APPLICATION OF PHASE CHANGE ENERGY STORAGE IN BUILDINGS
Classification of Phase Change Materials and Packaging Methods

by

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Phase change energy storage plays an important role in the green, efficient, and sustainable use of energy. Solar energy is stored by phase change materials to realize the time and space displacement of energy. This article reviews the classification of phase change materials and commonly used phase change materials in the direction of energy storage. Commonly used phase change materials in construction and their packaging methods are listed according to the properties of phase change materials. Through different packaging methods to enhance heat exchange, this work solves the problem of material leakage and summarizes the advantages and disadvantages of those methods through comparative analysis. The impact of macro-encapsulation and micro-encapsulation on material encapsulation are also outlined. The simulation and model construction methods of different packaging methods are reviewed. This research is dedicated to the comparative analysis of the selection of phase change materials and packaging methods in buildings a to actively promote the promotion and application of phase change energy storage in buildings.

Key words: *review, phase change materials, thermal energy storage, building, energy efficiency.*

Introduction

With the development of society, the energy crisis situation has become increasingly severe. The green, efficient, and sustainable use of energy has become an important link in economic and social development. Building energy utilization surveys show that more than one-third of global energy consumption is attributed to building and construction sectors, for which direct and indirect CO^2 emissions account for nearly 40% [1]. Improving building energy consumption is vital. The high-efficiency utilization of solar energy, valley power, and abandonment of wind and power sources has become a key issue of social concern. The disadvantages of solar energy and valley power are unstable and intermittent. To solve this problem, the technology of thermal energy storage (TES) was proposed. Energy is stored through this technology, and the energy is displaced in time and space to achieve efficient and sustainable use of energy [2, 3].

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The TES is divided into sensible heat thermal energy storage (SHTES), latent heat thermal energy storage (LHTES), and thermochemical energy storage [4-6].

In SHTES, heat energy is stored in the form of sensible heat, and the temperature increases without phase change within the TES temperature range.

In LHTES, heat energy is stored in the form of latent heat, the temperature is almost constant during the heat energy storage process, and energy is stored by changing the phase state.

In TES, heat is stored and reversed through a reversible endothermic exothermic reaction, fig. 1, [7].

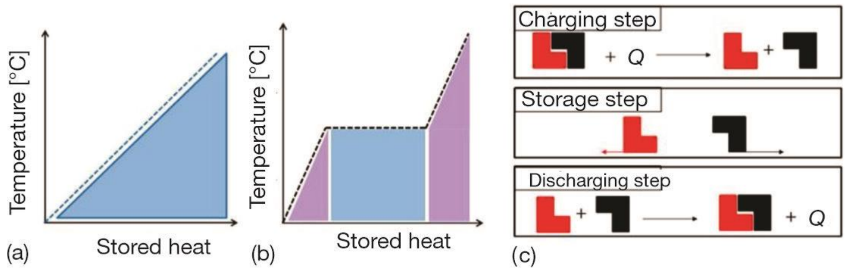

Figure 1. Methods of TES; (a) sensible heat, (b) latent heat, and (c) thermochemical reaction [7]

The phase change material (PCM), also known as the latent heat storage material, allows for considerable heat storage at constant temperature [8-10]. The commonly used phase change heat storage materials are divided into three categories: organic PCM, inorganic PCM, and hybrid PCM. Through the research of heat storage buildings in the past 10 years, the additional construction cost of LEED buildings increased by 7-10%, but the annual energy consumption cost was reduced by 30-40% [11]. In addition, the use of TES in a building can also play a role in smoothing the temperature.

In the context of efficient use of energy resources, the application of PCM in buildings is an important measure to promote the development of green buildings. On the basis of the types of PCM and PCM heat storage devices, this paper comprehensively analyzes the selection of PCM in buildings, the design classification of phase change devices. The advantages of using PCM in buildings and the problems that need to be solved at the technical level are explained in different aspects. The research direction of heat storage technology is summarized.

Classification of PCM

The PCM are classified into low temperature (≤20 °C), medium temperature (20~250 °C), and high temperature (≥250 °C). The optimal temperature of the human body is approximately 25 °C, so this article examines PCM with medium and low temperature ranges for classification research. Currently prevalent PCM in construction and those with broad application prospects are summarized.

The PCM classified by phase change states

According to their phase change states, PCM can be divided into solid-solid, solid-liquid, liquid-gas, and solid-gas PCM. In construction, solid-liquid PCM have become the first choice for materials [12,13]. However, a solid-liquid PCM has physical state changes, so

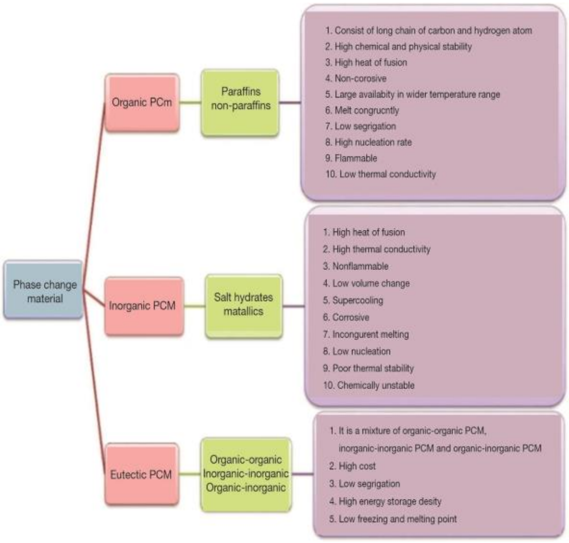

Figure 2. Broad classification and thermophysical properties of PCM [14]

choosing a suitable packaging method is vital. In addition, the problems of phase separation and large subcooling in the solid–liquid phase change process also need to be considered.

