HEAT AND MASS TRANSFER, PROPERTIES OF WORKING FLUIDS AND MATERIALS

Phase Change Materials for Applications in Building Thermal Energy Storage (Review)

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Abstract—A unique substance or material that releases or absorbs enough energy during a phase shift is known as a phase change material (PCM). Usually, one of the first two fundamental states of matter—solid or liquid—will change into the other. Phase change materials for thermal energy storage (TES) have excellent capability for providing thermal comfort in building's occupant by decreasing heating and cooling energy demands. Because of its latent heat property, a PCM has a high energy density. The building uses PCMs mainly for space heating or cooling, control of building material temperature and increase in building durability, solar water heating, and waste heat recovery from high heat loss locations. Phase change materials for thermal energy storage has been proven to be useful for reducing peak electricity demand or increasing energy efficiency in heating, ventilation, and air-conditioning systems. The primary grid benefit of PCM based thermal energy storage system is load shifting and shedding, which is accomplished by recharging the storage system during off-peak times and substituting heating, ventilation, and air-conditioning system operation during peak times. This study examines PCM based thermal energy storage systems in building applications and benefits, focusing on their substantial limitations, and closes with recommendations for further improvement of design for use.

INTRODUCTION

Because of the growing worldwide population [1, 2], the need for energy is increasing. Researchers are constantly exploring greener solutions for energy supply due to increased global energy demand and rising levels of greenhouse gases, both of which are hazardous to our environment [1, 3]. Phase change materials for TES applications offer the benefits of storing energy as sensible heat and latent heat and has become a necessary option for energy management. Using thermal energy storage with PCMs is a sophisticated and practical way to improve energy storage efficiency and usage in several homes and industrial sectors [4–9]. Thermal energy storage systems that use PCMs reduce demand-supply mismatches, improve the reliability and performance of electricity distribution networks, and aid in energy conservation [5, 10, 11].

Because PCM has high enthalpy of fusion, it can store or release substantial energy as latent heat with a relatively small volume during melting and solidification at a relatively constant temperature. It also has relatively high thermal conductivity for effective heat transfer and a congruent (exactly same composition of solid and liquid) phase change behavior to prevent permanent constituent separation [4, 12]. Habib and Rahman recently conducted a case study using two commercially available and environment friendly PCMs (BioPCM and DuPont Energain) with different melting ranges applied within the outer walls and the roof. They found that PCM can store heat energy from solar radiation, lowering heating and cooling energy usage [13].

In this study the current state-of-the-art PCMs for thermal energy storage systems in buildings are discussed, emphasizing their benefits and drawbacks.

THERMAL ENERGY STORAGE METHODS

In a phase change material, thermal energy can be stored, and when the process is reversed, the energy is released as heat. Figure 1 depicts the classification of thermal energy storage systems.

Sensible Heat Thermal Energy Storage

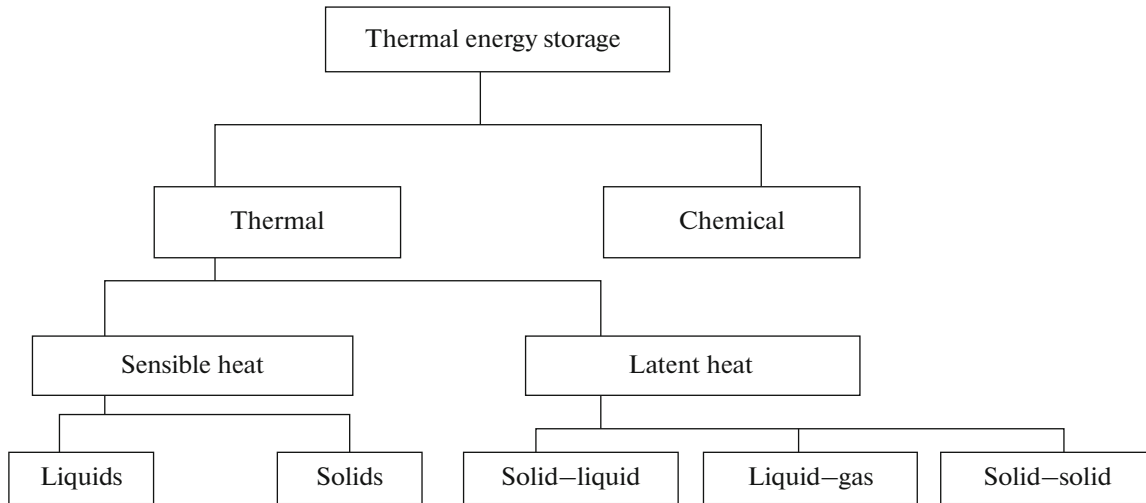Sensible heat storage (SHS) devices store thermal energy by elevating a solid or liquid's temperature. As

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                    ┌─────────────────────────┐
                    │ Thermal energy storage  │
                    └─────────────────────────┘
              ┌───────────────┴───────────────┐
        ┌───────────┐                   ┌───────────┐
        │  Thermal  │                   │ Chemical  │
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│  Sensible heat │        │   Latent heat  │
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│ Liquids │ │ Solids  │ │ Solid–liquid │ │ Liquid–gas │ │ Solid–solid│
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Fig. 1. Classification of TES-systems.

stated in Eq. (1) [4, 6], the quantity of heat stored Q functions the medium's specific heat, temperature change, and storage medium mass:

$$Q = \int\limits_{T_i}^{T_f} mc_p dT = mc_{pay}(T_f - T_i), \qquad (1)$$

where m is the mass of heat storage medium, kg; c_p is specific heat, J/(kg K); T_i, T_f are the initial and final temperature of the substance/material; K; c_{pay} is the average specific heat between initial and final temperature, J/(kg K).

