

# Research Status of Phase Change Energy Storage Materials for Multi-Temperature Zone Applications

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**Abstract:** This article provides a critical review of phase change thermal energy storage technology, structured around the three central elements of phase change materials (PCMs): their classification, energy storage mechanisms, and application advantages. The significant differences in phase change temperature requirements across various application scenarios have driven the development of targeted material systems. This paper systematically summarizes the research progress of PCMs covering the full temperature range, divided into low-to-medium temperature ( $\leq 200$  °C), medium temperature (150~450 °C), and high temperature ( $\geq 450$  °C), elaborating on the material types and performance regulation mechanisms for each segment. Additionally, typical applications of PCMs in photovoltaic power generation, electronic devices, green buildings, and other fields are presented. Finally, the challenges faced by typical materials in each temperature segment are proposed, providing reference directions for the future development of phase change energy storage technology.

**Keywords:** Phase Change Materials; Phase Change Temperature; Thermal Energy Storage; Renewable Energy

## 1. Introduction

Energy is the fundamental material basis for social development and a key driver of economic evolution. China mainly relies on fossil fuels, but their depletion and massive carbon dioxide emissions-exacerbating the greenhouse effect and global warming-have spurred the exploration of new energy sources. Meanwhile, energy systems face critical practical issues: on one hand, the intermittency and volatility of clean energy such as photovoltaic and wind power demand efficient energy storage technologies for spatiotemporal energy

regulation; on the other hand, a large amount of industrial waste heat is not effectively recovered, leading to energy waste and ecological pressure. Propelled by the "Dual Carbon" strategy, the energy sector's evolution has led to a growing recognition of Thermal Energy Storage (TES) technology, which comprises three main types: Sensible Heat Storage (SHS), Latent Heat Storage (LHS), and Thermochemical Energy Storage (THES).

Latent heat storage (LHS) technology uses phase change materials (PCMs) to store excess thermal energy-such as solar thermal energy, industrial waste heat, or off-peak grid electricity-and release it when needed, resolving the spatiotemporal mismatch between thermal energy supply and demand. As energy carriers, PCMs store and release large amounts of energy at specific temperatures, offering advantages like high energy storage density, near-constant phase change temperature, high safety, and strong stability, thus gaining widespread attention [1].

## 2. Classification of Phase Change Energy Storage Materials

Phase change energy storage materials can be classified in various ways. Currently, the common classification criteria are typically based on three key factors: the phase change process, material composition, and phase change temperature.

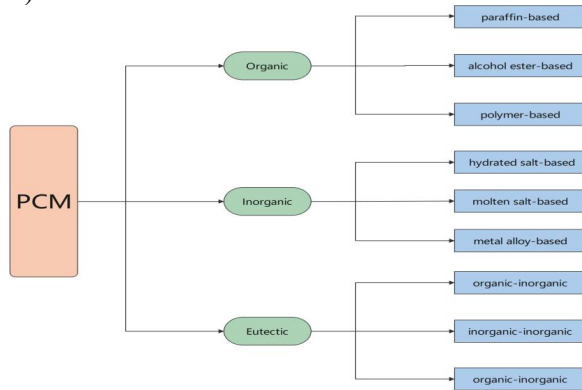
### 2.1 Phase Change Process

PCMs store or release heat through physical state changes. This process leads to a classification of five principal types: solid-solid, liquid-liquid, solid-liquid, liquid-gas, and solid-gas. Liquid-gas and solid-gas PCMs have high latent heat but suffer from significant volume changes during phase transition, requiring high-temperature and pressure-resistant materials and complex safety systems, limiting their application. In contrast, solid-solid and solid-liquid PCMs have stable

phase transition temperatures and minimal volume changes, making them more favored in research and practical applications.

## 2.2 Types of Phase Change Materials

Based on composition, PCMs are divided into organic, inorganic, and composite PCMs (Figure 1).