The PCM classified by material properties

Commonly used organic PCM include paraffins, fatty acids, alkanes, alcohols, and lipids. Inorganic PCM include alkalis, metals, salt hydrates, and hydrated salts. Hybrid PCM include inorganic-organic hybrids, organic-organic hybrids, and inorganic–inorganic hybrids. The detailed classification is shown in fig. 2. The ratio of PCM under different types and the corresponding thermophysical parameters are listed according to different classifications, tab. 1.

Table 1. Thermophysical properties of hybrid PCM

Hybrid PCM	Name	Proportion [%]	T_m [°C]	H [kJkg^{-1}]	References
Eutectic salts	Na_2S_4+$MgSO_4$+H_2O	25+21+54	24	n. a.	
	$CaCl_2$+NaCl+KCl+H_2O	48+4.3+0.4+47.3	26.8	188	
	CH_3CONH_2+NH_2CONH_2	50+50	27	163	
	CH_3CONH_2+$C_{17}H_{35}COOH$	50+50	65	218	
	$AlCl_3$+NaCl+$ZrCl_2$	79+17+4	68	234	
Eutectic hydrated salts	$CaCl_2\cdot 6H_2O$+Nucleat+$MgCl_2\cdot 6H_2O$	66.7+33.3	25	127	
	$CaCl_2\cdot 6H_2O$+$MgC_{l2}\cdot 6H_2O$	50+50	25	95	
	$Ca(NO_3)_4\cdot H_2O$+$Mg(NO_3)_3\cdot 6H_2O$	47+53	30	136	
	$CH_3COONa\cdot 3H_2O$+NH_2CONH_2	40+60	30	200.5	
	$Mg(NO_3)_3\cdot 6H_2O$+NH_4NO_3	61.5+38.5	52	125.5	
	$Mg(NO_3)_3\cdot 6H_2O$+$MgCl_2\cdot 6H_2O$	58.7+41.3	59	132.2	
	$Mg(NO_3)_3\cdot 6H_2O$+$MgCl_2\cdot 6H_2O$	50+50	59.1	144	
	$Mg(NO_3)_3\cdot 6H_2O$+$Al(NO_3)_2\cdot 9H_2O$	53+47	61	148	[12, 15-24]
	$CaCl_2\cdot 6H_2O$+EG+SPA+H_2O	67+0.5+25+7.5	27.9℃	147.9	
Hybrid organic	Capric+lauric acid	45+55	21	143	
	Capric+myrstic	73.5+26.5	21.4	152	
	Capric+palmitate	75.2+24.8	22.1	153	
	$C_{14}H_{28}O_2$+$C_{10}H_{20}O_2$	34+66	24	147.7	
	Capric+stearate	86.6+13.4	26.8	160	
	CH_3CONH_2+NH_2CONH_2	50+50	27	163	
	Triethylolethane+urea	62.5+37.5	29.8	218	
	Triethylolethane+urea	62.5+37.5	29.8	218	
	Lauric+palmitic acid	69+31	35.2	166.3	
	Lauric+palmitic acid	69+31	35.2	166.3	
	CH_3CONH_2+$C_{17}H_{35}COOH$	50+50	65	218	

Encapsulation of PCM in buildings

The use of PCM in buildings is a way to adjust the heat load and improve the comfort of the indoor environment on the premise of efficient energy use. The application of PCM is considered a revolutionary method for improving the thermal quality of building structures and building performance [25]. The PCM was first used in buildings by Lorsch and Kaufmann in 1976 [see in 26]. The phase change heat storage devices applied in buildings are divided into active and passive types. This article mainly introduces passive energy storage in buildings. The main types of passive energy storage are [27-30]:
- Impregnation PCM
- Stable-form PCM
- Macro-encapsulation PCM
- Micro-encapsulation PCM

Macro-encapsulation occurs when the PCM is encapsulated in a shell with a diameter greater than 1 mm, and micro-encapsulation occurs when the PCM is encapsulated in a shell with a diameter of less than 1 mm [31, 32]. Compared with micro-encapsulation, macro-encapsulation has the advantages of reducing production costs, design, and packaging flexibility, but the latter has the disadvantages of low heat transfer efficiency and uneven PCM melting and solidification [33-36].

Impregnation PCM

Impregnating PCM into building materials is an economical and simple method. Impregnation is divided into direct and vacuum impregnations. The common objects of PCM impregnation are ceramic tiles, gypsum board, and wood.

The impregnation technique was first proposed by Hawes [37] and involved directly immersing concrete products in liquid PCM. Barzin *et al.* [38] conducted a night-time ventilation comparison experiment with two test chambers combined with PCM-impregnated gypsum board and verified that using night-time ventilation to charge the PCM saves 73% of electricity within a week. Novais *et al.* [39] developed a new type of PCM tile by dipping, and PCM is directly integrated into lightweight tiles, as shown in fig. 3. The indoor temperature change was reduced by 22%, and the thermal performance of the tiles was affected by the PCM load. The optimal load of PCM tiles was 5.4wt.%.

