



Review on Latent Thermal Energy Storage for Building Applications

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Abstract

Increasing the energy efficiency of the building is an alternative to reduce energy consumption while improving thermal comfort in order to confront the climate change and fossil fuel limitations. One of the options is the use of thermal energy storage as a practical way to save energy and improve its utilization. Thermal energy storage, classified into sensible heat storage and latent heat storage, is presented in this paper focusing on phase change materials (PCMs) as a promising solution to reduce energy consumption in buildings. The identification of different PCM classifications (organic, inorganic and eutectic PCMs), their particular characteristics and the candidate materials for building applications are reviewed. This review identifies key gaps in PCM deployment, such as the low thermal conductivity of organic PCMs, the supercooling of inorganic PCMs, and proposes research priorities. Active and passive latent heat storage technologies used in building applications are also summarized. For passive systems, which do not require conventional energy, the common methods of PCMs integration in building materials such as concrete, gypsum board, ceiling or floor are enumerated in this paper.

Keywords: Phase Change Materials (PCM), Latent heat, Thermal Energy Storage (TES), Energy efficiency, Building

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1. Introduction

Regarding changes in the climate and fossil fuel limitations, the growing demand of energy all over the world is becoming a serious problem. New and renewable energy sources seem to be the solution. The building sector is one of the largest consumers of energy with a large amount directly related to the heating and cooling of buildings. Increasing the energy efficiency of the building is an alternative to reduce energy consumption while improving thermal comfort. One of the options is the use of thermal energy storage as a practical way to save energy and improve its utilization [1].

Thermal energy storage (TES) in buildings has gained considerable attention. Storage of energy in thermal form can generally be classified into sensible heat storage and latent heat storage. Sensible heat storage occurs when a material is driven to increase or decrease its temperature. The amount of energy stored depends on the specific heat of the material, the temperature change and the mass of the material [2]. The latent heat storage is based on the fact that the storage material absorbs or releases heat when it undergoes a solid / solid, solid / liquid or liquid / gas phase change or vice versa. Latent heat storage is the most efficient method for storing thermal energy due to the low temperature difference between storage and release cycles and the low volume required for storage.

Phase Change Materials (PCMs) use the latent heat of phase change to control temperatures within a specific range. When the temperature exceeds a certain point, the chemical bonds in the material begin to break and the material absorbs heat in an endothermic process where it changes state. When the temperature drops, the material releases energy and returns to its original state.

Based on the temperature range of phase change, PCMs can be classified into three main categories [3, 4]. Low temperature PCMs with a phase transition temperature less than 15 °C are generally used in air conditioning applications and in the food industry. Medium temperature PCMs with phase transition temperature between 15 °C and 90 °C are the most popular PCM Types and they can be applied in solar heating, textile, etc. Finally, high temperature PCMs with a phase transition temperature greater than 90 °C developed primarily for industrial and aerospace applications. On the other hand, PCMs can be classified according to their mode of phase change in gas-liquid, solid-gas, solid-liquid and solid-solid systems [3, 5].

Another common classification of these materials consists of distinguishing PCMs undergoing solid-liquid transformation into organic, inorganic and eutectic PCMs [6]. Organic materials are divided into paraffins and non-paraffins. Paraffin PCMs are available over a wide temperature range for use in a variety of applications. Non-paraffins used as PCMs include fatty acids, esters, alcohols, etc. Fatty acids have received the greatest attention for application in buildings. Inorganic PCMs consist of salts hydrates and hydroxides. Eutectic PCMs are compounds of organic and inorganic PCM.

Latent heat materials have applications in buildings, textiles, automobiles and solar installations, and recently in electronics and medicine [3]. Cabeza et al. [7] focused, in their review article, on Phase Change Materials for thermal storage in buildings. They presented the requirements of the use of PCMs, their classification, the materials available in the literature and on the market and the technical problems encountered with the possible solutions for their application in buildings.

Since the phase change temperature of PCMs is around the desired comfort temperature in buildings, the energy used to change the phase of the material leads to more stable and comfortable indoor conditions, as well as to reduce cooling and heating peaks [8]. As a result, latent heat materials represent a promising solution for reducing energy consumption and improving thermal comfort in buildings. Recently, several researchers [3-4, 6-23] have published review articles on the use of PCMs in the building sector for thermal storage systems and thermal comfort, showing that PCMs interest is increasing worldwide.

The ability to store thermal energy is important for efficient use of solar energy in buildings. Due to the low thermal mass in light buildings, these buildings tend to have large temperature fluctuations which lead to high heating and cooling demands [4]. The use of appropriate PCMs overcomes this problem while improving thermal comfort and optimizing wall thickness [24].

Latent heat storage technology can be classified as an active or passive heating / cooling systems in buildings [20]. For passive systems, which do not require conventional energy, PCMs can be encapsulated in building materials such as concrete [25], gypsum board [26, 27], ceiling or floor [28] in order to increase their thermal storage capacity. Also, PCMs can be integrated into conventional heating and cooling systems (solar heat pump system, ventilation system [29]). The optimization of PCM thermophysical properties and the enhancement of heat transfer through passive and active techniques [1] are thereby, essential to ensure the performance of phase change TES system.

Recently, latent heat storage through PCM has received considerable attention thanks to its ability to store a large amount of thermal energy in a small volume, making it one of the most promising technologies for the development of energy efficiency in buildings [30]. In order to quantify the technical and economic feasibility of these materials for building thermal comfort applications, modeling and numerical simulations of energy storage in the building are necessary. Several studies have addressed the mathematical modeling of PCM for building applications [31-33]. AL-Saadi et al. [33] present and compare the different modeling methods used in PCM simulations (advantages, disadvantages and limitations).