**Figure 1. Classification by Material Composition**

(1) Organic PCMs Organic PCMs mainly include paraffins, fatty acids/alcohols, and polymeric materials. Their melting temperature, latent heat, and thermal stability generally increase with hydrocarbon chain length. Advantages include no supercooling or phase separation, good formability, low corrosiveness, and high chemical stability. The low thermal conductivity and flammability of these materials limit their application in high-temperature environments.

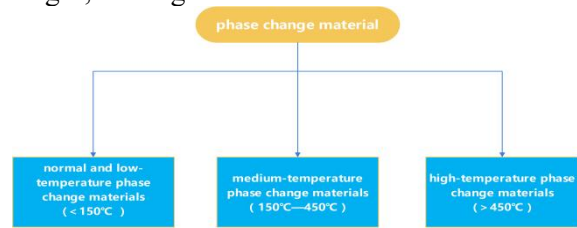
(2) Inorganic PCMs Inorganic PCMs primarily include hydrated salts, metal alloys, and molten salts. Hydrated salts, which store heat through hydration/dehydration, are a research focus due to their high energy storage density and high thermal conductivity., low cost, and diverse applications. Inorganic PCMs offer high latent heat, large energy storage density, and low-cost raw materials, but suffer from supercooling, phase separation, and significant volume changes during phase transition, restricting their

development.

(3) Composite PCMs Composite PCMs (CPCMs) include inorganic-organic, organic-organic, and inorganic-inorganic composites. By combining two or more PCMs through specific methods, they achieve superior properties such as high latent heat, small temperature fluctuations, and strong stability. Challenges include higher costs and insufficient comprehensive test data.

## 2.3 Phase Change Temperature

Based on phase change temperature, PCMs are designated as low-to-medium (<150 °C), medium (150–450 °C), or high-temperature (>450 °C) materials (Figure 2). While there is no strict universal demarcation and overlap exists, this classification is highly practical because heat sources for thermal energy storage in real applications correspond to specific temperature ranges, serving as the foundation for this review.



**Figure 2. Classification by Phase Change Temperature**

## 3. Low-to-Medium Temperature Phase Change Energy Storage Materials

Low-to-medium temperature PCMs (phase change temperature  $T_m$ : -50°C~200°C) mainly include most organic PCMs (e.g., mainstream high-density polyethylene (HDPE) has a melting point up to 130°C), inorganic hydrated salts, and organic mixed crystals. The widespread use of these materials in areas such as building energy management, electronic thermal control, and solar energy storage is underpinned by their thermophysical properties, with data for common low-to-medium temperature PCMs presented in Table 1.

**Table 1. Common Low-to-Medium Temperature Phase Change Materials**

Material	$T_m$ (°C)	$\Delta H$ (kJ•kg <sup>-1</sup> )	$\rho$ (kg•m <sup>-3</sup> )	Type	Refs
Paraffin wax	-12-90	128-250	880-950	Paraffin	[10] [11] [12]
Lauric acid	44	212	1007	Fatty acid	[11]
Stearic acid	54	157	940	Fatty acid	[10]
Palmitic acid	64	185	989	Fatty acid	[11]
Erythritol	117	340	1450	Polyol	[10]
Na <sub>2</sub> SO <sub>4</sub> ·10H <sub>2</sub> O	32	251	1420	Salt Hydrate	[13]
Na <sub>2</sub> CO <sub>3</sub> ·10H <sub>2</sub> O	33	247	1460	Salt Hydrate	[14]
Na <sub>2</sub> S <sub>2</sub> O <sub>3</sub> ·5H <sub>2</sub> O	46	210	—	Salt Hydrate	[15]
Ba(OH) <sub>2</sub> ·8H <sub>2</sub> O	78	255-256	2070	Salt Hydrate	[16]