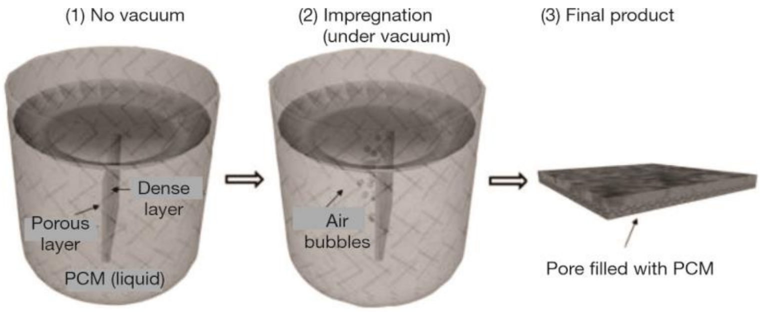

Figure 3. Schematic of PCM tile impregnation process [39]

Saavedra [40] immersed radiata pine in a container filled with liquid octadecane and then subjected the material to vacuum impregnation. It is provd that the impregnated wood can be used as an energy-saving building structure. Said *et al*. [41] treated the wood surface with ultraviolet curing coating and the retention rate of PCM in wood was effectively improved. Yang *et al*. [42] developed a multifunctional composite foam by dipping paraffin wax into melamine foam (MF), and then coating SiO_2 nanoparticles (SiO_2NP) to obtain paraffin @MF@ SiO_2NP composite foam, fig. 4. The latent heat value of paraffin @MF@ SiO2NP composite foam is 179.9 J/g. As a heat-regulating material, this composite foam can stabilize the indoor temperature and has the advantages of light weight and easy cutting.

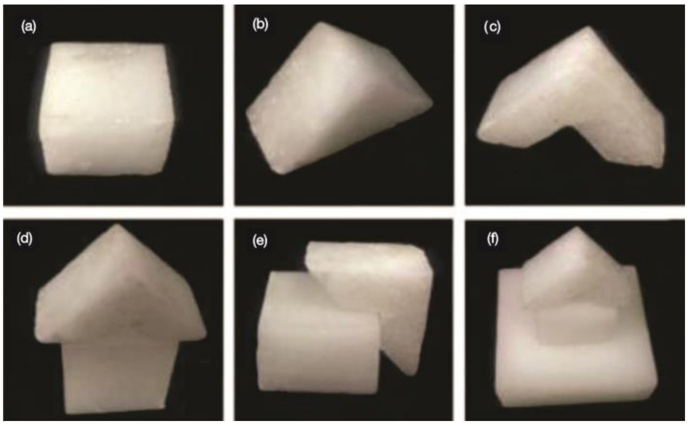

Figure 4. Paraffin @MF@ SiO_2NP composite materials of different shapes [42]

Stable-form PCM

Styling materials are of two types. One is based on a polymer as the supporting framework and is then mixed with PCM, such as PMMA, high-density polyethylene, polyvinyl alcohol, and polyurethane [43]. The other is based on porous material as the supporting framework. The PCM is prepared by dipping and adsorbing [44]. The supporting framework acts as a physical barrier to prevent the PCM from reacting with the surrounding environment after it leaks [45].

Polymer as the supporting framework

Kunping *et al*. [46] proposed a new PCM board with 75% paraffin as PCM and 25% polyethylene as the supporting framework. The application of the new PCM panel to the electric heating floor radiant heating proves that more than half of the electric heat energy used during off-peak hours can be transferred to peak hours. Qu *et al*. [47] modified the paraffin-HDPE shaped PCM to improve its comprehensive performance by adding two mixed carbon nano additives (EG-MWCNT and EG-CNF).

Kim *et al*. [48] used paraffin as PCM, mixed it with polypropylene and elastomer to prepare SSPCM sheets, and tested the effect of SSPCM in different installation positions on the heat storage performance in a cabin, fig. 5. The floor directly exposed to solar radiation has the best effect on adjusting the indoor temperature, and the same number of SSPCM with the largest application area can reduce the heating power better.

Porous materials as the supporting framework

To solve the leakage problem caused by the direct mixing of PCM into building materials, PCM is combined with porous materials to form a shaped PCM and is then mixed with building materials. Porous materials are divided into porous carbon materials, porous clay mineral materials, and bio-based porous materials [49-54]:

- Porous carbon materials: expanded graphite (EG) and graphite foam.
- Porous clay mineral materials: diatomaceous earth, expanded perlite (EP), and expanded vermiculite (EV).
- Bio-based porous materials: wood flour, cellulose, carbonized corn cob, and pine cone carbon.

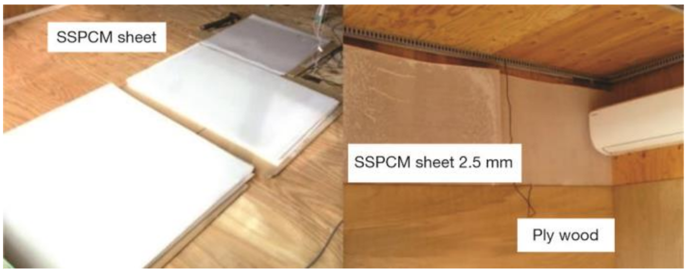

Figure 5. Different layout positions of SSPCM [50]

Ali *et al*. [45] used the recovered expanded glass aggregate (EGA) as a supporting framework and mixed it with PCM to obtain an EGA-PCM composite material, figs. 6 and 7. The absorption rate of EGA is as high as 80%, and the thermal stability of EGA-PCM is satisfactory. Research confirmed that the interface between EGA-PCM and the cement matrix is acceptable. The EGA-PCM is costly but provides feasibility for the recycling of EGA glass waste.