The choice of the PCM is governed by the application, the range of temperature for usage and the cost. A proper use of these materials can reduce heating and cooling peaks and thus reduce energy consumption. This is only possible if the best PCM is chosen according to its cost versus the specific thermal comfort conditions in buildings (temperature and humidity range). Hence, the identification of different PCM classifications, their particular characteristics, their

selection criteria and the candidate materials for building applications will be presented in this paper.

2. Thermal energy storage

Thermal energy storage technology stores heat and cold for later use as required, as an alternative to reduce the effects of the intermittency of the various renewable energy sources. This promising technology makes it possible to reduce energy consumption in buildings and increase energy efficiency and thermal comfort [34]. Cooling, heating, melting, solidifying or vaporising a material with the energy made available in the form of heat during the process reversal can achieve thermal energy storage [3]. There are mainly three methods of storing energy in thermal form: sensible heat storage, latent heat storage and thermochemical storage. Thermal storage by sensible heat occurs when a material is driven to increase or decrease its temperature. The amount of energy stored (Q_s in J) depends on the specific heat capacity of the material (c_p in $\text{kJ.kg}^{-1}.\text{K}^{-1}$), the temperature difference it undergoes (ΔT in K) and the amount of material present (m in kg) :

$$Q_s = mc_p \Delta T \quad (1)$$

The most widely used material for sensible energy storage is water, due to its availability, high specific heat, non-toxicity and low cost. Above 100°C , oils, molten salts and liquid metals are used [35]. Cement, concrete, marble, granite, clay and polymers are also widely used to store thermal energy in buildings.

On the other hand, latent heat storage is based on the fact that the storage material absorbs or releases heat when it undergoes a phase change from solid/solid, solid/liquid or liquid/gas or vice versa. Latent heat storage is a particularly interesting method because of the small temperature difference between the energy absorption and release cycles and the small volume required for storage. The heat stored in a phase change material (Q_l) is calculated as follows [36]:

$$Q_l = \int_{T_i}^{T_m} mc_p dT + ma_m \Delta h_m + \int_{T_m}^{T_f} mc_p dT \quad (2)$$

Where T_i , T_m and T_f are, respectively, the initial, melting and final temperatures ($^\circ\text{C}$). a_m represents the molten fraction, m is the amount of material present (kg) and Δh_m is the heat of fusion per unit mass (J/kg). Phase-change materials (PCMs) used for latent heat storage are numerous and can be grouped into organic, inorganic and eutectic PCMs [5, 6, 37, 38]. Organic materials are divided into paraffins and non-paraffins. Paraffin-based PCMs are available in a wide temperature range, enabling them to be used in a variety of applications. Non-paraffins used as PCMs include fatty acids, esters, alcohols,... Fatty acids have received the most attention for building applications. Inorganic PCMs include salts, hydrated salts and metallics. As for eutectics, these are compounds of organic and inorganic PCMs. They are subdivided into organic-organic, organic-inorganic and inorganic-inorganic PCMs.

3. Phase Change Materials (PCMs)

Latent heat storage is particularly attractive because of its ability to provide high storage density in a quasi-isothermal process. Phase-change materials (PCMs) use the latent heat of phase change to control temperatures within a specific range. When the temperature exceeds a certain point, the chemical bonds in the material begin to break and the material absorbs heat in an endothermic process where it changes state. As the temperature drops, the material releases energy and returns to its initial state.

3.1 Classification

Based on the phase-change temperature range, PCMs can be classified into three main categories [3, 4]. Low-temperature PCMs, with phase transition temperatures below 15°C, are typically used in air-conditioning applications and in the food industry. Medium-temperature PCMs with change-of-state temperatures between 15°C and 90°C, are the most popular and they can be applied in solar, medical, textile, electronic, building... Finally, high-temperature PCMs with phase change temperature above 90°C developed mainly for industrial and aerospace applications. Abhat [5] presented a state-of-the-art review of latent heat storage materials in the 0-120°C temperature range. He discussed the melting and freezing characteristics of paraffins, fatty acids, inorganic hydrated salts and eutectic compounds and their ability to undergo thermal cycling.

On the other hand, phase-change materials can be classified according to their phase transition mode into solid-liquid PCMs, solid-gas PCMs, gas-liquid PCMs and solid-solid PCMs. Of these groups, solid-liquid PCMs are the most suitable for thermal energy storage [11, 40]. Solid-liquid PCMs include organic, inorganic and eutectic PCMs. A comparison between these different types of PCM is made by several authors [4, 7, 11, 15, 35, 39, 41]. A summary of the main advantages and disadvantages of each type is given in the following table 1.

Table 1. Comparison of the advantages and disadvantages of different types of PCM.

Classification	Advantages	Disadvantages
Organic PCM:	+ Available over a wide temperature range	- Low thermal conductivity (approx. 0.2 W/m.K)
Paraffins and non-paraffins	+ High heat of fusion	- Low density
	+ Negligible overcooling	- Low enthalpy of phase change
	+ Chemically and thermally stable	- High cost
	+ Good compatibility with other materials	- Relatively high volume expansion
	+ Recyclable	- Flammable
	+ No segregation	
	+ Non-hazardous, non-reactive and non-corrosive	

Inorganic PCM:	+ High heat of fusion	- subcooling
Hydrated salts	+ High thermal conductivity (approx. 0.5 W/m.K)	- Corrosion
	+ Low volume expansion	- Segregation and lack of thermal stability
	+ High melting enthalpy	
	+ Low cost availability	- High volume change
	+ Non-flammable	
Eutectic PCM	+ High melting temperature	- Lack of data available on their thermo-physical properties
	+ High volumetric heat storage density slightly higher than organic compounds	

3.2 PCMs properties

For the use of PCMs as latent heat storage materials, these materials must fulfill certain desirable thermodynamic, kinetic and chemical criteria as shown in Table 2 [4, 5, 11, 35, 39, 42].

Table 2. Different properties of PCM.

