reduction of the energy consumption in buildings has been one of the priorities of the recent EU directives. The Energy Performance of Buildings Directive (EPBD) in 2002 requires all EU Member States to introduce a general framework and to set building energy codes based on the global building approach [2,3]. The most energy consumption in buildings is associated to ventilation, heating and cooling systems [4]. The necessity of improving the energy efficiency of the built environment resulted in the development of various techniques of better usage and conservation of energy for heating and cooling [5]. Thermal energy storage (TES) is useful technology for improving energy efficiency and energy saving [6]. TES in buildings can be implemented by sensible heat (increasing and decreasing the temperature of the building envelopes, for example), or by latent heat (with the inclusion of Phase change Materials (PCMs) which increases thermal inertia) [7]. The use of PCMs has been considered for TES in buildings prior to 1980. The first applications of PCMs were their use in heating and cooling applications by Telkes [8] and Lane [9,10]. Recently

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different applications for use of PCMs by several authors were developed. Research into TES for cooling and heating continues and has also been considered for waste heat recovery, load levelling for power generation, building energy conservation and air conditioning [11]. Literature review shows that several studies have been carried out in the field of TES and PCMs. However, in depth review on Air-PCM-TES emphasising on free heating and cooling is still missing. The applications and the advantages and disadvantages for active and passive methods of Air-PCM-TES are discussed in this review, enabling researchers to identify and select the most appropriate method for the intended application.

2. Relevance of air-PCM-TES systems

The necessity of improving the energy efficiency of the built environment has resulted in the development of various techniques of better usage and conservation of energy for heating and cooling [12]. Latent heat storage (LHS) has been qualified as the most efficient way to store thermal energy with higher storage density and smaller temperature changes when storing and releasing the heat [13,14]. In LHS systems, the thermal energy is stored as latent heat in substances undergoing a phase transition, e.g. the heat of fusion in the solid–liquid transition [15].

PCMs attract an abundance of research owing to three characters: the relative steady melting/freezing temperature in a certain range; the wide range of categories of PCMs such as organic, inorganic and eutectic with several of melting/freezing temperature and the high thermal density. Solar energy and TES have long been known for its passive design specifically using day time solar energy for heating and cold night-time ambient energy for cooling [16], known as free cooling. Free cooling is known as the process of storing the coolness of the night air to cool down the warm air during day time. Moreover, air-PCM-TES has been popular in buildings with the combination of Heating Ventilation and Air-Conditioning (HVAC) systems, supplied individually, or joined with construction materials in the construction wall, roof and ground. This review paper distinguished the air-PCM-TES systems in how the heat transfer fluid is supplied (passively or actively) and through their location of the TES within the building. Some studies propose them mounted in the ceiling [17–20] others in the floor [21,22] and also near to the walls [16,23].

3. Major applications

Based on the researches carried on by Zalba et al. [12], Regin et al. [24] and Kenisarin and Mahkamov [25] it is possible to summarise that the main applications of PCM-TES in buildings as listed in Table 1. They are also classified as low temperature thermal storage technologies as presented in Fig. 1. The TES can be encapsulated and applied in different locations within the building or integrated directly into the buildings materials. Also, they are classified as both short-time or annual storages. The former usually uses the daily storage/release cycles, whilst the latter work on a season basis. In other words, for short time storages we can consider the heat storage during the night-time and its release in the day time or vice versa. For annual storage, the heat is stored during the summer for its release in colder seasons or vice versa. LHS with PCMs can be categorized as active or passive space heating/cooling systems as shown in Fig. 2. In passive systems, PCMs can be encapsulated in building materials such as concrete, gypsum wallboards, ceiling or floor to increase their thermal storage capacity. Alternatively, storage units using PCMs can be used with conventional active space heating and cooling systems to improve the overall thermal efficiency [43]. PCMs with a melting temperature between 20 °C and 32 °C were recommended for thermal storage in conjunction with both passive and active solar storage for heating and cooling in buildings [20,26] Fig. 3.

Table 1
PCM-TES applications [12,24,25].

PCM-TES applications in buildings
Passive Storage in buildings in bioclimatic building/architecture (HDPE+paraffin)
Cooling: use of off-peak rates and reduction of installed power, ice-bank
Heating and hot water: using off-peak rate and adapting unloading curves
Thermal storage of solar energy

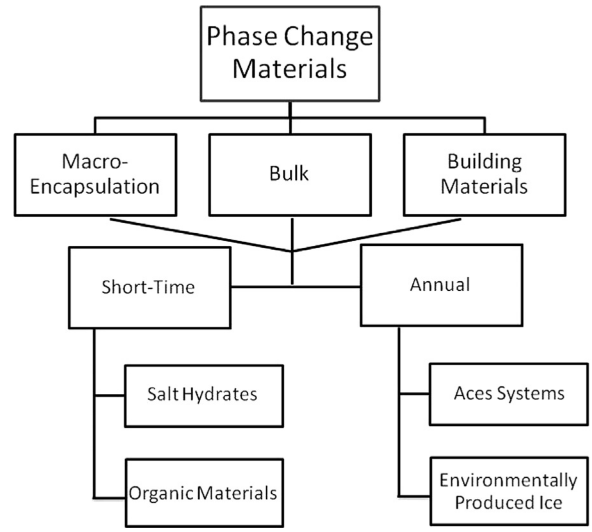


Fig. 1. Low temperature thermal storage technology classification.