Figure 6. The EGA-PCM composite material [45]

Figure 7. The EGA-PCM preparation [45]

Cheng *et al*. [55] mixed an EG/paraffin composite material with foam concrete to prepare a lightweight wall material (LMW) with energy storage characteristics. Kim *et al*. [56] used artificial lightweight aggregate as a supporting framework to absorb PCM to prepare a composite material with energy storage properties. The composite material mixed with concrete was used as an interior decoration material. Hatten *et al*. [57] developed a new type of composite material (SSPCM) with a novel silica fume (SF) as the support frame and polyethylene glycol 600 (PEG600) as the PCM. Das *et al*. [50] developed and tested a new type of water hyacinth biocarbon-based-PCM heat storage material with a stable shape. When the ratio of PCM to the biochar is 6:4, the latent heat is 179.4 J/g. The addition of water hyacinth biochar increased the thermal conductivity of PCM by 13.82 times. Chen *et al*. [58] developed a shape-stable energy storage material of polyethylene glycol (PEG)-jujube core biochar with a latent heat of 194.7 J/g, a phase change temperature of 51.4 °C, and a thermal conductivity of 0.280 W/Mk.

Macro-encapsulation PCM

Macro-encapsulation has the effect of preventing direct contact between the PCM and the surrounding environment while increasing the thermal conductivity. The plate, spherical, tubular, bagged, and brick techniques are the common macro-encapsulation methods [27].

Lee *et al*. [59] encapsulated hydrated salt PCM in a polymer bag to form a PCM thermal shield (PCMTS). A laboratory was established to test the effect of PCMTS installation depth on indoor heat flux. The location depths were numbered from 1 to 5, fig. 8. The average heat transfer of the wall with PCMTS during the day was reduced by 28%. The PCMTS placed on South Wall 3 (2.54 cm from the wall panel) and West Wall 2 (1.27 cm from the wall panel) have the best effect, and the heat flux was reduced to 51.3% and 29.7%, respectively.

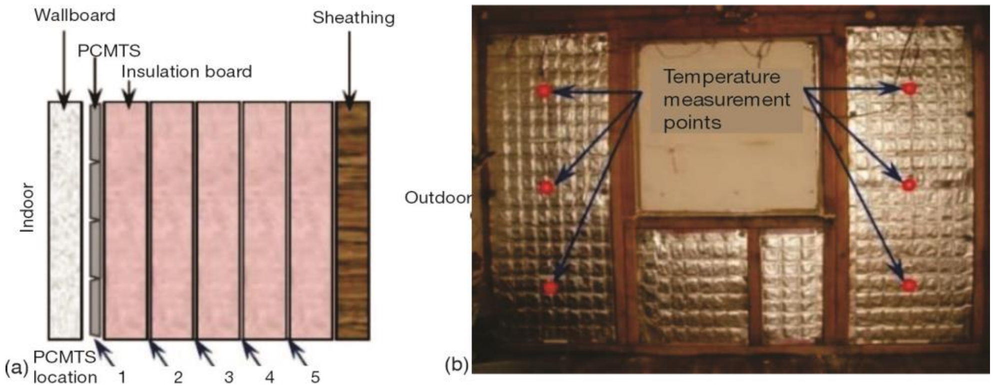

Figure 8. (a) Schematic of the PCMTS position section [59] and (b) PCMTS installed on the wall and its temperature measurement point [59]

Lai *et al*. [60] filled MPCM into an aluminum honeycomb wallboard, heat was stored by the MPCM, and the aluminum honeycomb could reduce the heat transfer and heat resistance evenly. Vicente *et al*. [61] inserted a large metal steel capsule (30 cm × 17 cm × 2.8 cm and 0.75 mm thick) into a hollow brick wall and filled the capsule with organic paraffin. Comparative experiments revealed that the indoor temperature fluctuation was reduced by the large metal steel capsule and the thermal amplitude was reduced by approximately 50% to 80%. Cui *et al*. [62] proposed a macro-encapsulation method that combines PCM hollow steel balls (HSB) and metal clips (PCM-HSBC-c).

Boobalakrishnan *et al*. [63] encapsulated paraffin in a grid and applied it on a metal roof to create a PCM roof, fig. 9. After testing from 8 a. m. to 6 p. m., the daily average temperature outside the roof of the PCM roof was lowered by 1.5 °C, the daily average temperature inside the roof was lowered by 5.5 °C, and the indoor daily average temperature was lowered by 5 °C.

Rathore *et al*. [64] used an aluminum alloy tubular container to encapsulate PCM OM37, and the PCM-encapsulated tubular container was embedded in a wall, fig. 10. Two identical compartments (the reference and experimental rooms) with dimensions of 1.12 m × 1.12 m × 1.12 m were manufactured. The peak temperature in the experimental compartment was reduced by 7.19~9.18%, and the indoor thermal amplitude was reduced by 40.67~59.79%.