PCM Proprieties	
Thermodynamic	- Melting temperature within desired operating temperature range. - High latent heat of fusion per unit volume. - High specific heat to provide significant additional sensible heat storage. - High thermal conductivity of solid and liquid phases. - Small volume change during phase transition and low vapor pressure at operating temperature to reduce containment problems. - Congruent melting
Kinetic	- Low or no supercooling during freezing; the melt should crystallize at its thermodynamic freezing point - High rate of nucleation. - High rate of crystals growth.
Chemical	- Full reversible freeze/melt cycle. - No degradation after a large number of freeze/melt cycles. - No corrosiveness to building/encapsulation materials. - Non-toxic, non-flammable and non-explosive.
Economic	- Abundant. - Available. - Cost-effective. - Easy to recycle and process.

3.3 Long-term stability of PCMs

For practical applications in latent heat storage, PCMs must maintain long-term stability with minimal changes in thermal properties after numerous thermal cycles. Thermal cycling tests on organics, salt hydrates, and salt hydrate mixtures are conducted to evaluate PCMs stability [43-45]. Some PCMs demonstrated good stability and favorable thermo-physical properties. Blackley et al. [44] introduces a phase change material composed of calcium chloride hexahydrate (CCH), sodium carbonate decahydrate (SCH) as a nucleating agent, and surface-modified expanded graphite (EG) treated with a nonionic surfactant. The PCM composite found to mitigate challenges associated with salt hydrate PCMs while ensuring robust cycling stability for large-scale applications. It exhibits a high thermal conductivity, significantly minimizes supercooling and eliminates phase separation with enhanced cycling stability for up to 200 thermal cycles. Lui et al. [45] focused on, improving thermal conductivity, supercooling, and phase separation of carbon-enhanced hydrated salt PCMs. They compare the performance of salt hydrates to organic PCMs like paraffin wax and they note that organic PCMs have a lower thermal conductivity (almost 0.2 W/mK) while a better cycling stability. The article highlights applications in solar thermal energy storage and building temperature regulation.

4. Application of PCMs in buildings

Phase-change materials find their applications in buildings, the textile industry, automotive and solar installations, and recently in electronics and medicine [3]. In recent years, several researchers [7, 8, 15, 16, 18, 20, 22, 23] have published review articles on phase-change materials for thermal storage in buildings and thermal comfort, showing that interest in PCMs is growing worldwide.

The use of latent heat storage in buildings can meet the demand for thermal comfort and energy savings. PCMs can be integrated into building cladding materials such as concrete, gypsum board, plaster, etc., to increase the thermal mass of light or even heavy buildings. They can also be installed in the water or air circuits of heating, ventilation and air-conditioning systems as thermal storage reservoirs. Latent storage through PCMs can be used for heating and cooling in buildings as either a passive storage system (i.e., the phase-change process takes place without the use of mechanical equipment) or an active one (using mechanical equipment).

4.1 Passive storage systems in buildings

Due to low thermal inertia, lightweight buildings suffer from sharp temperature fluctuations in summer, due to excessive overheating caused by a lack of thermal mass [19]. For passive applications and efficient use of solar energy in buildings, PCMs are integrated into the building envelope to increase its thermal mass. The building envelope is composed of the outer shell of the building that separates the interior space from the external environment. Thus,

walls, foundations, fenestration, roofs, floors, ..., are part of the building envelope [46]. Phase change material can be incorporated into all elements of the building envelope. Nevertheless, the most common integration of PCM into the envelope is in walls, floors, ceilings, roofs and windows thanks to easy installation and more efficient heat transfer [47]. Hawes et al. [48] found that the melting and solidification temperatures of PCMs vary slightly when integrated into building materials. Dardouri et al. [49] illustrate that the double-layer PCM system provided higher energy savings than the single-layer PCM system, especially in warm and arid regions. Alrashdan et al. [50] demonstrate a significant reduction in cooling load with PCM incorporation, with cement-based composites exhibiting superior thermal performance compared to gypsum-based alternatives.

During the day, the latent storage material undergoes a melting process, absorbing some of the solar energy flowing through the building structure. At night, when the outside or inside temperature drops, the PCM solidifies, releasing the stored heat into the surrounding environment. As a result, these materials help prevent the room from overheating during the day in hot summer periods, and can also provide heat to the room, reducing the need for heating at night in winter.

Having selected the appropriate storage material based on the temperature range of the application and its thermo-physical properties, it is necessary to choose the method of incorporating PCM into the building materials or components to avoid leakage. Three ways of incorporating PCM into conventional building materials have been reported by Hawes et al. [48] as the most promising: direct incorporation, immersion and encapsulation.

4.1.1 Direct incorporation

The direct incorporation method is the simplest. It involves mixing liquid or powder PCMs directly with building materials (gypsum, concrete or plaster) during production [41]. This method is also the most economical, as it requires no additional equipment, but it does face problems of leakage and incompatibility with certain construction materials [15].

4.1.2 Immersion

In the immersion method, porous building materials such as, for example, gypsum board, brick or concrete block, are immersed in molten PCM which is absorbed through the pores, by capillary action. Similarly, problems of leakage and incompatibility with certain building materials are encountered [51].

4.1.3 Encapsulation

The third method overcomes the adverse effects of PCM on the building material and avoids the problem of leakage. It relies on the fact that PCMs can be encapsulated before incorporation into the building components. Two main types of encapsulation exist: macro-encapsulation and micro-encapsulation [9].

- Macro-encapsulation involves packaging the PCM in a container such as tubes, spheres or panels, then incorporating it into the construction elements (Figure 1). This technology has the disadvantage of poor thermal conductivity, a tendency to solidify at the edges and complex integration with building materials [11].