Sensible heat storage has two key advantages: inexpensive and can usually be accomplished using non-toxic materials. The most significant disadvantage of adopting SHS in the construction industry is the large volume required, depending on whether the heat is actively or passively stored [14].

Latent Heat Thermal Energy Storage

The best way to store thermal energy is through latent heat storage. The overall latent heat storage system capacity with a phase change material can be calculated using the equation below [4, 6]:

$$Q = \int\limits_{T_i}^{T_m} mc_p dT + ma_m \Delta H_m + \int\limits_{T_m}^{T_f} mc_p dT, \qquad (2)$$

where a_m is the fraction melted; ΔH_m is the heat of melting per unit mass [4, 10], J/kg.

Compared to a sensible heat storage system, a latent heat storage system has a higher storage density and a smaller temperature range [4, 8, 15]. Solid–solid, solid–liquid, solid–gas, and liquid–gas phase changes can all be used to store latent heat. Solid–solid phase changes are frequently drawn out, making them a poor choice for storage. The liquid–gas phase change is also

impractical, despite having a larger heat of transformation than solid–liquid changes. Large volumes or high pressures are required for thermal storage of materials in the gas phase, making the system complex and impracticable. As a result, the sole phase change used for heat storage is the solid–liquid phase change [16].

The characteristics of solid–solid and solid–liquid PCMs is shown in Table 1.

Thermochemical Energy Storage

The thermochemical materials store and release heat using a reversible endothermic/exothermic reaction mechanism. Heat is delivered to material A during the charging process, resulting in separating two portions B + C. The finished products are simple to separate and store till the discharge procedure is finished. The temperature and energy conditions are released when the two portions B + C have been combined at a manageable pressure. Despite being the most energy-efficient technology available, it is still being researched and has not yet found any real-world uses in the building industry [18, 19]. This technique must overcome critical corrosion, low heat, and poor mass transfer performance [18, 20].

ADVANTAGES AND DISADVANTAGES OF DIFFERENT ENERGY STORAGE METHODS WITH REGARD TO BUILDINGS

The benefit of direct use in building space conditioning makes thermal energy storage a desirable on-site storage solution. Similar to this, there are numerous tested battery chemistries and systems that are commercially available that can be used to create applications for thermochemical storage.

A tested technology is TES in water storage systems. The choice of TES depends on the storage tank's

Table 1. The characteristics of solid−solid and solid−liquid PCMs [17]

Criteria	Solid−solid	Solid−liquid
Way to preserve heat	Crystal structure change	Phase change
Change of volume	Very small	Small
Encapsulation	Not required	Required
Storage density	Relatively (lower than solid−liquid PCMs)	Relatively (higher than solid−solid PCMs)
Containment	Less stringent	More stringent
Design flexibility	Higher	Moderate
Availability	Not available	Available
Cost	High	Relatively cheap

available space. Cold-water storage is favored if room is available due to its high chiller efficiency. Due to higher delta T or lower chilled water temperature, chiller efficiency will likely be affected if ice storage is required due to space restrictions.

A cutting-edge technology is phase change materials incorporated into building materials. The benefit would be that storing it wouldn't require a storage tank's own space and footprint. Thermal Energy Storage Using Phase Change Materials can be applied in reducing energy consumption in both heating and cooling seasons.

The majority of batteries have been employed in buildings for high-sensitive procedures or uninterruptible power supplies (UPS) in data centers. Only when line power fails UPS is used. It is not common practice to include batteries into load time-shifting schemes, hence doing so would need expensive custom design.

Commercial buildings rarely have on-site battery storage systems for uses other than specialized UPS applications. Although there are no technological restrictions on the use of battery storage to assist the integration of intermittent renewable technologies and/or time-shift building loads, the cost is quite high, making such applications commercially unviable.

PHASE CHANGE MATERIAL PROPERTIES

Several requirements such as thermophysical, kinetic, and chemical properties should be met by an ideal phase transition material [4, 10, 16, 21].

Thermal properties:

a melting point inside the desired operating range;

a high latent heat of phase transition per volume;

a high specific heat that significantly increases the storage capacity for sensible heat;

both phases have high thermal conductivity (solid and liquid).

Physical properties:

phase transformation causes a small volume change;

little vapor pressure at working temperature;

a favorable phase equilibrium;

congruent melting of the phase change material; density should be high.

Physical properties:

there is no supercooling;

adequate rate of crystallization;

nucleation rate is high.

Chemical properties:

a fully reversible cycle of freezing and melting;

chemical stability over time;

compatibility with building supplies;

building materials are not corroded;

it must not be explosive, flammable, or toxic.

CLASSIFICATION OF PHASE CHANGE MATERIALS

The physical transformation of energy (heat) absorption and desorbing capabilities is used to classify the phase change materials. The classification of PCMs is shown in Fig. 2.

Organic Phase Change Materials

The following are the two major groups of organic phase change materials: paraffin and non-paraffin.

Paraffin. Straight-chain *n*-alkenes $CH_3−(CH_2)−CH_3$ make up most paraffin waxes. A significant amount of latent heat is released during the crystallization of the (CH_3)-chain, and both the latent heat of fusion and the melting point rise with chain length. Only technical grade paraffin may be employed as PCMs for latent heat storage applications due to their cheap cost. Paraffin is also non-corrosive, predictable, and safe across a wide temperature range (5−80°C) [10, 15]. A list of possible organic paraffin PCMs for thermal energy storage is shown in Table 2.