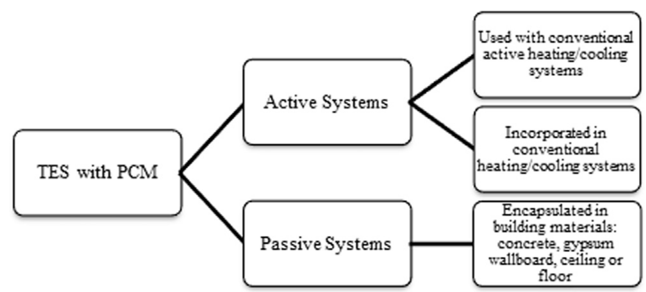


Fig. 2. Active and passive system for TES with PCM.

This paper reviews the active and passive methods of free cooling and heating in the buildings. Passive methods with TES integrated into several building components e.g. wallboards [27–32], glass [33], floor [34–36] or solar chimney [37] and active methods with the integration of TES in the celling [17–20], underfloor [21,22] and walls [16,38].

3.1. Free cooling and heating passive methods

Latent heat thermal energy storage (LHTES) can be encapsulated into building materials or structures. The system is said to be passive as no conventional energy is needed. In free cooling, the concept of PCMs integrated into buildings materials allows the PCM to absorb cold during the night-time which begins the solidification process, and during the day the cold is released by the melting process of the PCM, resulting in a lower heat flow from outdoors to indoors [39]. During the winter, the system can also be used for heating by utilising solar energy during the day. In passive methods, the stored heat or cold is automatically released when indoor or outdoor temperatures rise or fall beyond the melting point of PCM [40]. Passive methods used for the thermal energy management of the built environment include the

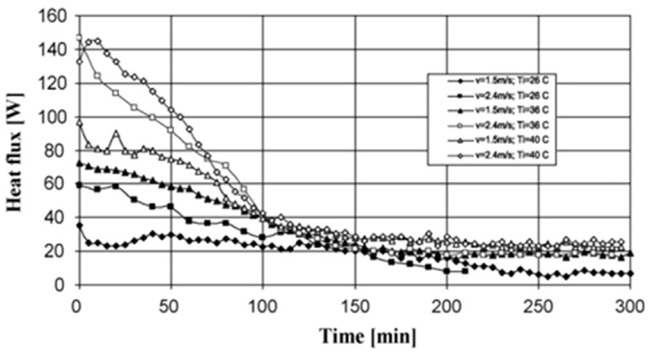


Fig. 3. Heat flux of the buffer at different inlet air temperatures and airflows [20].

thermal mass, which can contribute to the downsizing of air conditioning (AC)/heating equipment and the reduction of the AC/heating demand [41]. Lee et al. [32] studied experimentally the integration of a thin PCM layer into a wall via a thermal shield. It allowed the reduction of the peak heat flux by 51.3% and 29.7% for the south wall and west wall, respectively. The applications of PCM in structures of buildings have an advantage in not requiring separate plant and space. Therefore there are several studies about PCMs integrated into building materials (concrete, brick, glass, etc.) or components, such as wallboards, floors, ceilings and roofs, Table 2 and 3 list some of them. PCMs integrated in wallboards have been intensively investigated due to the following advantages:

- Being cheap and widely used in a variety of applications [42];
- Capable of minimising the effect of large fluctuations in the ambient temperature on the inside temperature of the building [43] and
- Twice greater than a room with conventional wallboards when the temperature was increased from 18.3 to 29.4 °C [25].

Table 2
Passive methods: PCM integrated into wallboards.

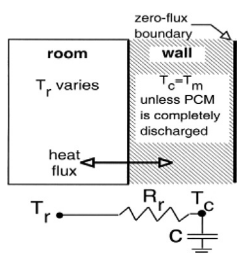
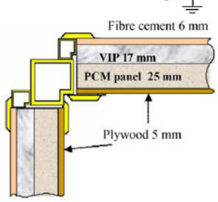
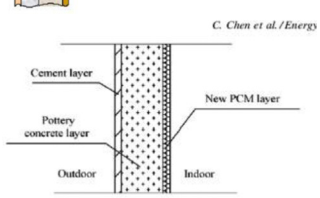
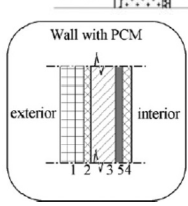
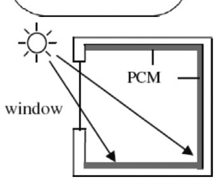
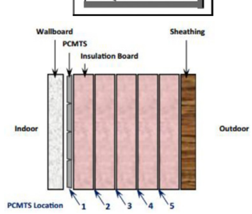
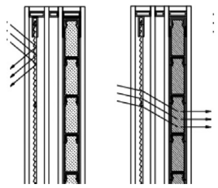
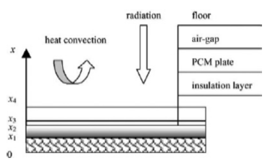
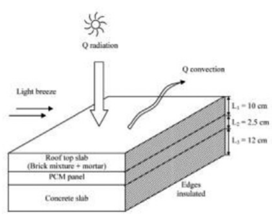
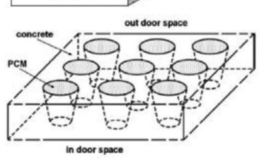
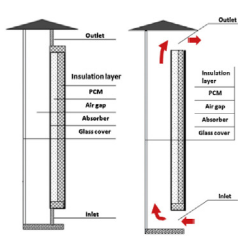
Structure	Images	Outcomes	Ref.
Walls		The maximum diurnal energy storage occurs at a value of the PCM melt temperature that is close to the average room temperature in most circumstances. The diurnal storage achieved in practice may be limited to the 2 range 300–400 kJ/m, even if the wallboard has a greater latent capacity	[27]
		In summer the amplitude of the temperature inside the cell with PCM is decreased by 20 °C on a daily cycle. In winter, this prevents negative indoor temperature whilst the temperature of the cell without PCM is −9 °C and that the outside temperature is below −6 °C	[28]
		Applying proper PCM to the inner surface of the north wall in the ordinary room can not only enhance the indoor thermal comfort dramatically, but also increase the utilisation rate of the solar radiation. The reduction in heating energy consumption led to energy saving. The energy saving rate of heating season η can get to 17% or higher. So the energy is effectively used and saved obviously	[29]
Walls		This stored energy prevents building rooms from overheating during hot days, and during the night, the released energy increases the minimum air temperature. On the whole, PCM allows a decrease in temperature fluctuations inside rooms	[30]
		The analytical results show that: the optimal phase change temperature depends on the average indoor air temperature and the radiation absorbed by the PCM panels; the interior PCM has little effect on average indoor air temperature; and the amplitude of the indoor air temperature fluctuation depends on the product of surface heat transfer coefficient and area of the PCM panels in a lightweight passive solar room	[31]
		At the optimal locations, the peak heat flux reductions were 51.3% and 29.7% for the south wall and the west wall, respectively. The maximum peak heat flux time delays were 6.3 h in the south wall and 2.3 h in the west wall. The maximum daily heat transfer reductions were 27.1% in the south wall and 3.6% in the west wall	[32]