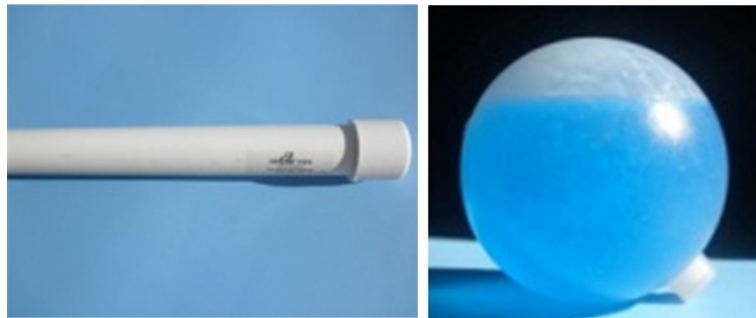


Figure 1. Examples of macro-encapsulation of commercial PCMs [19].

- Microencapsulation is a technique in which PCM particles are enclosed in a thin, continuous polymer film (Figure 2) that must be compatible with both the storage material and the materials of construction. This makes it possible to produce capsules in the micrometer to millimeter range (Figure 3), known as microcapsules [52, 53].



Figure 2. Model of a micro-encapsulated PCM with a wax core and polymer capsule [19].

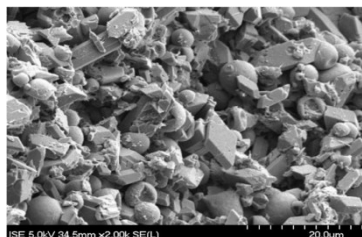


Figure 3. Image of PCM microcapsules in gypsum plaster with a diameter of around 8 mm [41].

Microencapsulation has the advantage of preventing PCMs from leaking during the phase-change process and contributing to the improvement of heat transfer processes by increasing the heat exchange surface area [54].

4.2 Active storage systems in buildings

Active storage systems are mainly used for storing thermal energy during off-peak hours in buildings. In this way, peak-hour loads can be reduced and shifted to the night when electricity costs are generally lower [54]. In the building sector, PCMs can be integrated into various systems such as solar heat pumps, heat recovery systems, underfloor heating systems, photovoltaic devices, etc., as active applications.

"Free cooling" is one of the main applications of thermal storage in active systems in buildings, where cold is collected and stored from outside during the night, and this stored cold is discharged inside the room (Figure 4) when there is a cooling demand for it [16].

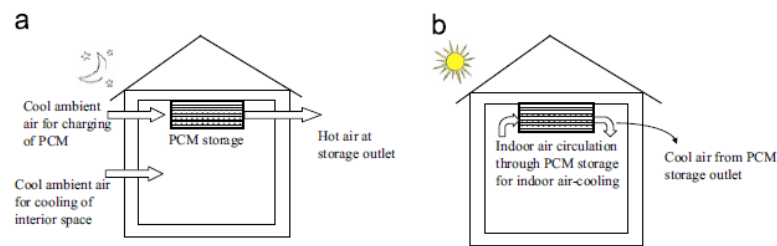


Figure 4. Free cooling" operating principle: (a) Charging process (during the night) and (b) Discharging process (during the day).

A thermally activated ceiling panel with PCM storage (Figure 5) is used for heating and cooling in buildings. When exposed to thermal loads, the PCM in the ceiling panels melts during the day and solidifies at night by means of an integrated water pipe system [10].

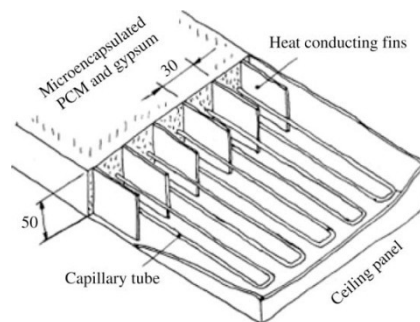


Figure 5. Schematic of ceiling panel thermally activated with MCP [55].

Latent heat storage is used in solar systems in buildings to convert an intermittent energy source and meet heating and domestic hot water demand [56]. In addition, thermal storage of solar

energy in active systems in buildings is being extended to integrate solar air collectors in building walls [57] and use PCMs in ventilated facades.



Figure 6. Distribution of PCMs on ventilated facades [58].

The active use of PCMs in the building sector is not limited to the implementation of renewable sources, but also enables the efficiency and performance of already existing technologies to be increased. Kaygusuz and Ayhan [59] studied the performance of a solar heat pump system combined with encapsulated phase-change material for residential heating.

5. Examples of potential PCMs

Several researchers have investigated various candidate substances for use in latent heat thermal storage [3, 7, 35, 40, 54]. As phase-change materials, these substances must have specific properties such as a melting temperature within the practical range of application, high latent heat, high thermal conductivity, competitive price, non-toxic and non-corrosive character. The thermal properties of three main families of PCMs (organic, inorganic and eutectic), reported in the literature, are summarized in the following tables (Table 2-6).

Paraffins are suitable for use as heat-of-fusion storage materials since they are available in a wide temperature range and possess a relatively high heat of fusion. Additionally, Paraffins are known to freeze without supercooling [5]. However, due to cost constraints, only technical-grade paraffins are typically used as phase change materials in latent heat storage systems.

Fatty acids are organic compounds that exhibit heat of fusion values similar to that of paraffins. They are characterized by consistent melting and freezing behavior and freeze with low or no supercooling, making them effective PCMs. However, their primary disadvantage is their cost, which is approximately 2 to 2.5 times higher than that of paraffins.

Salt hydrates, constitute a significant class of heat storage materials due to their high volumetric latent heat storage capacity. However, a key challenge in using salt hydrates as PCM is their tendency to melt incongruently; resulting in a saturated aqueous solution and a solid phase, typically a lower hydrate of the same salt.

5.1 Organic PCMs

Paraffins and fatty acids, which represent the most commonly used organic PCMs, are listed in the tables below (Table 3, 4 and 5), together with their melting point and latent heat of fusion [3, 35].

Table 3. Thermal properties of paraffins.