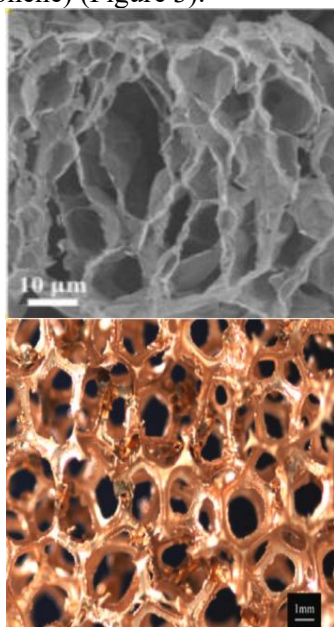
### 3.1 Organic Phase Change Energy Storage Materials

Common organic PCMs are divided into paraffin-based and non-paraffin-based types [2]. Paraffins (general formula  $C_nH_{2n+2}$ ) are extensively researched and industrially mature in the  $-50^{\circ}\text{C}\sim 200^{\circ}\text{C}$  range due to their unique molecular structure, excellent energy storage performance, and high safety. Their phase change temperature and thermal stability increase with hydrocarbon chain length, following Equation (1) (T: melting point; n: number of carbon atoms):

$$T = (415.5m/m - 94.4) - 273.15 \quad (1)$$

$$m = 2n + 2$$

During melting, paraffins absorb heat with a phase change enthalpy of 128~250 kJ/kg. They exhibit high chemical stability, a wide range of phase change temperatures, non-corrosiveness, and non-toxicity [3]. The main drawbacks limiting the application of paraffins—an inexpensive and abundant petroleum refining by-product—are their low thermal conductivity and tendency to leak. To address these issues, researchers are developing PCMs with stable chemical properties and enhanced thermal conductivity, mainly by incorporating thermally conductive materials or high thermal conductivity agents such as porous metal foams and carbon-based materials (expanded graphite (EG), graphene) (Figure 3).



**Figure 3. Partial Enlarged Views of Copper Foam and Expanded Graphite (EG)**

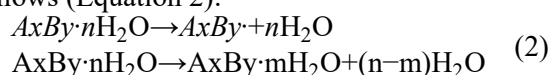
Adding highly thermally conductive metal foam can improve thermal conductivity. CUI et al. [4]

compared the thermal storage performance of pure paraffin wax (PW) and PW composite with high-porosity metal foam, finding that metal foam improved temperature distribution uniformity and reduced heat storage time. Dai et al. [5] designed a composite with PW and porous aluminum foam as the support skeleton; the composite retained PW's phase change temperature, with stable melting ( $61^{\circ}\text{C}$ ) and solidification ( $51^{\circ}\text{C}$ ) peaks, showing good physical properties.

Carbon-based materials, with thermal conductivity approximately five times that of metals, plus large specific surface area and light weight, are preferred for improving organic PCM thermal conductivity. Li et al. [6] employed a microwave irradiation method to encapsulate paraffin wax (PW) within expanded graphite (EG) pores, creating a binary composite. At an EG loading of 10%, the resulting material's thermal conductivity reached 3.7 W/(m·K), representing a 16.2-fold increase over pure PW, while also boasting high heat transfer efficiency and exceptional capacity retention (~100%) throughout thermal cycles. Wu et al. [7] reported that a Ag@EG/PW composite with 1% Ag exhibited enhanced thermal stability and a 292.5% higher thermal conductivity (0.989 W/(m·K)) than pure PW, showing promise for temperature-sensitive applications. Non-paraffin organic PCMs mainly include fatty acids, alcohols, esters, and polymers. Fatty acids, extracted from plant oils (palm oil, soybean oil) or animal fats, are natural renewable resources with the general formula  $\text{CH}_3(\text{CH}_2)_{2n}\text{COOH}$  (n: even number 12~28). They have relatively high melting points and stable chemical properties, with phase change temperature dependent on carbon chain length, but generally higher costs.