Table 3
Passive methods: PCM integrated into glass, floors and roofs.

Structure	Images	Outcomes	Ref.
Glass		Up to 1186 W/m^2 of latent thermal storage. Average 8–14 h latent storage. It reduces the average interior room temperatures by 4 °C–12 °C. In the winter it creates an average reduction of heating Load by 150–200 kW h/m^2 per year	[33]
Floor		The heat of fusion and the thermal conductivity of PCM should be larger than 120 kJ/kg and 0.5 W/(mK); the thickness of PCM plate should not be larger than 20 mm and the air-gap between PCM plats and the floor should be as smaller as possible	[34]
Roof		A double layer PCM incorporated in the roof is suggested and recommended to narrow indoor air temperature swing and to suit for all seasons	[35]
		The heat gain is reduced when the PCM is incorporated in the roof and the conical geometry of the PCM container is the best in term of thermal effectiveness. The heat flux at the indoor space can be reduced by up to 39%	[36]
Solar		The results showed that the inclusion of the PCM to a solar chimney reduces the air flow during charging period but increase it during discharging period compared with the solar chimney without PCM	[37]

However, PCM wallboards also present some disadvantages:

- The heat storage is limited by the low value of the heat transfer coefficient (h_c) between the air and the wallboards [25,44];
- Presence of an unpleasant odour in the room with the PCM wallboard [45];
- Layer of corrosion formed on some metallic (copper and aluminium) surfaces in the room with PCM due the vaporisation of impurities from the fatty acids [46];
- PCMs without the addition of fire retardants, organic PCMs had unacceptable flammability characteristics [25]; and
- Any replacement of the PCM wallboards will affect the aesthetic of the room.

David et al. [47] demonstrated that even accounting for the possibility of having mixed convection in both laminar and turbulent regimes, the use of the most common correlations available in the literature would still provide small convection coefficient $h_c \leq 2.5$ W/m^2 °C for limited temperature differences between wall and air ($T < 2$ °C). This implies a poor heat transfer between the wallboard and the indoor environment, thus reducing the daily thermal energy storage in the PCM if compared with its storage potential [38].

The main problem with incorporating PCMs in the building envelope is the difficulty of exchanging a high rate of heat between the air and the PCM. Passive ways for cooling may also not be as effective in extreme climate conditions. This is mainly because of the outdoor ambient air temperature does not decrease sufficiently at night. Stetiu and Feustel [48] found that for climates with relatively high ambient temperatures (above 18 °C) during the night, it would be beneficial to force the supply air along the wall surfaces to facilitate good heat exchange.

3.2. Free cooling active methods

Free cooling is based on the use of the coolness of a source, such as outside air, to cool down buildings. If, for example the night coldness is stored and utilised during daytime to achieve comfort temperatures in indoor spaces, mechanical ventilation can be either totally eliminated during the day time or at least can be limited only to certain periods [49]. As there will be no need for energy to produce a cold source, this process is commonly known as free cooling. Free cooling may also be accomplished through LHTES systems improving the cooling potential of mechanical ventilation systems [50], or even helping reduce the size of the mechanical ventilation system. This provides more favourable temperatures and therefore better thermal comfort conditions [23]. The main advantages of free cooling are: cooling with reduction of greenhouse gases and the maintenance of excellent indoor air quality within the building [50]. For free cooling systems, PCMs have to be selected so that the cooled air temperature is within the range of human comfort. For instance, in summertime, the human comfort zone lies between 23 °C and 27 °C [51]. In order to achieve sufficient heat transfer, the temperature difference between the air temperature and the melting temperature of the PCM should be within the range of 3–5 °C [51]. Table 4 lists the studies on active methods for free cooling applications. An active free cooling system is said to be active because of the use of electric devices. A free source of cooling is used (the night coolness for example) and the storage of this coolness is ensured with an active system. In active methods, storage as heat transfer fluid (HTF) is actively moved known as forced convection. This can operate optimally in reducing the internal dry bulb temperature. It has the potential not only to significantly impact on energy consumption, but to reduce it to a small fraction of its current level. Only the energy consumption for a fan remains [52]. This type of systems also allows full control of the process during the charging/discharging of the PCM, thus optimising the performance of the whole system. However, if the system is not sufficiently designed, it can be ineffective. The key benefits of using the storage system as a component of an air conditioning system can be summarised as a reduction in equipment size, capital cost savings, energy saving, operational cost savings, peak power savings and improved system operation [53–55]. One of the first experimental works on free cooling combined with a ventilation system was from Turnpenny et al. [17]. In this study, the coldness of the night air was stored in the PCM and discharged during the daytime. The novelty was not only that the night ventilation system used LHS system, but also in the use of a reversible heat pipe embedded in the PCM (Table 4). In this study it was possible to achieve 70–90 W for the outside air and the PCM difference temperature was around 12 °C, although to melt and freeze the PCM in a practical timescales (7–

Table 4
Summary of active systems for free cooling of building.