Non-paraffin. Numerous esters, alcohols, fatty acids, and glycols have been found to contain non-paraffin based PCMs that are appropriate for thermal energy storage applications [26, 27]. Basic characteristics of these organic phase change materials include flammability, extremely high heat of fusion, low flash-
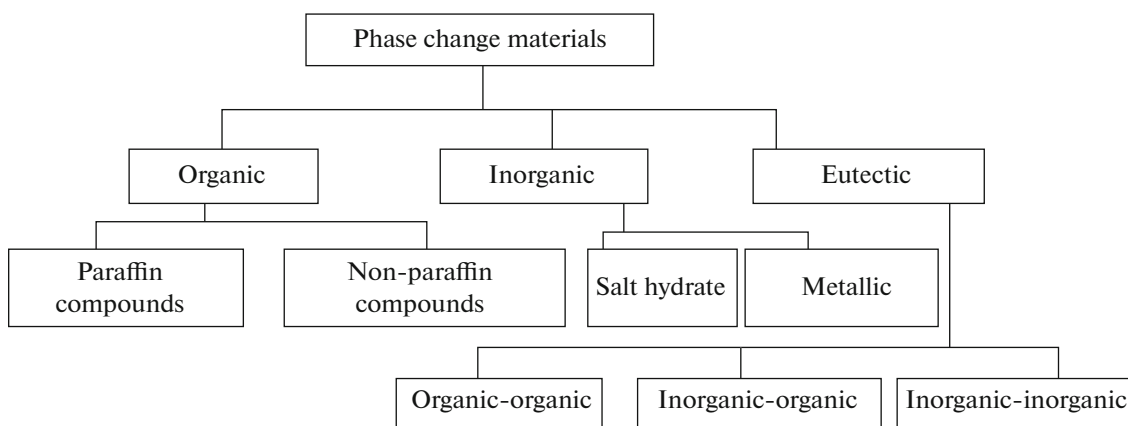
Fig. 2. Classification of phase change materials.

point, restricted thermal conductivity, and instability at high temperatures. Table 3 shows a list of organic fatty acid PCMs for thermal energy storage applications.
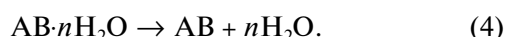
Inorganic Phase Change Materials

In high-temperature applications, inorganic PCMs are typically employed. The following are the two types of important inorganic phase change materials: salt hydrate and metallic.

Salt hydrate. Congruent, incongruent, and semi-congruent salt hydrates are characterized based on their melting technique [10, 26]. They consist of n kmol of water and inorganic salts (AB), and they have the general formula AB. The salt is hydrated and dehydrated as a result of the solid−liquid transition of $n\mathrm{H_2O}$. Either a salt hydrate with fewer or more moles of water forms when a salt hydrate melts, i.e.,

$$AB \cdot n\mathrm{H_2O} \rightarrow AB \cdot m\mathrm{H_2O} + (n - m)\mathrm{H_2O}, \qquad (3)$$
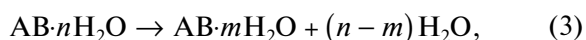
or to its anhydrous form,

$$AB \cdot n\mathrm{H_2O} \rightarrow AB + n\mathrm{H_2O}. \qquad (4)$$

The hydrate crystals divide into anhydrous salt and water or a lower hydrate and water at a melting temperature. Because not all of the solid phases in a salt hydrate can be completely dissolved by the water gen-erated during crystallization, incongruent melting occurs frequently. Due to differences in density, the lower hydrate settled near the bottom of the container.

Salt hydrates have been extensively researched in thermal energy storage applications due to their advantageous properties, such as a relatively high thermal conductivity (nearly twice that of paraffin), high latent heat of fusion per unit volume, minimal corrosiveness, and compatibility with polymers. Supercooling and incongruent melting are two drawbacks that can be solved in various ways (mechanical stirring, adding thickening agents, encapsulating the PCM to reduce separation, etc.).

Numerous studies have discovered that salt hydrates are suitable for storing thermal energy [26, 34]. When subjected to heat, salt hydrates break into anhydrous salts, release water vapor, and store energy for dehydration when heated. To evaluate the effectiveness of three distinct salt hydrates, a computational analysis was carried out. These are: magnesium sulfate ($\mathrm{MgSO_4 \cdot 7H_2O}$), cupric sulfate ($\mathrm{CuSO_4 \cdot 5H_2O}$), and gypsum ($\mathrm{CaSO_4 \cdot 2H_2O}$) in storing thermo-chemical energy. The chemical reaction was found to commence most quickly and efficiently with cupric sulfate, requiring the least amount of heating [26]. Table 4 selects inorganic hydrate PCMs for thermal energy storage applications.