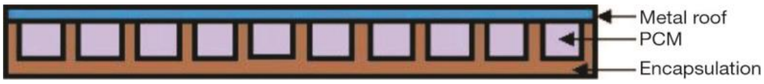

Figure 9. Schematic of the PCM roof [63]

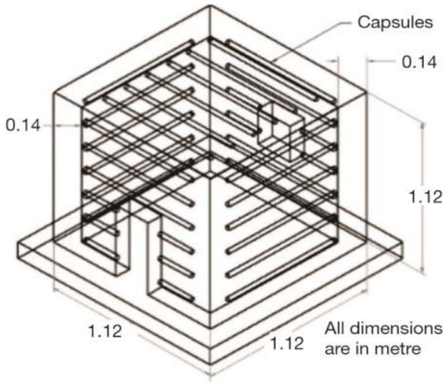

Figure 10. Aluminum alloy tubularpackaging container and schematic of the packaging container embedded in the experimental compartment [64]

Qudama *et al*. [65] placed PCM aluminum heat storage containers of different shapes and sizes in concrete bricks, fig. 11, to study the influence of shape and size on the concrete brick performance. The thermal performance of the PCM container E with a square cross-section is optimal. The heat transfer efficiency first increased and then decreased with the increase of the heat transfer area. A study of the optimal heat transfer area is crucial for the energy storage capacity of the PCM heat storage container.

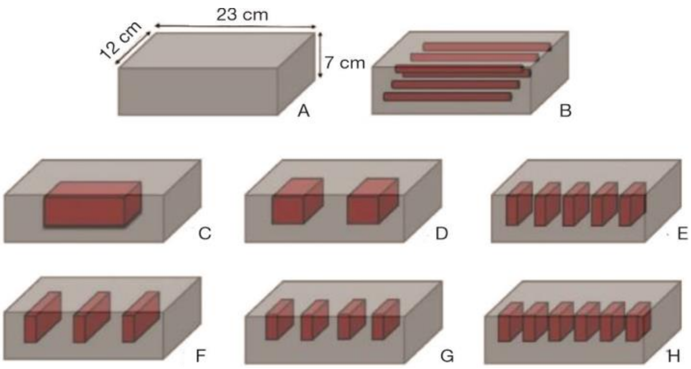

Figure 11. Schematic of a PCM heat storage container combined integrated in a concrete brick [65]

Navarro *et al*. [66] proposed a new type of prefabricated slab concrete house. The solar air collector pumps hot air into the hollow slab and then achieves cross-flow heat exchange with the PCM encapsulated by the aluminum tube, fig. 12. During the day, the PCM was melted to absorb heat because of the hot air provided by the solar air collector; at night, the ambient temperature decreased and the PCM was solidified to release heat to increase the room temperature. The results show that the efficiency of the solar air collector in winter was 30% which was enough to provide for the entire charging process of the PCM.

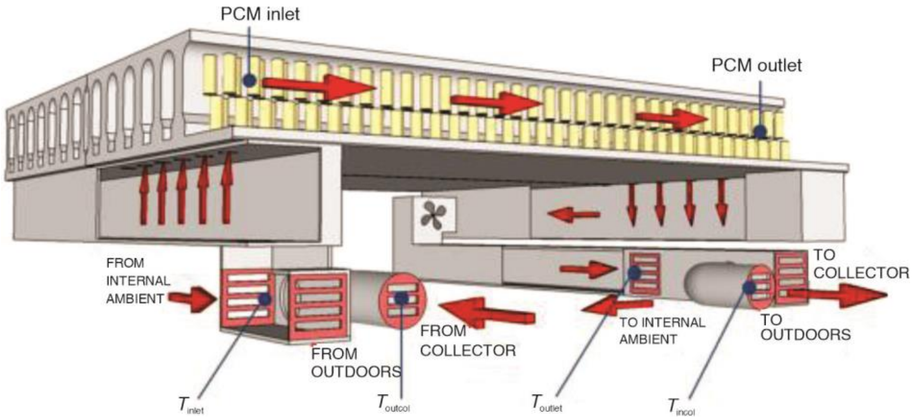

Figure 12. Scheme of the active slab operation [66]

Micro-encapsulation PCM

The microcapsule concept

A single particle or drop (core material) of a solid or liquid PCM is coated with a polymer material (shell material) to form microcapsules in the range of micrometers to millimeters, tab. 2, [64-67]. Microcapsule encapsulation renders the PCM shielded from the influence of the external environment. Compared with other packaging methods, the problems of volatility, leakage, decomposition, supercooling, phase separation, and metal corrosion of the PCM can be solved. The form of particles can effectively increase the heat transfer area and improve the heat transfer performance [68, 69]. Combination with building materials is readily achieved, and the leakage problem during the material phase change process can thus be solved.

Table 2. Preparation methods of EPCM [70]

Methods	Physical method	Chemical methods	Physical-chemical methods
1	Spray drying method	In-situ polymerization	Coacervation
2	Solvent evaporation method	Interfacial polymerization	Sol-gel encapsulation
3	Wurster fluidized bed process	Emulsion polymerization	Phase separation method
4	–	Miniemulsion polymerization	–
5	–	Suspension polymerization	–

Huang *et al*. [71] prepared PMMA/$Na_2HPO^4 \cdot 7H_2O$ microcapsule phase change material (MEPCM) with $Na_2HPO^4 \cdot 12H_2O$ as the core material. A series of verifications confirmed that the prepared MEPCM had a phase change temperature of 51 °C and a latent heat of 150 kJ/kg. Nikpourian *et al*. [72] prepared a new type of microcapsule energy storage material with modified paraffin as the core material and polyurethane (PU) as the shell material.