Paraffin	Number of Carbon atoms	Melting temperature (°C)	Latent Heat (kJ/kg)
n-tetra-decane	14	5.8–6	227–229
n-penta-decane	15	9.9–10	206
n-hexa-decane	16	18–20	216–236
n-hepta-decane	17	22–22.6	164–214
n-Okta-decane	18	28–28.4	200–244
n-Nona-decane	19	32	222
n-Eicozane	20	36.6	247
n-Heneicozane	21	40.2	213
n-Docozone	22	44.0	249
n-Trikozane	23	47.5	234
n-Tetracozane	24	50.6	255
n-Pentacozane	25	53.5	238
n-Hexacozane	26	56.3	256
n-Heptacozane	27	65.4	235
n-Oktacozane	28	58.8	254
n-Nonacozane	29	63.4	239
n-Triacontane	30	41.2	252

Table 4. Thermal properties of fatty acids.

Fatty acid	Number of carbon atoms	Melting temperature (°C)	Latent heat (kJ/kg)
Caprylic acid	8	16.3	148
CA	10	31.3-31.6	163
LA	12	41-44	183-212
MA	14	51,5-53,6	190-204.5
PA	16	61-63	203.4-212
SA	18	70	222
Arachidic acid	20	74	227
Undecylenic acid	22	24.6	141

Table 5. Thermal properties of non-paraffin PCMs.

Non-paraffin	Melting temperature (°C)	Latent heat (kJ/kg)
Formic acid	7.8	247
Glycerine	17.9	198.7
D-Lactic acid	26	184
Methyl palmitate	29	205
Camphenilone	39	205
Docasyll bromide	40	201
Capryllone	40	259
Phenol	41	120

5.2 inorganic PCMs

Pielichowska and Pielichowski [3] have presented various inorganic components considered as potential PCMs and intended for low- and high-temperature applications. However, Tyagi and Buddhi [54] listed inorganic PCMs frequently used for applications in the 20-32°C temperature range.

The melting point and latent heat of fusion of hydrated salts are shown in Table 6.

Table 6. Thermal properties of hydrated salts [35].

Hydrated salt	Melting temperature (°C)	Latent Heat of fusion (kJ/kg)
K ₂ HPO ₄ -6H ₂ O	14	109
FeBr ₃ -6H ₂ O	21	105
FeBr ₃ -6H ₂ O	27	105
LiClO ₃ -3H ₂ O	8	253
KF-4H ₂ O	18.5–19	231
Mn(NO ₃) ₂ -6H ₂ O	25.3	125.9
CaCl ₂ -6H ₂ O	28–30	190–200
LiNO ₃ -3H ₂ O	30	256
Na ₂ SO ₄ -10H ₂ O	34	256
Na ₂ CO ₃ -10H ₂ O	33	247
NaCH ₃ COO-3H ₂ O	55.6–56.5	237–243
CaBr ₂ -6H ₂ O	34	115.5
Na ₂ HPO ₄ -12H ₂ O	35–45	279.6
Zn(NO ₃) ₂ -6H ₂ O	36	146.9
Na ₂ S ₂ O ₃ -5H ₂ O	48–55	201
Na(CH ₃ COO)-3H ₂ O	58	226
Na ₂ P ₂ O ₇ -10H ₂ O	70	184
Ba(OH) ₂ -8H ₂ O	78	266
(NH ₄)Al(SO ₄) ₂ -12H ₂ O	95	269
MgCl ₂ -6H ₂ O	117	169
Mg(NO ₃) ₂ -6H ₂ O	89.3	150

5.3 Eutectic PCMs

The table below (Table 7) lists the best-known eutectic PCMs.

Table 7. Thermal properties of eutectic PCMs [35].

Eutectic	Composition (%)	Melting temperature (°C)	Heat of fusion (kJ/kg)
CaCl ₂ -6H ₂ O + CaBr ₂ -6H ₂ O	45 + 55	14.7	140
C ₁₄ H ₂₈ O ₂ + C ₁₀ H ₂₀ O ₂	34 + 66	24	147.7
CaCl ₂ + MgCl ₂ -6H ₂ O	50 + 50	25	95
CH ₃ CONH ₂ + NH ₂ CONH ₂	50 + 50	27	163
Ca(NO ₃) ₂ -4H ₂ O + Mg(NO ₃) ₂ -6H ₂ O	47 + 53	30	136
CH ₃ COONa-3H ₂ O + NH ₂ CONH ₂	40 + 60	30	200.5
NH ₂ CONH ₂ + NH ₄ NO ₃	53 + 47	46	95
Mg(NO ₃) ₂ -6H ₂ O + NH ₄ NO ₃	61.5 + 38.5	52	125.5
Mg(NO ₃) ₂ -6H ₂ O + MgCl ₂ -6H ₂ O	58.7 + 41.3	59	132.2
Mg(NO ₃) ₂ -6H ₂ O + MgCl ₂ -6H ₂ O	50 + 50	59.1	144
Mg(NO ₃) ₂ -6H ₂ O + Al(NO ₃) ₂ -9H ₂ O	53 + 47	61	148
CH ₃ CONH ₂ + C ₁₇ H ₃₅ COOH	50 + 50	65	218
Mg(NO ₃) ₂ -6H ₂ O + MgBr ₂ -6H ₂ O	59 + 41	66	168
NH ₂ CONH ₂ + NH ₄ Br	66.6 + 33.4	76	151
LiNO ₃ + NH ₄ NO ₃ + NaNO ₃	25 + 65 + 10	80.5	113
LiNO ₃ + NH ₄ NO ₃ + NH ₄ Cl	27 + 68 + 5	81.6	108

5.4 PCMs used in buildings

Three phase-change temperature ranges have been suggested by Cabeza et al. [7] for the use of PCMs for thermal storage in buildings (up to 21°C for cooling applications, between 22 and 28 °C for thermal comfort applications and between 29 and 60 °C for hot water applications). Kalnæs et al. [19] included in their study examples of PCMs with phase change temperatures ranging from 15 to 32°C. In this study, we focus on thermal energy storage as an application to thermal comfort in buildings.