### 3.2 Inorganic Salt Hydrate Phase Change Energy Storage Materials

Inorganic salt hydrates (general formula  $A_xB_y \cdot n\text{H}_2\text{O}$ ) have attracted attention due to high thermal conductivity, high energy storage density, excellent flame retardancy, and low cost. During heat storage, when ambient temperature exceeds the melting temperature (MT), crystalline water is partially or fully released, and heat is absorbed; when temperature drops below MT, latent heat is released. Their behavior follows (Equation 2):



However, inorganic salt hydrates suffer from high-temperature liquid leakage, supercooling, and phase separation, shortening their service life. Current solutions for phase separation include compositing with porous supports, microencapsulation, and adding thickeners.

Porous materials form continuous thermal conduction pathways, enhancing heat transfer, and prevent liquid leakage via capillary forces, surface tension, and hydrogen bonding between the porous surface and hydrate molecules. Xin et al. [8] composited 3D flower-like  $\text{NiCoO}_4$ -modified expanded graphite (EG) with  $\text{Na}_2\text{CO}_3 \cdot 10\text{H}_2\text{O}/\text{Na}_2\text{HPO}_4 \cdot 12\text{H}_2\text{O}$  eutectic hydrate salt; the N-EG matrix exhibited excellent thermal conductivity ( $5.52 \text{ W/m}\cdot\text{K}$ ), high enthalpy ( $173.21 \text{ J/g}$ ), good thermal stability, and phase separation suppression. Jia et al. [9] developed a sodium acetate trihydrate (SAT) composite by incorporating modified expanded graphite (MEG), xanthan gum (XG), and a nucleating agent. This formulation significantly reduced the supercooling degree from  $10.6 \text{ }^\circ\text{C}$  to  $0.3 \text{ }^\circ\text{C}$ , enhanced thermal conductivity by 71%, and improved latent heat and cycling stability, thereby broadening its application potential.

Microencapsulation coats inorganic materials with a dense shell, isolating them from the external environment and preventing supercooling and phase separation

during heat absorption/release. Dong et al. [10] prepared  $\text{Na}_2\text{SO}_4 \cdot 10\text{H}_2\text{O}$ -core/polymethyl methacrylate (PMMA)-shell microcapsules by adjusting emulsifier and initiator ratios; optimal core-shell ratio yielded uniform particle size and phase change enthalpy of  $174.8 \text{ J/g}$ . Lu et al. [11] prepared  $\text{Na}_2\text{HPO}_4 \cdot 12\text{H}_2\text{O}@/\text{SiO}_2$  microcapsules (MPCMs) via interfacial polymerization, compounding with MXene to form MXene/MPCMs; the S1 sample (1 wt% MXene) achieved latent heat of  $156.64 \text{ J/g}$ , enhanced photothermal conversion and heat transfer rate, and reduced supercooling from  $14.2 \text{ }^\circ\text{C}$  to  $10.1 \text{ }^\circ\text{C}$ , suitable for solar thermal power generation and waste heat recovery.

Through porous material compositing and microencapsulation, inorganic salt hydrate PCMs can be better applied in thermal energy storage, building energy efficiency, textile processes, and waste heat utilization.

#### 4. Medium-Temperature Phase Change Materials

There is no unified international standard for medium-temperature PCM temperature classification; this paper adopts the practical application range of  $150^\circ\text{C}\sim 450^\circ\text{C}$ .

Medium-temperature PCMs, which primarily include metal/alloy and inorganic salt systems, find applications in waste heat recovery, solar power generation, and building energy conservation. Their phase change enthalpy and melting temperature are summarized in Figure 5.