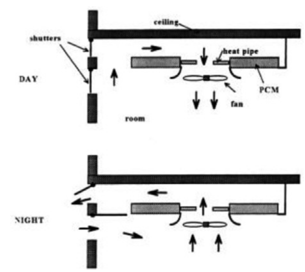
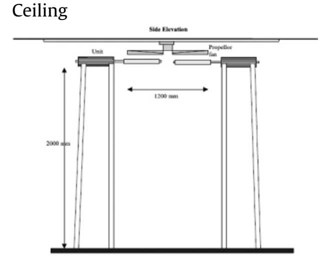
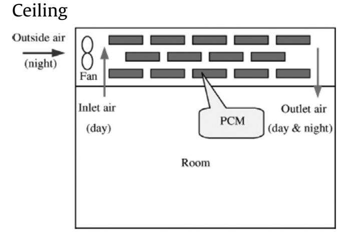
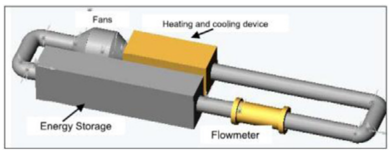
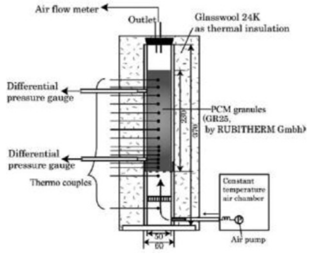
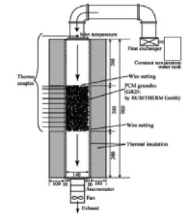
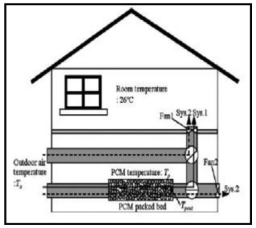
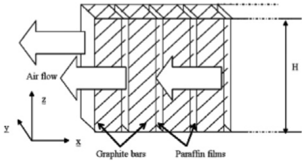
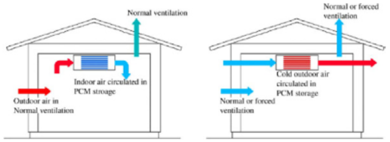
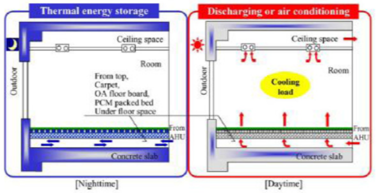
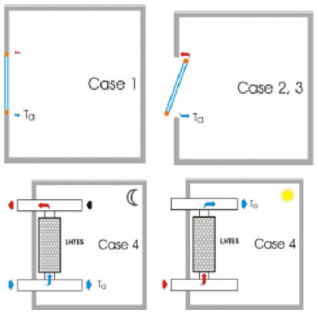
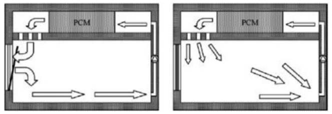
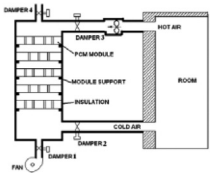
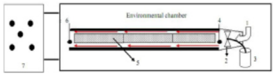
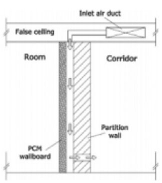
Ref.	Objectives of the study	Key arguments	PCM considered	Geometry of PCM structure	PCMs location and system design	Type of heat exchanger	Methodology	Major results
[17]	Development of latent heat storage unit incorporating heat pipe (novel since it is reversible) embedded in PCM for free cooling buildings	LHS incorporating reversible heat pipe incorporate of finning arrangements spiral wire fins	-	Cylindrical PCM jacket	Ceiling 	Heat pipe	Experimental and Mathematical (one-dimensional	Heat transfer rate of 40 W over a melting period of 19 h for a temperature difference of 5 °C between air and PCM Heat storage of 270W h over 8hours Large temperature difference of 15 °C between the air and PCM was needed to melt and freeze the material in a practical time scale (7-10h)
[54]	Improvement of previous study through: new fins arrangement (plate fins arranged longitudinally along the PCM end of the heat pipe); guaranty of full contact between all the extend surface and the PCM gel	Ceiling fan with model with 3 blades	-	Cylindrical PCM jacket	Ceiling 	Heat pipe	Experimental	Heat transfer rate of 200 W is sufficient for the summer load Heat storage of 100 W can be stored over 2-3 hours
[18]	Analyse of thermal behaviour of a proposed Night Ventilation with PCM Packed Bed Storage (NVP)	Predict energy consumption ;-Air flow resistance ;-Convective heat transfer	RT 25	Plates PCM packed bed storage	Ceiling 	Direct contact between PCM and air	Experimental and Mathematical	Convective heat transfer coefficient is 12 to 19 $W/m^2.°C$ Air flow resistance through PCM is less than 20 Pa
[14]	Study of free cooling with night ventilation system	Determination of the mains influence parameters for melting/freezing of PCM	RT 25	Plates of encapsulated PCM		Direct contact between PCM and air	Experimental, Statistical method and Empirical	Relative long duration of loading (4h)and unloading (8h) process Very high power consumption of the fans
[22]	Predict the heat transfer coefficient to estimate the amount of exchanged heat	Creation of dimensional numbers to predict heat transfer coefficient	GR 25	Packed bet of PCM granules		Direct contact between PCM and air	Experimental, Numerical and Computer simulation	Exchanged heat per unit time and unit area is proportional to the face velocity and the difference of temperature in the PCM packed bed Heat transfer coefficient can be used to estimate the amount of exchanged heat and time required phase transformation to be completed