The energy used to ensure the phase transition of the material leads to more stable and comfortable indoor conditions, as well as reducing cooling and heating peaks [8]. In order to keep indoor temperatures within the desired comfort temperature range for as long as possible and without heating or cooling loads, candidate materials need to have a fairly high heat of fusion and a melting temperature within the thermal comfort temperature range. In order to select the appropriate PCM for application to thermal comfort in buildings, a scan of some potential PCMs studied in the literature is presented in Table 8.

Table 8. Thermal properties of PCMs used for thermal comfort in buildings [7].

PCM	Type	Melting temperature (°C)	Heat of fusion (kJ/kg)	Thermal conductivity (W/mK)
Paraffin C ₁₆ -C ₁₈	Organic	20-22	152	-
Paraffin C ₁₃ -C ₂₄	Organic	22-24	189	0.21
Paraffin C ₁₈	Organic	28	244	0.15
Butyl stearate	Organic	19	140	-
1-dodecanol	Organic	26	200	-
n-octadecane	Organic	28	200	-
Vinyl stearate	Organic	27-29	122	-
Dimethyl sabacate	Organic	21	120-135	-
Polyglycol E600	Organic	22	127.2	0.189
Propyl palmitate	Organic	16-19	186	-
Octadecyl 3- mercaptopropylate	Organic	21	143	-
34% C ₁₄ H ₂₈ O ₂ + 66% C ₁₀ H ₂₀ O ₂	Organic Eutectic	24	147.7	-
Octadecane + docosane	Organic Eutectic	25.5–27	203.8	-
FeBr ₃ 6H ₂ O	Inorganic	21	105	-
Mn(NO ₃) 6H ₂ O	Inorganic	25.8	125.9	-
CaCl ₂ 6H ₂ O	Inorganic	29.2	171 [39]	-
50% CaCl ₂ + 50% MgCl ₂ 6H ₂ O	Inorganic Eutectic	25	95	-
48% CaCl ₂ + 43% NaCl + 0.4% KCl + 47.3% H ₂ O	Inorganic Eutectic	26.8	188	-

Many components have been investigated as potential PCMs, but a limited number have been commercialized [7]. Kalnæs et al. [19] introduced an overview of commercial PCM products for application in buildings and their thermal properties, as well as their industrial manufacturers. Konuklu et al. [18] listed companies that offer commercial PCMs in a wide range of phase change temperature, such as ‘BASF’ and ‘Rubitherm GmbH’ in Germany, ‘Cristopia’ in France, ‘TEAPEnergy’ in Australia, ‘PCM Products’ in the UK, ‘Climator’ in Sweden and ‘Mitsubishi Chemical’ in Japan. However, they pointed out that only BASF and ‘Microteklab’ have developed micro-encapsulated PCMs designed for application to thermal

comfort in buildings. Examples of commercial PCMs available on the international market and used in buildings are given in the following table 9 [7, 54].

Table 9. Thermal properties of commercial PCMs used for thermal comfort in buildings.

PCM name	Type	Melting temperature (°C)	Heat of fusion (kJ/kg)	Thermal conductivity (W/mK)	Manufacturer
RT 20	Paraffin	22	172	0.88	Rubitherm GmbH
Climsel C23	Hydrated salt	23	148	-	Climator
ClimselC24	Hydrated salt	24	108	1.48	Climator
RT 26	Paraffin	26	179	-	Rubitherm GmbH
RT 25	Paraffin	25	180	0.2	Rubitherm GmbH
STL 27	Hydrated salt	27	213	1.09	Mitsubishi chemical
S27	Hydrated salt	27	190	0.79	Cristopia
RT 30	Paraffin	28	206	0.2	Rubitherm GmbH
RT 27	Paraffin	28	179	0.87	Rubitherm GmbH
TH 29	Hydrated salt	29	188	-	TEAP
RT31	Paraffin	31	165	0.2	Rubitherm GmbH



Figure 7. Examples of BASF products: (a) Micronal PCM dispersed in a liquid and in powder form (b) Gypsum wallboard with Micronal PCM.

6. Conclusion

The ability to store thermal energy is important for the efficient use of solar energy in buildings. Due to the low thermal mass of materials in lightweight buildings, they tend to have large temperature fluctuations, resulting in high heating and cooling demands. Currently, thermal energy storage has become an important aspect of energy management.

- A review of different types of thermal energy storage is carried out focusing on the latent heat storage through phase change materials (PCMs).
- Phase change materials (PCMs) must have a melting/solidification temperature within the practical range of the application and they must have a high latent heat of fusion and high thermal conductivity.

- An overview of the classification and properties (thermo-physical, kinetic, chemical and economic) of potential PCMs and their application in buildings as passive and active storage systems is presented in this study.
- Examples of latent thermal energy storage materials are listed, specifying their temperature and heat of fusion according to their type and practical application.