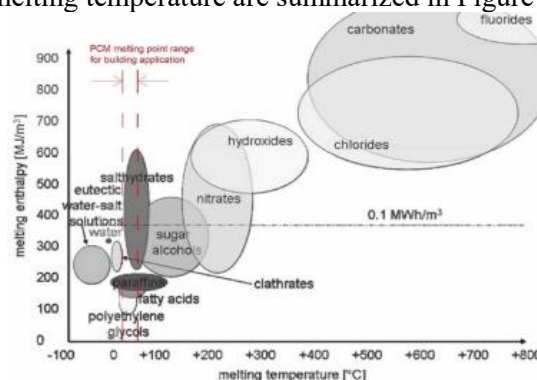


Figure 5. Phase Change Enthalpy and Melting Temperature of PCMs

#### 4.1 Medium-Temperature Molten Salt Phase Change Energy Storage Materials

Molten salts are classified by anion type into nitrates, carbonates, chlorides, etc. They offer high energy storage density, no supercooling/phase separation, excellent thermal conductivity, and easy operation, making them promising heat storage media for solar power generation.

Zhong et al. [12] added expanded graphite to  $\text{LiNO}_3\text{-KCl}$ ,  $\text{LiNO}_3\text{-NaNO}_3$ , and  $\text{LiNO}_3$ -based binary eutectic salts; modified composites showed 4.9~6.9 times higher thermal conductivity and excellent thermal stability.

Mixed molten salts, by adjusting component proportions, meet specific melting point requirements, offering higher energy storage density than single-component salts. To control costs, high-performance expensive salts can be mixed with cheaper ones; thus, binary/ternary eutectic salts or salt composites are more widely used than single-component salts in practical heat storage.

#### 4.2 Low-Melting-Point Metal and Alloy Phase Change Energy Storage Materials

Compared to salts and organic materials, metal PCMs have high thermal conductivity, high volumetric energy density, low supercooling, and long service life, making them excellent for

solar energy utilization, waste heat recovery, and large-scale energy systems. Current mainstream research focuses on pure aluminum (Al), Al-Si binary eutectic alloys, and Al-Mg-Zn ternary alloys.

Sheng et al. [13] synthesized microencapsulated Al–25 wt% Si using a three-step method. First, Al-Si microspheres underwent a 3-hour Böhmite treatment in boiling distilled water (pH 6–9 adjusted with  $\text{NH}_3 \cdot \text{H}_2\text{O}$ ) to form a precursor shell. Then, the sample was cooled to 75°C for 16-hour precipitation, and finally calcined at 1150°C for 6 hours under oxygen flow to form the final  $\text{Al}_2\text{O}_3$  shell. Thermal cycle tests (3000 cycles) showed the pH=8 sample had the best stability without shell breakage, demonstrating microencapsulation's effectiveness in improving Al-Si alloy thermal stability.

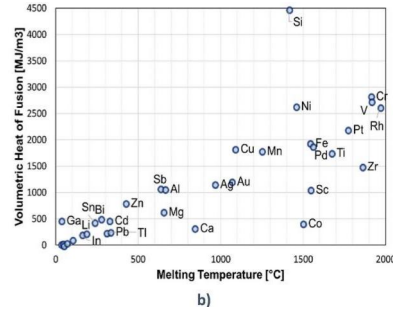
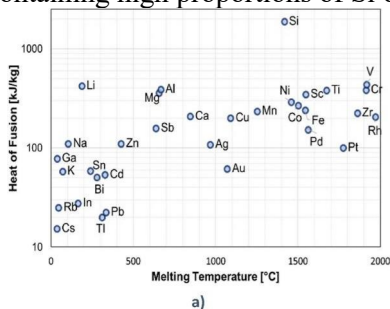
**5. High-Temperature Phase Change Materials**

High-temperature PCMs ( $T_m > 450^\circ\text{C}$ ) are mainly used in photovoltaic power generation, industrial waste heat recovery, aerospace, and industrial thermal management, categorized into metals/alloy systems, molten salts/composite salts, and high-temperature composite PCMs.