Table 4 (*continued*)

Ref.	Objectives of the study	Key arguments	PCM considered	Geometry of PCM structure	PCMs location and system design	Type of heat exchanger	Methodology	Major results
[21]	Ventilation system with packed bed of granules containing PCM in air supply ducts (for cooling)	Definition of factor "latent heat corresponding to flow rate,(D[1])" Definition of factor load ratio (η^2)	GR 25	Plates of encapsulated PCM	Under floor  	-	Experimental and Computer simulation	It is found that the benefit depends more on the range of daily temperature variation than on average temperature Reduction of ventilation load is by 62.8% (for Kyoto)
[56]	Improvement of previous study through: graphite compounded material with PCM to enhance heat transfer	Designing a TES using air and porous matrix of graphite embedded into the PCM for efficient free cooling	RT 25	Plates of encapsulated PCM embedded into a graphite matrix		Direct contact between PCM-air	Experimental and Numerical	Response time much lower (50% in time) Power consumption of the fans is decreased by 50% Very low reduction of the energy is stored (12 and 20%) based on the storage volume occupied by the graphite
[19]	Free cooling of buildings	The possibility of use of phase change materials integrated into a building is explored	-	Plates of encapsulated PCM	Ceiling 	Direct contact between PCM and air	Mathematical	Heat transfer coefficient between the airflow and the PCM increases significantly when the surface is rough compared to a smooth surface (valid for toughness of 0.02 m) Heat transfer coefficient for air velocity of 4 m/s ranges within 16-30 W/m^2. °C
[22]	Remove the cooling load in the room	New floor supply air conditioning system ;-Performance of charge/discharge experiments to simulate office air conditioning over 24 h periods	C_6H_{34} and $C_{18}H_{38}$	Packed bed of the granular PCM	Floor 	Direct contact between PCM-air	Experimental and Computer Simulation	89% of daily cooling load could be stored each night for 30 mm thick packed bed of the granular PCM 1.79 MJ/m^2 heat storage by the end of each night that allowed a daytime air conditioning limited to 3h
[23]	Free cooling of low energy building using LHTES	LHTES integrated into a mechanical ventilation system LHTES optimization made for selected parameters: PCM's phase change temperature	RT20	Cylindrical LHTES filled with spheres of encapsulated PCM		Direct contact between PCM and air	Numerical and Computer Simulation	LHTES with 6.4 kg/m^2 of PCM of floor area offers suitable thermal comfort conditions LHTES can be used as heat storage during winter if the ventilation system is combined with an air

		range, PCM melting temperature and ratio of the PCM's mass to the air volume flow rate						solar collector or a ventilated façade element
[20]	Free cooling of buildings	Study of the ceiling and floor free cooling principle, as well as passive cooling	RT 20	Plate incorporating fins	Ceiling 	Direct contact between PCM and air	Experimental	After 200 min the outlet air temperature equals the inlet air temperature Bigger difference of the air inlet temperature and environment temperature reduces the time for cooling Higher airflow reduces lightly the time for cooling
[57]	Free cooling of buildings	Modular heat exchanger developed: shell and tube type exchanger with PCMs in the shell portion of the module and passage for the flow of air through the tubes. Determine the PCM solidification characteristics and to verify the suitability of the selected geometrical dimensions	-	Cylindrical container		Direct contact between PCM and air	Experimental and Computer Simulation	The air spacer provided between the module increases the retention time of the air for better heat transfer -The increase in the surface heat transfer coefficient on the tube side due to an increase in the frontal velocity has a considerable effect in reducing the time for solidification -The PCM present adjacent to the inner ring of the tubes is subcooled when the PCM present in the region between the two outer rings of tubes attains the solidus temperature
[49]	Free cooling of buildings	Storage unit for building ventilation in dry and hot climates Experimentally investigate the influence of air flow rate and the air inlet temperature on cold accumulation in PCM.	SP29	Plates of encapsulated PCM		Direct contact between PCM and air	Experimental	The experimental results indicate that the PCM storage can be used to keep the hot air within the defined temperature limits during day time by releasing the cold stored in PCM during night-time
[38]	Improve summer thermal comfort in buildings	Identify the temperature distribution along the ventilated cavity Numerical efficiency evaluated through a case study	Micronal T23	Plates of encapsulated PCM	Wall 	Direct contact between PCM and air	Mathematical	Allowed reduction of the average room operative temperature in July of about 0.4 °C with respect to the common practice of attaching PCM wallboards directly on the partition wall Indoor conditions were kept for a longer time in a comfortable range, and occasional discomfort sensations are less intensive