Declaration statement

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

- [1] X. Zhai, Z. Xu, W. Zhang, Q. Zhang, X. Yang, J. Qu, G. Liu, B. Yu, Phase change thermal energy storage: Materials and heat transfer enhancement methods, *J. Energy Storage*. 123 (2025) 116778.
- [2] MF. Demirbas, Thermal energy storage and phase change materials: an overview, *Energy Sources Part B.1* (2006) 85–95.
- [3] K. Pielichowska, K. Pielichowski, Phase change materials for thermal energy storage, *Prog. Mater. Sci.* 65 (2014) 67–123.
- [4] M.M. Farid, A.M. Khudhair, S.A.K. Razack, S. Al-Hallaj, A review on phase change energy storage: materials and applications. *Energy Convers. Manage.* 45 (2004) 1597–1615.
- [5] A. Abhat, Low temperature latent heat thermal energy storage: heat storage materials, *Sol. Energy*. 30 (1983) 313–332.
- [6] M.K. Rathod, J. Banerjee, Thermal stability of phase change materials used in latent heat energy storage systems: a review, *Renew. Sustain. Energy Rev.* 18 (2013) 246–258.
- [7] L.F. Cabeza, A. Castell, C. Barreneche, A. de Gracia, A.I. Fernández, Materials used as PCM in thermal energy storage in buildings: a review, *Renew. Sustain. Energy Rev.* 15 (2011) 1675–1695.
- [8] R. Baetens, B.P. Jelle, A. Gustavsen, Phase change materials for building applications: a state-of-the-art review, *Energy Build.* 42 (2010) 1361–1368.
- [9] A.M. Khudhair, M.M. Farid, A review on energy conservation in building applications with thermal storage by latent heat using phase change materials, *Energy Convers. Manage.* 45 (2004) 263–275.
- [10] N. Zhu, Z. Ma, S. Wang, Dynamic characteristics and energy performance of buildings using phase change materials: a review, *Energy Convers. Manage.* 50 (2009) 3169–3181.
- [11] D. Zhou, C.Y. Zhao, Y. Tian, Review on thermal energy storage with phase change materials (PCMs) in building applications, *Appl. Energy* 92 (2012) 593–605.
- [12] F. Kuznik, D. David, K. Johannes, J.J. Roux, A review on phase change materials integrated in building walls, *Renew. Sustain. Energy Rev.* 15 (2011) 379–391.
- [13] E. Osterman, V.V. Tyagi, V. Butala, N.A. Rahim, U. Stritih, Review of PCM based cooling technologies for buildings, *Energy Build.* 49 (2012) 37–49.
- [14] M. Pomianowski, P. Heiselberg, Y. Zhang, Review of thermal energy storage technologies based on PCM application in buildings, *Energy Build.* 67 (2013) 56–69.
- [15] N. Soares, J.J. Costa, A.R. Gaspar, P. Santos, Review of passive PCM latent heat thermal energy storage systems towards buildings' energy efficiency, *Energy Build.* 59 (2013) 82–103.
- [16] A. Waqas, Z.U. Din, Phase change material (PCM) storage for free cooling of buildings – a review, *Renew. Sustain. Energy Rev.* 18 (2013) 607–625.
- [17] S.A. Memon, Phase change materials integrated in building walls: a state of the art review, *Renew. Sustain. Energy Rev.* 31 (2014) 870–906.
- [18] Y. Konuklu, M. Ostry, H.O. Paksoy, P. Charvat, Review on using microencapsulated phase change materials (PCM) in building applications, *Energy Build.* 106 (2015) 134–155.
- [19] S.E. Kalnæs, B.P. Jelle, Phase change materials and products for building applications: A state-of-the-art review and future research opportunities, *Energy Build.* 94 (2015) 150–176.
- [20] M. Iten, S. Liu, A. Shukla, A review on the air-PCM-TES application for free cooling and heating in the buildings, *Renewable and Sustain. Energy Rev.* 61 (2016) 175–186.