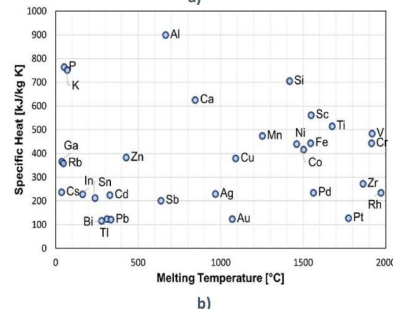
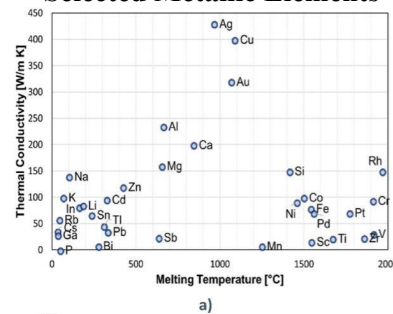
**5.1 High-Melting-Point Metal and Alloy Phase Change Energy Storage Materials**

The research on metallic and alloy phase change materials was first proposed in 1976. Relevant researchers verified their feasibility, prepared binary and ternary alloys, and analyzed their related thermophysical properties.

Costa Pereira [14] summarized metallic phase change materials (M-PCMs) thermophysical properties; Figure 6 presents the specific heat capacity and volumetric latent heat of fusion for selected metallic elements, while Figure 7 shows the thermal conductivity and specific heat capacity of some metallic elements. The prepared alloys had a phase change temperature range of 780~850 K, with optimal heat storage density when containing high proportions of Si or Al.



**Figure 6. (a)(b) Specific Heat Capacity and Volumetric Latent Heat of Fusion for Selected Metallic Elements**



**Figure 7. (a)(b) Thermal Conductivity and Specific Heat Capacity of Some Metallic Elements**

Sun et al. [15] explored the heat storage characteristics of Mg-25Cu-15Zn eutectic alloy ( $T_m=452.6^\circ\text{C}$ ); after 500 thermal cycles, phase change behavior and structure showed no significant changes, latent heat of fusion/solidification decreased by 6.65%/7.53%, and thermal conductivity increased from 120  $\text{W}/(\text{m}\cdot\text{K})$  ( $25^\circ\text{C}$ ) to the corresponding  $400^\circ\text{C}$  value, demonstrating excellent long-term thermal stability.

**5.2 Molten Salts and Composite Inorganic Salts**

Common molten salts include nitrates, chlorides, carbonates, fluorides, and multi-component mixed salts. In the 120–1000°C medium-to-high temperature range, molten salts and metal alloys, with high volumetric energy storage density, well-defined and widely distributed melting points, thermal conductivity superior to organic PCMs, and good high-temperature tolerance, are

ideal for phase change energy storage. However, leakage during phase transition limits their commercial application-causing thermal energy loss, reducing system efficiency, and posing safety hazards and equipment corrosion risks.

To address leakage, researchers have developed encapsulation technologies to prevent leakage, increase heat storage temperature/density, and enhance performance. Xiao et al. [16] prepared expanded graphite (EG)/binary nitrate composites via aqueous solution casting and ultrasonication; ultrasonication exfoliated EG into nano-sheets, improving uniform dispersion in nitrate solution. The composite's thermal conductivity was 2.15 times that of pure nitrate, with a slight reduction in latent heat.

The molten salt infiltration method is widely used in composite PCM preparation due to simplicity and broad applicability, but has limitations: strict requirements on porous matrix pore size/porosity and high energy consumption for high-temperature processing. In recent years, bio-inspired porous scaffolds-mimicking natural optimized structures-have provided new directions for technology upgrading.

### 5.3 Composite Phase Change Energy Storage Materials

Inorganic salt PCMs offer a promising solution for high-temperature thermal energy storage, owing to their favorable attributes such as a broad phase change temperature range, high storage density, good stability, and low cost. However, strong container corrosion and low thermal conductivity hinder large-scale engineering application. To address these issues, researchers commonly compound inorganic salts with porous materials to prepare shaped composite PCMs. Porous materials act as support skeletons with high porosity and specific surface area, providing abundant adsorption sites for molten salts, along with high-temperature and corrosion resistance, overcoming inorganic salt PCM application bottlenecks. Mainstream composite PCMs typically feature a porous matrix (e.g., metal foam, expanded graphite, porous ceramic, or clay mineral) impregnated with an inorganic salt.