The best ratio was 0.35 g Novolac + 0.09 g TDI + 0.1 g paraffin, the phase transition temperature was 62.4 °C, and the latent heat value was 153.9 KJ/Kg. Hu *et al.* [73] developed a new type of MEPCM with PU as the shell. The study found that the MEPCM had an enthalpy value of 136.2 J/g and had excellent thermal stability and energy storage stability. Commonly used microcapsule materials and their thermophysical properties as shown in tab. 3.

Table 3. Commonly used microcapsule materials and their thermophysical properties

Core material	Shell material	T_m [°C]	H [kJkg^{-1}]	Reference
$Na_2HPO_4 \cdot 12H_2O$	PMMA (Polymethyl methacrylate)	51	150	[6]
Paraffin	Polyurethane	62.4	153.9	[12]
Eicosan	PMMA (Polymethyl methacrylate)	41	54.6	[66]
N-heptadecane	$CaCO_3$	16	85.6-147.3	[74]
Lauric acid	SiO_2	41.7	186.6	[75]
Lauryl alcohol	Melamine formaldehyde	24	–	[76]
N-octadecane	Melamine formaldehyde	30.5	170	
N-octadecane	Melamine formaldehyde	40.6	144	
Paraffin	Urea formaldehyde	54	157.5	
Micronal DS 5008X (BASF)	–	29	102.008	
DPNT06-0182 (Qiba specialty chemicals)	–	35	96.968	
Paraffin	Gelatin-sodium alginate (GE-SA)	60.4	126.8	[77]

Application of microcapsules in buildings

For their application in construction, microcapsules are mixed with building materials to prepare composite energy storage materials, such as concrete and gypsum boards [78-81].

Teng *et al.* [82] prepared a cement-based composite material mixed with microcapsules and cement. When the content of microcapsules in the composite material was 30 wt.%, the thermal insulation performance of the cement paste was improved by 55.5%. Wi *et al*. [83] coated a composite material prepared by mixing microcapsules and mortar on a building insulation finish layer. The time lag effect of indoor temperature was enhanced and the peak temperature was reduced.

Zhang *et al*. [84] mixed the microcapsules into a gypsum matrix. The gypsum board with the microcapsule content of 10 wt.% had the characteristics of high mechanical strength, high thermal conductivity, and good energy storage. Li [85] prepared a mixed PCM wallboard and explored the energy storage performance and position distribution influence of a mixed PCM wallboard through comparative experiments. Cheng *et al*. [86] mixed prepared carbon nanotube microcapsules into RPUF to create a wall with energy storage properties and compared them with a single microcapsule. The influence of the addition of carbon nanotubes on energy storage and temperature regulation performance was tested. The maximum temperatures of the C-RPUF test room was be decreased by 11.5 °C. Serrano *et al*. [87] developed a polyurethane foam containing microcapsules to reduce the heat loss of the envelope structure.

Kara *et al*. [88] added Rubitherm® GR35 and GR41 to the plaster of a wall respectively and constructed a new three-layer glass and PCM wall, fig. 13. The comparative experiments show that the GR35 wall had better performance. The PCM wall provided 14% of the laboratory's annual load, and the overall daily efficiency was 20% to 36%. The presence of the other three layers of glass significantly reduced the excessive energy storage of PCM and plays a role in preventing overheating in summer.

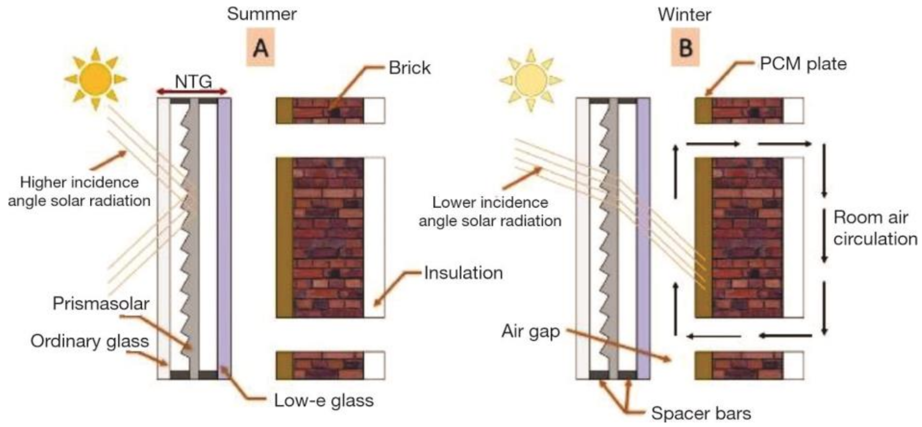

Figure 13. Working principle of the combination of the new three-layer glass and the cross section of the PCM wall [88]

Specific instructions (Word Style TS Heading 3)
Microencapsulated phase-change slurry

Microcapsule slurry (MPCS) is a functional thermal fluid formed by dispersing phase change microcapsules into a base fluid. Compared with traditional fluid or pure solid PCM, MPCS has the following main advantages [89-91]:

– High energy storage capacity.
– Store and transfer heat energy in the state of pumping fluid.
– High heat transfer rate and almost constant heat transfer capacity.
– High specific heat capacity.