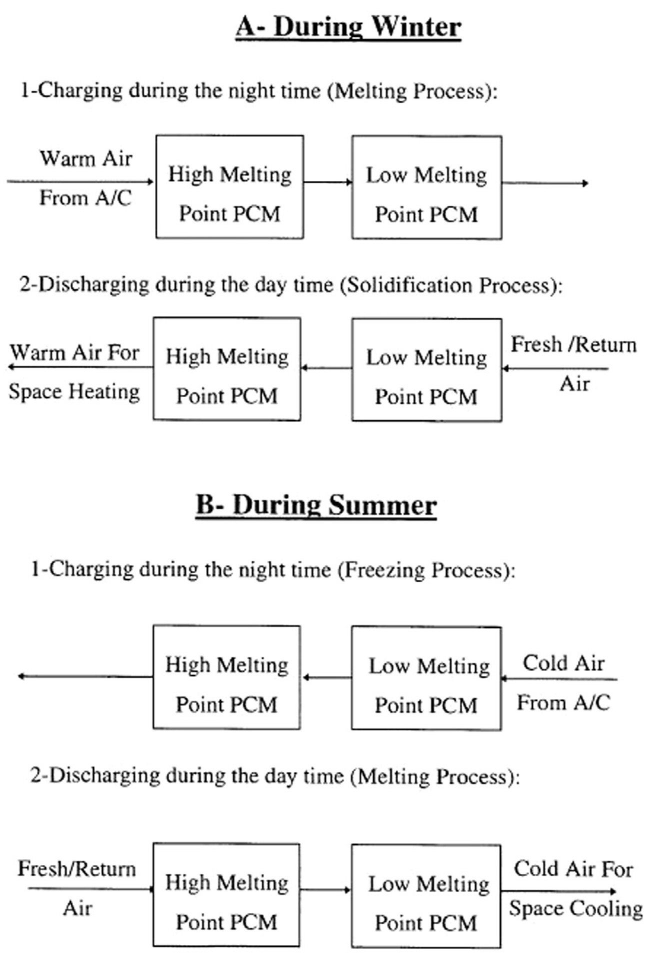


Fig. 4. The proposed storage system for storing heat using two phase change materials [58].

10 h) a difference above 15 °C is needed. Another innovative study with active free cooling systems was developed by Yanbing et al. [18]. In this study LHTES (PCM Packed Bed Storage –NVP) system was mounted above the ceiling and surrounded by air ducts (Table 4). At night the cooled outside air was blown through the LHTES system to solidify the PCM. During the daytime the air circulated between the LHTES system and the room, so the cold stored within the PCM was discharged into the room. The cool discharging rate in the night-time was 0–1000 W and in the daytime was 0–300 W. Butala and Stritih [20] also suggested TES mounted above the ceiling (Table 4) and it was observed that for air inlet temperatures of 26 °C, 36 °C and 40 °C and air inlet velocity varying between 1.5 m/s and 2.4 m/s, the heat flux released into the room varied between 10 and 145 W.

3.3. Space heating (using auxiliary source) active methods

A concept similar to active free cooling has been developed for space heating. However, for heating purposes the PCM-TES usually needs to be linked to auxiliary heat sources such as heat pumps or solar thermal collectors as the desirable warm air temperature is not freely available during the winter. This will again allow the reduction of the heating system capacity and the annual running costs respectively. Space heating is possible through building different layers of PCMs with different phase change temperatures in order to fit with different auxiliary heat sources. These are provided mostly by solar thermal collector panels, air conditioning systems and heat pumps. Vakilaltojjar [58] designed and developed a thermal storage system consisting of two phase change materials for use with a reverse cycle air conditioner. The feasibility for using PCMs in residential houses was investigated (Fig. 4).

The aim of this type of storage system was to be used for both space heating in winter and space cooling in summer. The chosen PCM layers were calcium chloride hexahydrate ($CaC_{12} \cdot 6H_2O$) and potassium fluoride tetra hydrate ($KF \cdot 4H_2O$). Three different configurations were used for encapsulating these materials: flat plain plastic bags, flat plastic bags with dimples, and conical capsules.

Zukowsky [59] studied numerically a system composed by a short term storage module that can cooperate with the UFAD (under floor air distribution) for heating applications. In this study PCM was not encapsulated into rectangular slabs but in polyethylene film bag.

Yamaha and Misaki [60] investigated the use of paraffin mixture containers in the air ducts as storage devices for air conditioning equipment. The air passed through a closed loop of the PCM tank and the air conditioner during the charging operation (Fig. 5(1)). Once the charging was finished, the air conditioning ran at its normal operation mode and the air bypassed the storage tank (Fig. 5(2)). The tank was completely discharged from 13:00 to 16:00 h when the air flowed through the storage tank and cooled down the inlet temperature of the room (Fig. 5(3)). Real et al. [61] focussed on improving the performance of a heat pump based HVAC system with two thermal storage tanks using PCM. A cold tank was used to take advantage of the low outside temperatures at night to cool the PCM with a high coefficient of performance (COP) and it is used later to cool the building when the outside temperature rises. The second tank was operated as an alternative hot reservoir which provided the system with the flexibility to dissipate the heat to the tank at a constant temperature preventing the reduction of the COP below a minimum value. The HVAC system catered for the needs of the house during the required period and successfully kept the temperature within the established limits.