Table 2. Latent heat of fusion and melting point for paraffin PCMs

Material	Melting point, °C	Latent heat, kJ/kg
n-Tetradecane [4, 22, 23]	5.8−6.0	227−229
n-Pentadecane [4, 22, 23]	9.9−10.0	206
n-Hexadecane [4, 22−25]	18.0−20.0	216−236
n-Heptadecane [5, 22, 24, 25]	22.0−22.6	164−214
n-Octadecane [4, 22, 24, 25]	28.0−28.4	200−244
n-Nonadecane [4, 24]	32.0	222
n-Eicosane [4, 24]	36.58	247
n-Heneicozane [4, 24]	40.18	213

Table 3. Latent heat of fusion and melting point for fatty acid PCMs

Acid	Melting point, °C	Latent heat, kJ/kg
Caprylic acid [4, 28]	16.3	148
Lauric [4, 29]	41—44	183—212
Myristic [4, 28, 29]	51.5—53.6	190—204.5
Palmitic [4, 30—33]	61—63	203.4—212
Stearic [4, 30—32]	70.0	222
Arachidic [4, 28]	74.0	227
Undecylenic [4, 25]	24.6	141

Table 4. Latent heat of fusion and melting point for hydrate PCMs

Material	Melting point, °C	Latent heat, kJ/kg
$LiClO_3 \cdot 3H_2O$ [4, 34]	8	253
$KF \cdot 4H_2O$ [4, 24, 26]	18.5—19.0	231
$Mn(NO_3)_2 \cdot 6H_2O$ [4, 22]	25.3	125.9
$CaCl_2 \cdot 6H_2O$ [4, 24, 26]	28.0—30.0	190—200
$LiNO_3 \cdot 3H_2O$ [4, 22]	30	256
$Na_2SO_4 \cdot 10H_2O$ [4, 22]	34	256
$Na_2CO_3 \cdot 10H_2O$ [4, 34]	33	247
$NaCH_3COO \cdot 3H_2O$ [4, 35]	55.6—56.5	237—243
$CaBr_2 \cdot 6H_2O$ [4, 24]	34	115.5
$Na_2HPO_4 \cdot 12H_2O$ [4, 24]	35—45	279.6
$Zn(NO_3)_2 \cdot 6H_2O$ [4, 7]	36	146.9
$Na_2S_2O_3 \cdot 5H_2O$ [4, 24]	48—55	201
$Na(CH_3COO) \cdot 3H_2O$ [4, 36]	58	226
$Na_2P_2O_7 \cdot 10H_2O$ [4, 36]	70	184
$Ba(OH)_2 \cdot 8H_2O$ [4, 7, 34]	78	266
$(NH_4)Al(SO_4)_2 \cdot 12H_2O$ [4, 36]	95	269
$MgCl_2 \cdot 6H_2O$ [4, 7, 36]	117	169
$Mg(NO_3)_2 \cdot 6H_2O$ [4, 34]	89.3	150

For applications involving the storage of thermal energy, several researchers have employed inorganic salt phase change materials. A collection of inorganic salt PCMs for thermal energy storage applications is shown in Table 5.

Metallic phase change material. This category includes metals and alloys with low melting points. Due to their low melting enthalpy per unit weight and although great thermal conductivity, they are rarely employed in thermal energy storage applications [26, 40]. Some characteristics of these metallics include high thermal conductivity, low heat of fusion per unit weight, and comparably low vapor pressure. Table 6 lists the materials that were chosen.

Eutectics

The melting point of the resulting eutectic combination can be changed by adjusting the weight percentages of each ingredient because eutectic materials rarely segregate as they melt and freeze [10, 26]. As a result, even though they are less diffused than other groups of materials and have lower thermal conductivity, they are a good form of phase change material [26, 41]. Table 7 shows a collection of inorganic eutectics PCM combinations for TES applications.

The temperature range is one of the most crucial considerations when selecting a PCM in any application. Figure 3 illustrates a classification system based on melting temperatures that can assist in selecting the appropriate PCM [26, 40].

The pros and cons of different types of phase change materials are discussed briefly in Table 8.

PHASE CHANGE MATERIALS APPLICATIONS FOR THERMAL STORAGE SYSTEMS IN BUILDINGS

Phase change materials applications for thermal energy storage systems in buildings are discussed next.

Table 5. Latent heat of fusion and melting point for salt PCMs

Material	Melting point, °C	Latent heat, kJ/kg
$AlCl_3$ [4, 37]	192	280
$LiNO_3$ [4, 37]	250	370
$NaNO_3$ [4, 38, 39]	307	172
KNO_3 [4, 39]	333	266
Na_2O_2 [4, 37]	360	314
KOH [4, 39]	380	150
$KClO_4$ [4, 37]	527	1253
LiH [4, 37]	699	2678
$MgCl_2$ [4, 38]	714	452
NaCl [4, 38, 39]	800	492

Table 6. Latent heat of fusion and melting point for selected metallic PCMs [26, 40]

Material	Melting point, °C	Latent heat, kJ/kg
Gallium−gallium antimony	29.8	−
Bi−Pb eutectic	125.0	−
Gallium	30.0	80.3
Cerrolow eutectic (bismuth alloy)	58.0	90.9
Bi−ln eutectic	72.0	25.0
Bi−Cd−ln eutectic	61.0	25.0

Table 7. Latent heat of fusion and melting point for eutectic mixtures PCMs

Material	Melting point, °C	Latent heat, kJ/kg
45% $CaCl_2·6H_2O$ + 55% $CaBr_2·6H_2O$	14.7	140
66.7% $CaCl_2·6H_2O$ + 33.3% $MgCl_2·6H_2O$	25	127
50% $CaCl_2$ + 50% $MgCl_2·6H_2O$	25	95
48% $CaCl_2$ + 4.3% NaCl + 0.4% KCl + 47.3% H_2O	27	188
47% $Ca(NO_3)_2·4H_2O$ + 53% $Mg(NO_3)_2·6H_2O$	30	136
40% $CH_3COONa·3H_2O$ + 60% NH_2CONH_2	30	200.5
61.5% $Mg(NO_3)_2·6H_2O$ + 38.5% NH_4NO_3	52	125
58.7% $Mg(NO_3)_2·6H_2O$ + 41.3% $MgCl_2·6H_2O$	59	132
53% $Mg(NO_3)_2·6H_2O$ + 47% $Al(NO_3)_2·9H_2O$	61	148
59% $Mg(NO_3)_2·6H_2O$ + 41% $MgBr_2·6H_2O$	66	168

Solar Water Heating

Solar water heating is one of the most popular technologies. It involves warming water in solar collectors, which then warms the liquid in a storage tank. The heated fluid is then transferred to the building via a heat exchanger [43].