The phase-change MPCS with stable performance can be directly recycled in an equipment pipeline and has a wide range of applications, fig. 14.

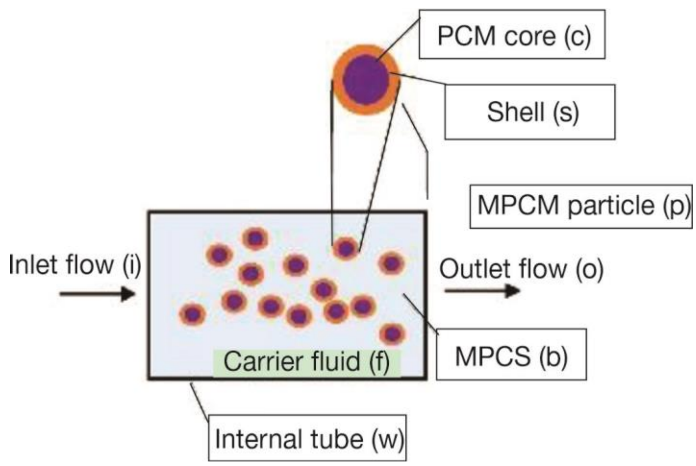

Figure 14. Schematic of the microcapsule slurry [92]

The low thermal conductivity of the microcapsule particles leads to poor heat transfer performance of the MPCS. The enhancement mechanism can be used to increase the heat transfer, such as by improving the micro-convection and the specific heat capacity effects, adding nanoparticles and magnetic particles, upgrading the material of the microcapsule shell, and altering the tube type for increased heat transfer [92-94]. The fluidity of the MPCS is also related to its viscosity, pressure drop, and pumping power. Morimoto [95] investigated the heat transfer characteristics of the MPCS in the flow direction of a horizontal circular tube. The average Nusselt number of the PCM emulsion flowing in the horizontal direction was greater than that of the PCM emulsion flowing upward. Ran *et al*. [96] simulated the flow characteristics of a phase change slurry in spiral coils. The influencing factors of the slurry flow characteristics were studied. The greater the slurry inlet flow rate, the greater the pumping power consumption and friction coefficient. Pu *et al*. [97] proposed the combination of the MPCS and tree pipes. Comparison of the thermal and flow characteristics of pure water and microcapsules flowing through different pipes (horizontal straight pipes and tree pipes) reveal that the thermal performance and pressure loss were reduced by the combination of the MPCS and the dendritic structure. Kong *et al*. [98] tested the MPCS used in ground source heat pumps and verified that the MPCS showed higher thermal performance than water in terms of latent heat. The ratio of the heat load to the pumping power of the MPCM slurry was increased by 34% compared with water. In addition, after 123252 pumping cycles, no significant rupture of MPCM particles was detected.

Su *et al*. [99] conducted theoretical calculations (for a compacted MEPCM bed system for a solar TES system) on the basis of a MEPCM bed system for a solar TES system, fig. 15. Compared with a pure water system unit, the TES unit with microcapsules had a higher energy storage density per unit volume. Although its effective thermal conductivity was lower than that of a water system, the TES unit had twice the thermal conductivity of other PCM storage units.

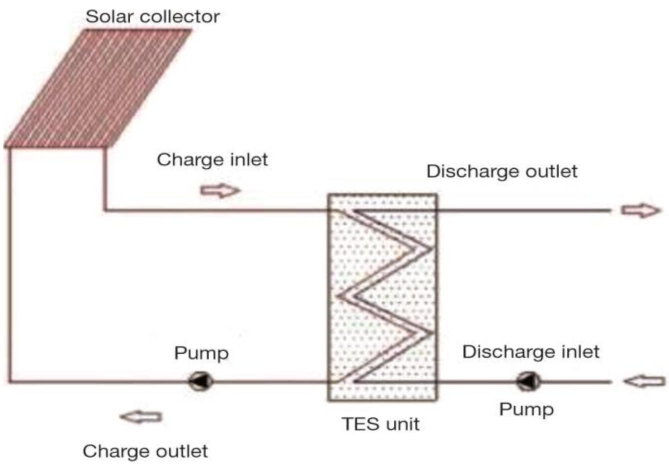

Figure 15. Compacted MEPCM bed system for solar TES system

Combination of microcapsule slurry and macro-encapsulation

As MMPCM is an important direction for the development of the energy storage industry, the stability of microcapsules, product cost, and market issues in industrialization must be considered. However, the widespread application of microcapsules will inevitably play a substantial role in promoting green buildings and low-carbon life. The flow and heat transfer mechanism of the phase change slurry needs further study. The heat transfer performance of the phase change slurry is improved by adding metal particles and carbon nanotubes, and the pipeline is optimized to increase heat transfer.

Our research group conducted related experiments on the application of phase change energy storage in buildings. The phase change slurry was applied to the floor radiant heating of the test room for energy storage.