The heat pump coupled to TES was also investigated by Moreno et al. [62]. In this study the cold TES tank was used for shifting the cooling load of a small house-like structure. The PCM tank was able to supply 14.5% more cold and to maintain the indoor temperature within the comfort zone of 20.65% longer than the water tank. An experimental study was conducted to investigate a suitable PCM to take advantage of an off-peak electricity tariff while a heat pump was in use [63]. Results demonstrated that with an improvement in heat transfer techniques, the store size of the heat pump can be reduced by 30%. An extensive review on PCMs in domestic heat pump and air conditioning can be found in Moreno et al. Chaiyat [64] also investigated the use of PCM to improve the efficiency of an air conditioner (Fig. 6) under Thailand's climate. The electrical power of the modified system could save around 9% or 3.94 kW h/day compared to the normal system at around 39.36 kWh/day. The payback period was around 4.12 years Fig. 7.

Extensive efforts have been made to apply TES to solar energy systems where heat is required to be stored during the day for use at night. This solution has also been investigated due to the high operating temperatures that induce a loss of efficiency in solar photovoltaic and thermal panels [65]. One of the first air-based heating systems was carried out by Morrison and Abdel Khalik [66]. Halawa [67] developed a similar storage system incorporating different layers of PCMs, but for use with a solar collector. The experimental data was collected from Vakilaltojjar [58] and further developed the theoretical model. The study showed that the PCM with melting temperature of 29 °C was suitable for space heating, as thermal comfort levels were found to be acceptable during the discharge tests. When the energy storage unit was discharged at a flow rate of 16 m^3/h, the heat transferred was initially 2.75 kW and then reduced from 1.5 to 1 kW over the next 6 h.

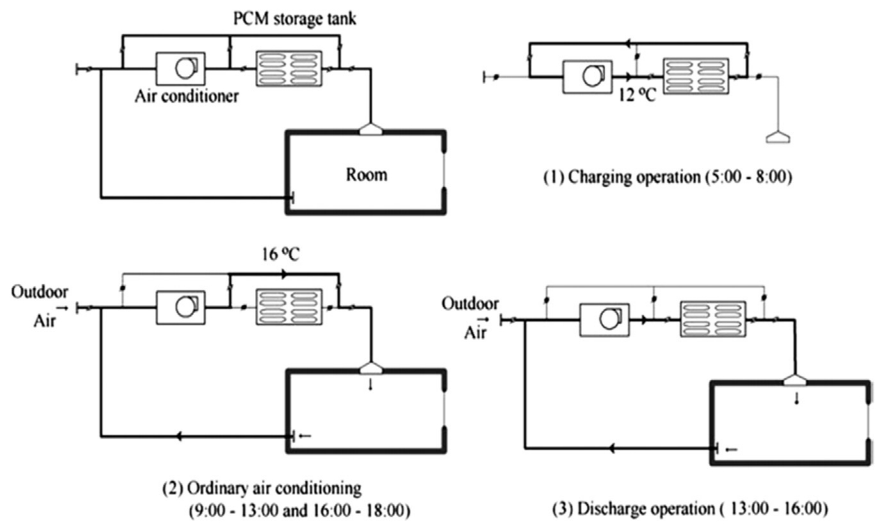


Fig. 5. Diagrams of air conditioning system allied with PCM [60].

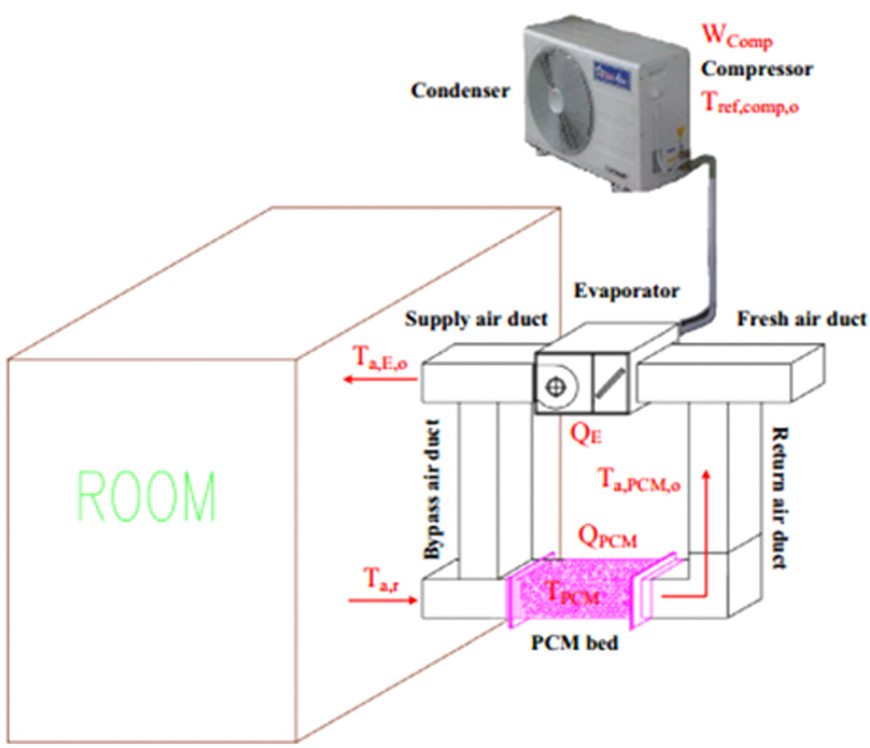


Fig. 6. Prototype of the air conditioner integrating with the PCM bed [64].

Biwole et al. [65] numerically investigated a system composed of an impure PCM situated in the back of a solar panel (SP). Results show that adding a PCM on the back of a solar panel can maintain the panel's operating temperature under 40 °C for 80 min under a constant solar radiation of 1000 W/m^2. Arkar and Medved [16] studied a solar air heating system composed of a vacuum tube air solar collector and a TES. The system performance for the different intensities of solar irradiation throughout the day has shown that 54–67% of the heat produced by solar air heating systems in the daytime can be delivered during the night-time for building heating.