In his research on phase-change materials for solar water heaters, Bhargava found that the system's efficiency and output water temperature rose in the eve-ning [44]. Additionally, if water pipelines are positioned close to the phase change material's surface, hot water can be obtained continuously throughout the day. In a thorough study of phase change materials for water heaters, Tiwari et al. considered the impact of water flow through a parallel plate placed at the solid−liquid interface [45]. In their investigation, the provision of moving insulation covering the system was used to reduce nocturnal heat losses from the exposed surface. They stated that the hot water tem-
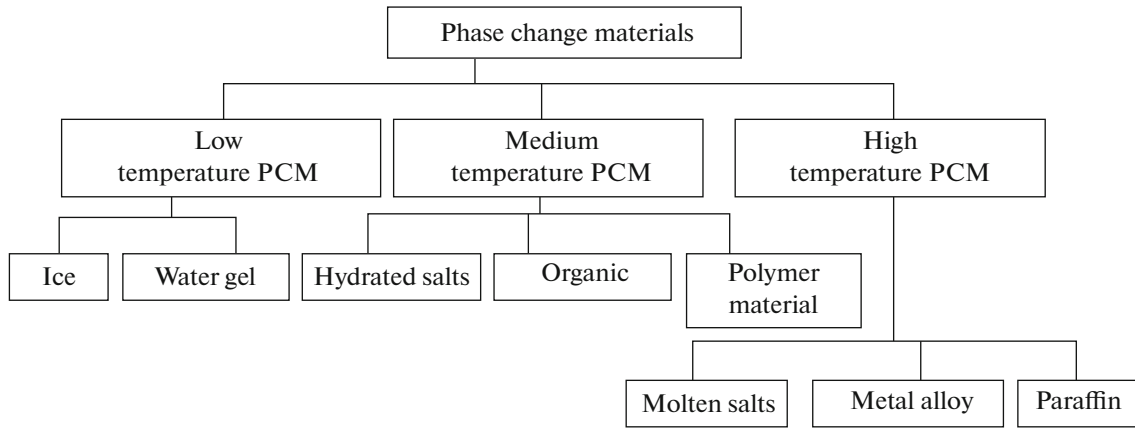
Fig. 3. PCM classifications based on melting point [26, 40].

perature might remain constant throughout the day and night (15−20°C above ambient air temperature) and that temperature variations are reduced as the melted portion of the phase change material expands.

Space Heating/Cooling

Phase change materials can be used in cooling and heating systems that are both active and passive [46]. Passive heating and cooling operate by utilizing thermal energy directly from solar or natural convection. Phase change materials, such as those used to construct the building's ceiling, floor, concrete, or gypsum wallboard, could be incorporated as a passive system [47]. The system's ability to store thermal energy is increased by the inclusion of phase-change materials. As a result of less temperature swings and longer periods of time at the target temperature, passive systems have increased occupant comfort by up to 32% [48].

Latent heat storage PCMs are used by solar collectors in active systems to capture solar energy during the day and store it [21]. The extra electricity needed by the household's occupants during periods of high electrical demand is then supplied by the stored heat. Active systems improve building thermal efficiency while reducing the amount of electricity needed to operate the building's heating/cooling system [46]. Table 9 summarizes different researcher study findings.

Waste Heat Recovery

A system that recycles heat produced by another operation is what is commonly referred to as a waste heat recovery process [65]. These techniques use waste heat from interior electrical appliances to store thermal energy [66]. Heat storage systems based on low-temperature PCMs were studied by Kabbara and Abdallah [67]. They employed a salt hydrate phase

Table 8. Comparison of various PCM types [17, 42]

Phase change materials	Pros	Cons
Organic	Available in an extensive temperature range; latent heat of fusion is high; no supercooling; recyclable as well as thermally and chemically stable; good compatibility with another materials; nonreactive and safe	Low thermal conductivity; relatively large volume change; low phase change enthalpy; flammable
Inorganic	The intense fusing heat; excellent thermal conductivity; minimal volume shift; sudden phase change; inexpensive; nonflammable	Supercooling; corrosion; segregation; reduction in efficiency after repeated use
Eutectics	Wide range of phase change temperature; high heat capacity; no or little supercooling; strong thermal and chemical stability	A minimal heat conductivity; leaking during the phase transition

change compound enclosed in cylindrical capsules for storing energy from hot exhaust air. They found that higher effective mass flow rates result in more energy absorption by the system. These findings revealed that phase change material waste heat recovery systems function better when more waste heat is stored, making them more suitable for high heat loss locations like kitchens.

Phase Change Materials Use in Refrigeration System

To keep refrigerator contents consistently cold, PCMs can be used in commercial refrigeration to reduce or transfer the cooling burden while maintaining a stable temperature for commercial end-use. Phase change materials can help customers save money on energy expenditures, increase the refrigeration system's effectiveness, prolong the equipment's life, and lower maintenance costs. Reducing the amount and volatility of temperature swings in the context of refrigeration benefits food quality, vaccine integrity, and other PCM-refrigerated products. Because PCMs deliver stored cooling energy, precooling a refrigeration system with them before a peak event or power outage enables building managers to allow flexible energy load management [68].