The floor heat storage device, figs. 16 and 17, was designed, and the heat storage device was divided into the heating, heat storage, and heat preservation layers from top to bottom. Several heat storage units were included by the heat storage layer, and a heat storage unit is a regular hexagonal prismatic structure cavity. The heat storage unit was provided with an inner cavity and an outer cavity adjacent to each other. The inner cavity was filled with an inorganic salt phase change filler, and the phase change slurry flows around the outside of the cavity. The PCMS lows in the outer cavity for heat exchange and energy storage. The MPCS and PCM macro-encapsulation are combined in this device to increase the heat storage capacity of the device. The phase change slurry has a heat storage effect, and the problem of energy waste caused by uneven heat storage of inorganic salt materials in the cavity is also solved.

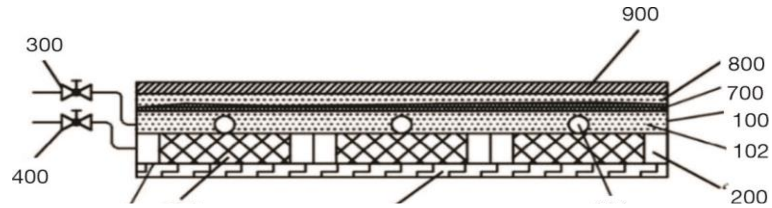

Figure 16. Schematic of the heat storage floor structure;
100: Heating layer, 101: Heating water pipe, 102: Concrete,
200: Heat storage layer, 201: Heat storage unit, 300: The first solenoid valve,
400: The second solenoid valve, 500: Insulation layer,
600: Heat reflection layer, 700: Auxiliary heating layer, 800: Leveling layer,
900: Decorative layer

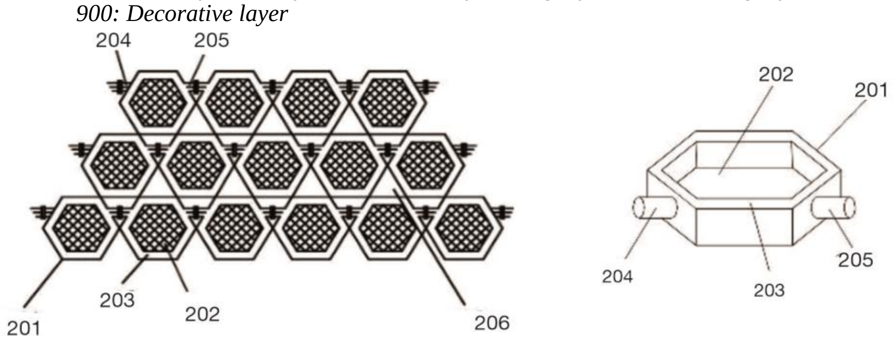

Figure 17. Cross-sectional view of the heat storage layer and schematic of the structure of a single heat storage unit; *201: Heat storage unit, 202: Inner cavity, 203: Outer cavity, 204: Inlet pipe, 205: Outlet pipe, 206: Stainless steel bracket*

Conclusions and recommendations

As building consumption accounts for a large proportion of total energy consumption, the use of PCM in buildings is a low-carbon and environmentally friendly development direction to improve building performance. This article examines commonly used energy storage methods in buildings by focusing on passive energy storage. The selection of phase change heat storage materials and the packaging methods of PCM are classified and explained. The development of green buildings in recent years is summarized. The conclusions are obtained as follows.

- *Material selection*: The PCM, is non-toxic and harmless and has low phase separation, supercooling, high latent heat value, suitable temperature range, low cost, and is the direction of the continuous development of the industry. At present, the commonly used paraffin wax in organic PCM has the advantages of wide temperature range, high latent heat value, stable chemical performance and low cost and the disadvantages of low thermal conductivity and easy leakage. This material is modified by adding metal particles and carbon nanotubes, and the packaging method is changed to enhance heat transfer. Organic PCM has small density, large volume, and large space occupation area. Hybrid PCM can adjust the phase transition temperature and has high latent heat, and these features can solve the problem of large phase separation and undercooling of a single PCM. However, the hydrated salt phase change process readily loses water and thus affects the performance of the material. After several hundred cycles, the latent heat value is significantly reduced, and the corresponding subcooling degree will also increase. Metal particles and carbon nanotubes are added to improve the thermal conductivity. Looking for PCM with stable performance, good thermal conductivity, and low cost is the direction of the industry's continuous development.
- *Material encapsulation*: The fact that composite materials prepared by impregnation are prone to leakage and insufficient PCM filling makes it difficult to effectively solve the heat storage problem. As the most widely used packaging method in buildings, macro-encapsulation has the advantages of simple construction and low cost. However, the material is prone to incomplete melting and solidification during the phase change process, thereby causing some energy waste. As an important direction for the development of energy storage, microcapsules can effectively solve the problems of volatility, leakage, decomposition, supercooling, phase separation, and corrosion of metals currently faced by material packaging. However, the production cost of microcapsules is high, so the cost issue is the key to the urgent solution of microcapsule industrialization. Based on the research of microcapsules with stable performance and latent heat value effects, the preparation process of microcapsules is upgraded and optimized to reduce industrialization costs.
- The phase change slurry developed on the basis of microcapsules has also become a hot spot in the industry. The phase change slurry has liquid fluidity and high energy storage capacity. However, the high viscosity of the phase change slurry leads to high transmission resistance. To improve the energy transport capacity of the slurry, further in-depth research must be conducted on the flow and heat transfer mechanism.

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