3.4. Patent research on air-PCM-TES and commercial technologies

There are a few technologies available on the market of active and passive methods with TES for free cooling and heating (Table 6). Some of them are related with the patents listed in Table 5, as the cool-phase developed and patented by Nottingham University and Monodraught [68].

The Cool-phase during daytime analyses the internal temperature, the CO_2 level and the external air temperature every minute. If internal temperature or CO_2 thresholds are exceeded, it automatically allows Cool-phase to bring in fresh air. During summer operation, night-time cooling is activated to purge the room with fresh air and at the same time the PCM is solidified and

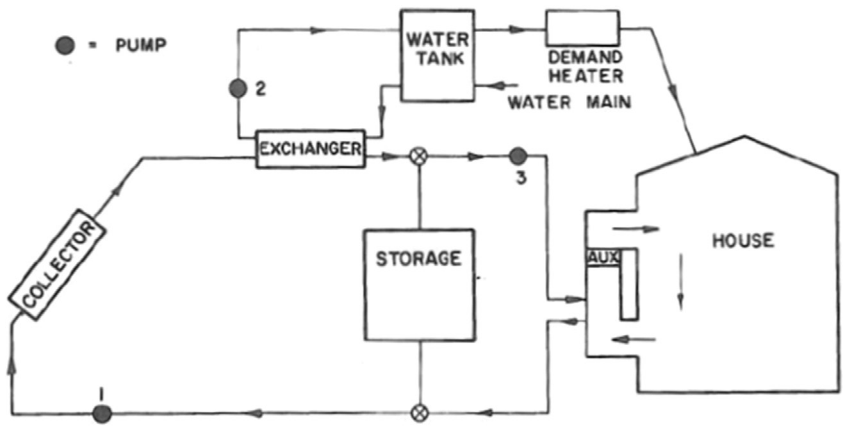


Fig. 7. Schematic diagram of the air-based system used with storage [67].

Table 5
Publication of patents related with PCM-air exchange in the recent years.

Title	Inventor	Company/Country	Year of publication
Energy storage air conditioner	Liu Yongyan	Electronic Institute of Cendu Xiwag/China	2004
Phase-change cold-storage device for air conditioner	Fang Guiyin Yang	Najing University/ China	2006
Building cooling apparatus using PCM	Hopper, Nicholas, John	Monodraught ltd/UK Butters Martin/UK	2009

Table 6
Commercial technologies of free cooling and heating.

A: Cool-phase [68]	 
B: CoolDeck [69]	
C: Emcovent [70]	
D: Project Napevomo [71]	

stores the coolness for the following day. The second Cool-phase model and the most recent, corresponds to an air handling unit mounted in the ceiling containing an intelligent control system, fan, dampers and filters. The control system monitors the indoor air quality, inside and outside air temperatures and reacts accordingly. It does also control the fresh air flow rate into the building, recirculate the air within the building and the energy released or stored by the thermal batteries. Units represented as “A”, “B” and “C” in Table 6 represents independent air-PCM-TES systems and unit “D” as integrated technology with air cooling system. The outside air is supplied directly to the system and released after crossing the phase change material. Unit “B” represents a simple panel containing a PCM that can be mounted directly in the ceiling and once again the air is cooled/heated by passing through the solidified panel. Unit “C” was firstly applied as a PCM individual room conditioning system in the Imtech headquarters in Hamburg, Germany. Statistics obtained from their use show that: 5 kg of PCM per square metre of floor space are sufficient for office areas with cooling loads up to 60 W/m^2; the system is capable of managing summer periods with overnight temperatures below 18 °C and keeping the room temperatures below 26 °C, the equipment must be considered with regards to the design of the facade in order to avoid the supply of overheated air. Another technology is Napevomo [71] (unit D), a prototype that has been set in a positive-energy house which participated to an international competition called “Solar Decathlon Europe”. It contains an air-cooling system designed by Ango et al. [72] integrated inside the house floor between its structure poles. The system is composed of four LHTES devices each containing a horizontal energy storage device, namely a box-section tube bundle filled with paraffin wax. Two paraffin waxes were used, one with a 245,000 J/kg latent heat capacity (Rubitherm RT28 HC) and a melting temperature range spread around 28 °C, the second with a 134,000 J/kg latent heat capacity and a melting point of around 21 °C (Rubitherm RT21) [73].

4. Conclusions

The free cooling with air-PCM-TES applications rely on the solidification of the PCM during night-time and release of the cold to the warm air during day time. Space heating occurs in the vice versa process. Present study carried out rigorous technological review of air-PCM-TES applications for heating and cooling applications in the buildings. The conclusions from the study are summarised as follows:

- Passive methods include the insertion of PCM into walls, glass, floor, roof and solar chimney in contact with ambient air and the heat transfer between them occurs naturally.

- Passive methods present advantages as low initial and running costs, however, the heat storage is limited, not operating effectively for much warmer climates where higher temperature differences are required.
- Active methods can overcome these issues by forcing the air and therefore enhancing the heat transfer with the PCM-TES unit. For active free cooling applications only the energy consumption for a fan remains and the cooling depends solely on the night-time air ambient temperature allowing solidifying the PCM overnight time and consequently cooling down the warm ambient air during day time.
- Most of the works related with the heating of buildings have been studied using auxiliary sources such as air conditioning, heat pump and solar collectors.
- Some cooling and heating applications using passive and active methods have been successfully investigated, patented and inserted into the market.

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