LIMITATION AND IMPROVEMENT OF PHASE CHANGE MATERIAL APPLICATIONS FOR THERMAL STORAGE SYSTEMS IN BUILDINGS

In this section, we are discussing the limitations and improvement of phase change material applications for thermal energy storage systems in buildings.

Supercooling Effects

It is known as supercooling when a liquid solidifies above its usual freezing point and as a result takes longer to solidify [69, 70]. Most salt hydrates have a tendency to supercool after extended use before freezing due to the release of heat from storage [71]. The phase change material's performance suffers, and heat recovery is slowed. This constraint occurs more frequently in inorganic PCMs. The performance of organic phase change materials contained in microcapsules was found to be degraded by the absence of nuclei in small spaces [72].

Research has shown that adding a nucleating agent can reduce supercooling [73]. However, the scientists found that the presence of relatively large amounts of additive led to a decrease in the latent heat of fusion, which negatively impacted the phase change material's thermal performance [1]. Some information

about the nucleating agent and its particle size, μm, is provided below:

Carbon	1.5–6.7
TiO$_2$	2–200
Borox	20 × 50–200 × 250
Copper	1.5–2.5
Aluminum	8.5–20.0

Low Thermal Conductivities

Heat transfer rates for latent heat thermal energy storage applications are slower if phase change materials have low thermal conductivities [74]. Because low thermal conductivity decreases the heat release/absorption rate during the solid–liquid phase transition, it can limit the potential of phase change materials in thermal energy storage applications [75]. Numerous research projects have been carried out to enhance the thermal conductivities of phase change materials using additives and composites [76]. Stearic acid nanocomposite, for instance, can be used to integrate carbon-based compounds [77]. This study shows that a 5 wt % addition of graphite can boost the phase change material's thermal conductivity by up to 12 times. This lessens the material's latent heat of fusion and natural convection, though. Low thermal conductivities in phase change material systems could have a big impact on a performance characteristic in applications for residential building.

Prior to installing a phase change material system in a structure, it is crucial to think about accelerating heat transmission. The system's overall performance and efficiency are strongly impacted by improvements to the heat transfer rate. According to Al-Abidi et al. [78], adding fins could enhance the thermal efficiency of a latent heat thermal energy storage application.

M. Auriemma and A. Iazzetta [79] performed a study and found that the low conductivity of sodium nitrate (SN), 0.57 W/(m K) in the solid-state, is a severe drawback to using this material as a PCM, especially during discharge cycles where the heat transfer through the solid layer is only by conduction. Several research confirmed that the thermal conductivity of SN-based PCMs doped with alumina nanoparticles (ANPs) is higher than the base salt SN. The higher the concentration of ANPs, the higher increment of thermal conductivity. Hence, nePCMs have a higher heat transfer rate compared to the same mass of non-doped PCM. Nonetheless, the viscosity of SN-based PCMs doped with alumina nanoparticles increases with the mass concentration of ANPs. On the other hand, the higher dynamic viscosities for the ANPs-doped nanofluids will negatively affect heat transmission by convection. The cp of SN-based nanofluids with ANPs decreases with the addition of the concentration of ANPs. They also found that the charging and dis-

Table 9. Summary of recent review articles–energy savings and peak load reduction

Author (s)	Location of study performed	Findings
Chen et al. [49]	Beijing (China)	Throughout the entire winter, the heating season's energy savings rate was 10%
Evers et al. [50]	Lawrence (USA)	Average daily heat flow and peak heat flux both decreased by 9.2 and 1.2%, respectively
Kuznik and Virgone [51]	Villeurbanne (France)	Room air temperature with PCM decreased up to 4.2°C
Lai et al. [52]	Lawrence (USA)	Average peak heat transmission decreased by 29.1%, while average total heat transfer decreased by 16.3%
Sharma et al. [10]	Lisbon (Portugal)	Peak cooling load decreased by 35.4%, overall cooling load decreased by 1% (energy savings for AC), and yearly energy savings for heating decreased by 12.8%
Kara and Kurnuç [53]	Erzurum (Turkey)	The PCM walls reduced the test room's annual heat load by 14%
Ahmed et al. [54]	Lyon France)	Room maximum temperature decreased up to 2.2°C
Kuznik et al. [55]	Amphilochia (Greece)	Time lag increased approximately to 100 min
Hichem et al. [56]	Ouargla (Algeria)	Inner wall temperature decreased by 3.8°C, and heat flux entering the internal environment reduced by 82.1%
Lee et al. [57]	Lawrence (USA)	Peak heat flux decreased by 51.3 and 29.7% for the south and west walls, respectively
Kong et al. [58]	Tianjin (China)	The reference room was 1°C and more than 2°C warmer in the PCMOW and PCMIW rooms, respectively
Mandilaras et al. [59]	Hong Kong (China)	The highest temperature plummeted by as much as 4°C (the model with PCM laminated within the concrete walls). The relative humidity was reduced by 16 percent from the control model (the PCM-equipped type was positioned on the inside of concrete walls)
Castell et al. [60]	Lleida (Spain)	Peak temperature decreased up to 1°C; electricity peak temperature decreased up to 1°C, electricity usage was lowered by 15%, resulting in CO_2 emissions reductions of 1.0–1.5 kg/m² per year
Shi et al. [61]	Beijing (China)	The energy-saving rate was 10% or higher during the whole winter
Tiago et al. [62]	Aveiro (Portugal)	Thermal amplitude decreased from 10 to 5°C, and the time delay was about 3 h
Principi and Fioretti [63]	Ancona (Italy)	Peak heat flux decreased up to 25% and delayed 6 h
Diaconu [64]	Lisbon (Portugal)	The highest energy savings was approximately 10 kWh (PCM melting point value was approximately 19°C)

charging cycles are slightly shortened with the addition of ANPs. This is mainly due to the enhancement of the thermal conductivity with ANPs, despite the lower convection heat transfers due to higher dynamic viscosities for ANP doped nanofluids. Discharging cycles usually are more prolonged than charging ones because of the formation of a solid layer of lower conductivity that becomes a barrier to heat conduction.