- [21] F. Souayfane, F. Fardoun, P.H. Biwole, Phase change materials (PCM) for cooling applications in buildings: A review, *Energy Build.* 129 (2016) 396–431.
- [22] A. Kasaeian, L. bahrami, F. Pourfayaz, E. Khodabandeh, W.M. Yan, PCM-mortar based construction materials for energy efficient buildings: A review on research trends, *Energy Build.* 154 (2017) 96–112.
- [23] V. Venkateswara Rao, R. Parameshwaran, V. Vinayaka Ram, PCM-mortar based construction materials for energy efficient buildings: A review on research trends, *Energy Build.* 158 (2018) 95–122.
- [24] A. Pasupathy, R. Velraja, R.V. Seeniraj, Phase change material-based building architecture for thermal management in residential and commercial establishments, *Renewable and Sustain. Energy Rev.* 12 (2008) 39–64.
- [25] T.C. Ling, C.S. Poon, Use of phase change materials for thermal energy storage in concrete: an overview, *Construct. Build. Mater.* 46 (2013) 55–62.
- [26] F. Kuznik, J. Virgone, J.J. Roux, Energetic efficiency of room wall containing PCM wallboard: a full-scale experimental investigation, *Energy Build.* 40 (2008) 148–156.
- [27] K.O. Lee, M.A. Medina, E. Raith, X. Sun, Assessing the integration of a thin phase change material (PCM) layer in a residential building wall for heat transfer reduction and management, *Appl. Energy* 137 (2015) 669–706.
- [28] E. Alawadhi, H.J. Alqallaf, Building roof with conical holes containing PCM to reduce the cooling load: numerical study, *Energy Convers. Manag.* 52 (2011) 2958–64.
- [29] C. Arkar, B. Vidrih, S. Medved, Efficiency of free cooling using latent heat storage integrated into the ventilation system of a low energy building, *Int. J. Refrig.* 30 (2007) 134–143.
- [30] M. Saffari, C. Roe, D.P. Finn, Improving the building energy flexibility using PCM-enhanced envelopes, *Appl. Therm. Eng.* 217 (2022) 119092.
- [31] Y. Dutil, D.R. Rousse, N.B. Salah, S. Lassue, L. Zalewski, A review on phase change materials: mathematical modeling and simulations. *Renewable and Sustain. Energy Rev.* 15 (2011) 112–130.
- [32] F. Agyenim, N. Hewitt, P. Eames, M. Smyth, A review of materials, heat transfer and phase change problem formulation for latent heat thermal energy storage systems (LHTESS). *Renewable and Sustain. Energy Rev.* 14 (2010) 615–628.
- [33] S.N. AL-Saadi, Z.J. Zhai, Modeling phase change materials embedded in building enclosure: A review, *Renewable and Sustain. Energy Rev.* 21 (2013) 659–673.
- [34] L.F. Cabeza, *Advances in Thermal Energy Storage Systems: Methods and Applications*, Cambridge, Woodhead Publishing, 2015.
- [35] A. Sharma, V.V. Tyagi, C.R. Chen, D. Buddhi, Review on thermal energy storage with phase change materials and applications, *Renew. Sustain. Energy Rev.* 13 (2009) 318–345.
- [36] G.A. Lane, *Solar heat storage: latent heat materials*. Technology, Boca Raton, USA: CRC Press, 1985.
- [37] E. Oró, A. de Gracia, A. Castell, M.M. Farid, L.F. Cabeza, Review on phase change materials (PCMs) for cold thermal energy storage applications, *Appl. Energy* 99 (2012) 513–533.
- [38] G. Alva, Y. Lin, G. Fang, An overview of thermal energy storage systems, *Energy* 144 (2018) 341–378.
- [39] B. Zalba, J.M. Marín, L.F. Cabeza, H. Mehling, Review on thermal energy storage with phase change: materials, heat transfer analysis and applications, *Appl. Therm. Eng.* 23:3 (2003) 51–83.
- [40] H. Akeiber, P. Nejat, M.Z.A. Majid, M.A. Wahid, F. Jomehzadeh, A review on phase change material (PCM) for sustainable passive cooling in building envelopes, *Renew. Sustain. Energy Rev.* 60 (2016) 1470–1497.
- [41] Y. Zhang, G. Zhou, K. Lin, Q. Zhang, H. Di, Application of latent heat thermal energy storage in buildings: state-of-the-art and outlook, *Build. Environ.* 42:6 (2007) 2197–2209.
- [42] N.I. Ibrahim, F. A. Al-Sulaiman, S. Rahman, B.S. Yilbas, A.Z. Sahin, Heat transfer enhancement of Phase Change Materials for thermal energy storage applications: A critical review, *Renew. Sustain. Energy Rev.* 74 (2017) 26–50.
- [43] K.Yu, Y. Liu, Y. Yang, Review on form-stable inorganic hydrated salt phase change materials: Preparation, characterization and effect on the thermophysical properties, *Appl. Energy* 292 (2021) 116845.
- [44] E. Blackley, T. Lai, A. Odukomaiya, P.C. Tabares-Velasco, L.M. Wheeler, J. Woods, Surface-Modified Compressed Expanded Graphite for Increased Salt Hydrate Phase Change Material Thermal Conductivity and Stability, *ACS Appl. Energy Mater.* 6:17 (2023) 8775–8786.
- [45] Y. Liu, X. Li, Y. Xu, Y. Xie, T. Hu, P. Tao, Carbon-Enhanced Hydrated Salt Phase Change Materials for Thermal Management Applications. *Nanomater.* 14:13(2024),1077.
- [46] S.B. Sadineni, S. Madala, R.F. Boehm, Passive building energy savings: a review of building envelope components, *Renew. Sustain. Energy Rev.* 15 (2011) 3617–3631.
- [47] N.B. Geetha, R. Velraj, Passive cooling methods for energy efficient buildings with and without thermal energy storage – a review, *Energy Sci. Res.* 29 (2012) 913–946.
- [48] D.W. Hawes, D. Feldman, D. Banu, Latent heat storage in building materials, *Energy Build.* 20:1 (1993) 77–86.

- [49] S. Dardouri, E. Tunçbilek, O. Khaldi, M. Arıcı, J. Sghaier, Optimizing PCM Integrated Wall and Roof for Energy Saving in Building under Various Climatic Conditions of Mediterranean Region, *Build.* 13 (2023), 806.
- [50] A. Alrashdan, A. M. Ghaleb, K. H. Ahmad, A. N. Daoud, Integration of Phase Change Materials in Service Areas of Building Envelopes for Improved Thermal Performance: An Experimental Study in Saudi Arabia, *Build.* 14 (2024), 904.
- [51] P. Schossig, H.M. Henning, S. Gschwander, T. Haussmann, Microencapsulated phase-change materials integrated into construction materials, *Sol. Energy Mater. Sol. Cells.* 89:2–3 (2005) 297–306.
- [52] A. Ismail, J. Wang, B.A. Salami, L.O. Oyedele, G.K. Otukogbe, Microencapsulated phase change materials for enhanced thermal energy storage performance in construction materials: A critical review, *Constr. Build. Mater.* 401 (2023) 132877.
- [53] V.V. Tyagi, S.C. Kaushik, S.K. Tyagi, T. Akiyama, Development of phase change materials based microencapsulated technology for buildings: a review, *Renew. Sustain. Energy Rev.* 15:2 (2011) 1373–1391.
- [54] V.V. Tyagi, D. Buddhi, PCM thermal storage in buildings: A state of art, *Renew. Sustain. Energy Rev.* 11 (2007) 1146–1166.
- [55] M. Koschenz, B. Lehmann, Development of a thermally activated ceiling panel with PCM for application in lightweight and retrofitted buildings, *Energy Build.* 36:6 (2004) 567–78.
- [56] A. de Gracia, L.F. Cabeza, Phase change materials and thermal energy storage for buildings, *Energy Build.* 103 (2015) 414–419.
- [57] G. Fraisse, K. Johannes, V. Trillat-Berdal, G. Achard, The use of a heavy internal wall with a ventilated air gap to store solar energy and improve summer comfort in timber frame houses, *Energy Build.* 38 (2006) 293–302.
- [58] A. de Gracia, L. Navarro, A. Castell, A. Ruiz-Pardo, S. Alvarez, L. F. Cabeza, Experimental study of a ventilated facade with PCM during winter period, *Energy Build.* 58 (2012) 324–332.
- [59] K. Kaygusuz, T. Ayhan, Experimental and theoretical investigation of combined solar heat pump system for residential heating, *Energy Convers. Manage.* 40 (1999) 1377–1396.