A thorough review by Mohit et al. [80] revealed that one viable method for enhancing the thermophysical characteristics of phase change materials and the functionality of latent thermal energy storage systems is the dispersion of nanoparticles. They discovered that the addition of graphene to PCM increased thermal conductivity by 14 times.

A study by Grigor'ev et al. [81] revealed that the PCMs' potential for widespread use as a foundation for thermal energy storage is constrained by their extremely low conductivity [less than 1 W/(m K)]. However, it is possible to increase the thermal conductivity of the primary material by adding some carbon nanotubes, whose thermal conductivity is four to five orders of magnitude higher. According to their preliminary studies and numerical simulations of the heat-conduction improvement in a PCM doped with carbon nanotubes, a PCM with about 20% carbon nanotubes could increase the material's heat conductivity by two to four times.

Phase Segregation

Phase segregation is one of the most prominent negative consequences of phase change materials' cyclic thermal stability [82]. When the phase change material compositions are at different phases during cyclic loading, phase segregation can occur [83]. It is prevalent in multicomponent phase change materials with dissimilar component densities, which leads to eventual component separation owing to gravity, changing the phase change material's melting point [82]. Another major cause of phase segregation in phase change material systems is incongruent melting (when a solid component does not melt uniformly) of salt hydrate-based phase change materials [84]. The PCM's long-term stability is hampered by phase segregation.

Ryu et al. [85] looked into the feasibility of thickening agents as a solution method to get rid of or lessen phase segregation from inorganic hydrated salt PCMs. The super-absorbent polymer sodium sulfate decahydrate ($Na_2SO_4 \cdot 10H_2O$) was a powerful thickener for preventing phase separation. The majority of high hydrate salts may be stabilized by adding 3 to 5 weight percent thickener, per the research. Phase separation was also avoided by adding low hydrated salts such sodium thiosulfate pentahydrate ($Na_2S_2O_3 \cdot 5H_2O$) and 2 to 4 wt percent carboxymethyl cellulose.

Fire Safety Phase Change Materials (PCMs)

The materials used in a residential building's envelope can have a big impact on how a fire develops inside a structure [86]. Gypsum plasterboards are a common home building material that has been shown to be reasonably reliable and generally safe [87]. Gypsum wallboard impregnated with roughly 24 percent paraffin-based phase change material, according to Banu et al., was less fire-resistant than regular gypsum wallboard and failed to meet building safety requirements [88]. Paraffin becomes a vapor when a fire ignites, and this vapor prefers to escape its container and infiltrate the porous structure of gypsum wallboard [89]. The paraffin vapor is ignited by the high fire temperatures, increasing the building's fire load, and decreasing its fire protection features. The use of fire retardants to lessen the detrimental effects of organic phase change compounds in building envelopes on fire safety has been the subject of several research.

Corrosion

When designing thermal energy storage systems for buildings, compatibility is of utmost importance. The container will corrode and the PCM attributes will change if the PCM material is incompatible with the container. The heat storage system consequently operates poorly. Before creating a latent heat thermal energy storage system for building applications, it is important to consider the compatibility of the phase change material and containment [17].

Cost

An additive must be applied to the phase change material to attain a given benefit, as stated in the preceding sections. A phase change material's cost is expected to skyrocket due to this. The end-user must decide if phase change material systems are worth investing in. However, it is fair to say that the general population is unaware of phase change materials and their benefits. As a result, more companies are forced to market products to the public that emphasize their benefits [1].

We know that using thermal energy storage with PCMs permits the efficient use of clean energy sources, decrease of energy consumption, and enhancement of energy system performance. That is why in a recent work, L.F. Cabeza et al. [90] noted that over the past 20 years, TES had continually attracted scientists, resulting in a massive scientific output that has been steadily growing. Despite the large number of publications, more studies are still needed to completely assess the practicality of TES in particular building locations. This study offered a perspective on the state-of-the-art of TES by highlighting the research trends and the research gaps of several TES technologies. The most significant research needs were identified in their article are in the areas of social, environ-
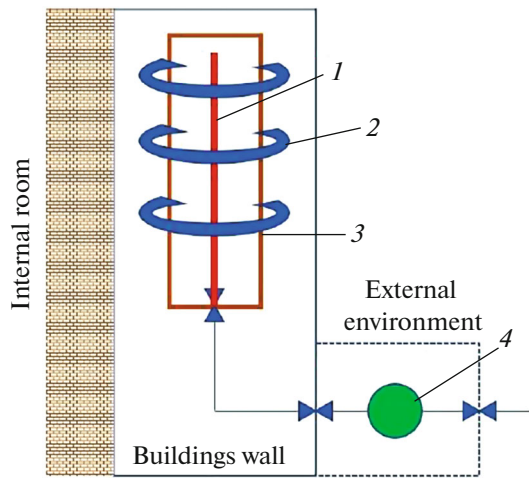
Fig. 4. Schematic Drawing of PCM Pump System [1]. (*1*) Phase change material; (*2*) heating coil; (*3*) macro capsule for PCM; (*4*) two-way pump.

mental, and economic concerns by bibliometric analysis approaches.

After conducting an assessment, Mohammad and Ravindra [91] offered some suggestions for future improvements. Since there is a dearth of research, they suggested that it be necessary to investigate the PCM's stability. In order to maximize the PCMs' potential benefits, they also mentioned that the usage of numerous phase change materials in linked or conjugate applications may be further investigated.

In their review of phase change materials for thermal energy storage in buildings: Heating and hybrid applications, Khaireldin et al. [92] concluded that further experimental studies on commercial constructions, as well as the development and optimization of hybrid systems, are needed. Last but not least, certain active and passive heating application combinations are highlighted for their positive effects on enhancing energy efficiency.

## METHODS OF PCM DISPOSAL SYSTEM

Some methods of phase change material disposal system are discussed next.

Pump and Tap System Proposal

Bland et al. [1] provided a concept proposal for installing and removing a phase change material from a building, as shown in Fig. 4. Pumping liquid phase change material into macro-capsules on the inside of the wall is how this idea works. This process allows the degraded material to be removed from the walls because most phase change materials are projected to have a lifetime of roughly 1000 heat cycles. The inefficient phase change material is then removed from the capsules by liquefying it using heating coils and then removing it with a two-way pump and emptying it via

a drain. New phase change material can now be injected into the system, allowing it to function properly once more. While the system is in use, valves prevent the phase change material from escaping and can be opened to allow the material to be drained. This procedure would most likely be carried out by a well-trained engineer who would also be in charge of removing the old ineffective PCM.

This technology has the advantage of allowing fresh PCM to be fitted when the old one has decayed without having to modify the building materials. The pump and heating coils would use very little energy because they would only be used every 3–4 years. However, one significant drawback is that it is unlikely that this system could be installed in many existing structures, making it primarily useful for new construction. Due to its exorbitant cost, this design would most likely only be erected on one side of a house. Furthermore, removing material could be hazardous to an untrained person, necessitating the assistance of an expert.

Wall Panel System Proposal

Another, more straightforward approach presented by Bland et al. [1] is depicted in Fig. 5. They proposed encapsulating phase change materials in removable modules and placing them inside a building wall. The basic idea behind these designs is that the phase change material can be replaced by the occupant, and that the modules can be safely stored within thanks to a custom-built wall. These smaller modules will be accessed either a sliding roller system that pulls out from the wall or a cabinet system that uncovers the modules and manually pulls them away from the wall. A locking mechanism will be necessary to safeguard occupants and keep the system secure, which will require a unique key to open. The phase change materials can be delivered in modules that can be replaced without any outstanding training, which is an expected benefit of this system when compared to the pump system. This method appeals to retrofitting applications more than the pump system. Because this system is only accessible from the inside, tenants are unlikely to cover the wall panels with wallpaper. Because of the uncommon nature of having removable wall panels inside an apartment, this limitation may eventually make the operation less enticing. It's also unclear how such a system would be insulated, so more study is needed to make it appealing. Customers can purchase lower-cost, lower-quality phase change materials through both methods. Costly phase change materials with additions to improve performance can be avoided, saving tenants money, because the materials can be changed. The lifetime stability of the latent heat thermal energy storage system is provided by the replacement phase change material, which is major achievement in this system.
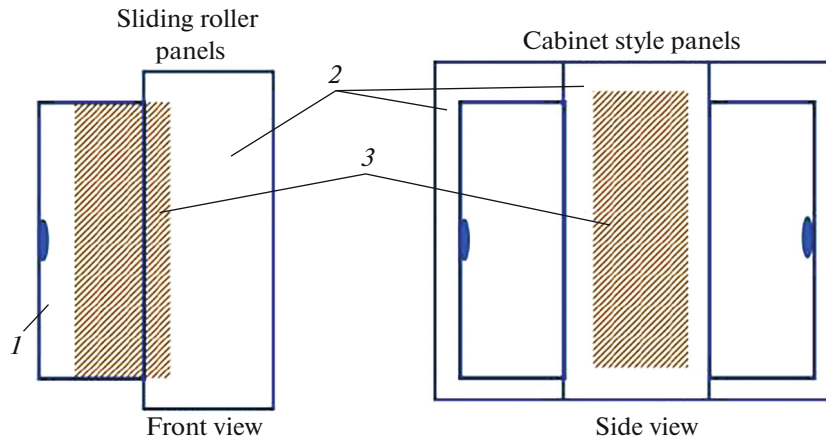
Fig. 5. Schematic of Roller PCM Wall Panel and Cabinet Style Panel [1]. (*1*) Slide opening door; (*2*) wall panel; (*3*) encapsulated PCM modules.

CONCLUSIONS

(1) Although utilizing PCMs in buildings might enhance energy efficiency and occupant comfort, the considerable disadvantages may restrict their potential.

(2) Many PCMs have poor thermal conductivities, which prolong the material's phase transition and unintentionally affect occupant comfort and system energy efficiency. Supercooling, phase segregation, fire safety, and cost are important disadvantages.

(3) Phase change materials include a number of drawbacks that could have a detrimental impact. For instance, low public awareness of phase change materials and expensive implementation costs mean that final solutions are still being explored. Other traits were identified as areas that called for more study and increased public awareness of phase change materials.

(4) Non-intrusive maintenance techniques for phase change material systems in residential buildings need to be created before becoming a well-known choice because the majority of phase change materials experience cyclic thermal degradation.

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CONFLICT OF INTEREST

The authors of this work declare that they have no conflicts of interest.

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