Zhang et al. [17] used  $\text{NaNO}_3\text{-KNO}_3$  eutectic salt as high-temperature PCM, investigating heat transfer in energy storage devices via experiment and numerical simulation; metal foams enhanced heat recovery efficiency, but excessively high porosity copper/nickel foams reduced composite

thermal conductivity. Han et al. [18] prepared a high-temperature composite with high heat storage capacity, high thermal conductivity, and low leakage by immersing Al-12%Si alloy particles in silica sol, mixing with mullite powder, and sintering; the composite had a latent heat of 90.84 J/g, retaining 93.4% after 3000 thermal cycles (thermal conductivity value not provided in the original text).

These porous scaffolds restrain molten salt flow via capillary forces and surface tension, effectively mitigating leakage, serving as important technical means for industrial waste heat recovery, power peak shaving, and solar energy storage.

### 6. Future Major Challenges

With the deepening of national energy strategies, PCM demand is growing, with broad application potential in thermal energy storage and management (building energy efficiency, new energy, electronic cooling). However, large-scale practical application faces multi-dimensional challenges related to inherent properties, preparation processes, long-term stability, and engineering compatibility, summarized as follows:

- ① Low thermal conductivity is a common issue for most PCMs (especially organic PCMs and some hydrated salts), a major development constraint.
- ② Leakage affects some solid-liquid PCMs; developing high-performance, low-cost microencapsulation technologies is a current research focus.
- ③ Lack of unified testing standards leads to significant variations in thermophysical property data (thermal conductivity, phase change enthalpy, melting point) for the same PCM across studies. Establishing international test standards (sample pretreatment, equipment calibration, parameter calculation) and authoritative databases is necessary to provide reliable basis for PCM selection and system design.
- ④ Nanoparticles (graphene,  $\text{Al}_2\text{O}_3$ ) can enhance PCM thermal conductivity by 2–5 times, but cost and agglomeration issues need to be addressed. Additionally, research on hybrid nanoparticle synergistic enhancement is scarce; most studies focus on single nano-fillers, failing to leverage multi-component advantages.
- ⑤ Existing encapsulation technologies have

limitations: high raw material costs, uneven particle size in mass production, and low adsorption rates. Developing low-cost, highly sealed, cycle-resistant encapsulation processes is key to large-scale PCM application.

⑥ Mismatch often exists between PCM thermal performance (phase change temperature, heat storage rate) and TES system requirements. Future work should involve customizing PCM design (adjusting phase change temperature, optimizing thermal conductivity) based on specific TES scenarios and developing compatible structures between PCMs and system components (heat exchangers, piping).

⑦ Current research focuses on PCM thermal performance, neglecting environmental impact and recyclability. Most PCMs are discarded after use, causing resource waste. Establishing a full Life Cycle Assessment (LCA) system, evaluating environmental impact from production to disposal, and developing biodegradable, recyclable green PCMs are necessary.

⑧ AI technology can efficiently analyze large-scale data to match PCMs with specific scenarios, accelerating R&D, simulate PCM performance under various conditions to suggest optimization directions, and optimize preparation processes, reducing production inputs.

## 7. Conclusions and Outlook

Based on existing research and the current PCM technological landscape, key conclusions are drawn across four dimensions: material properties, technical challenges, R&D directions, and application prospects:

(1) **Material Characteristics and Application Suitability:** Different PCM types have distinct advantages and limitations. Organic PCMs, with suitable low-temperature phase transition ranges and good chemical stability, are valuable in building energy efficiency and electronic thermal management but are hindered by low thermal conductivity and flammability. Inorganic PCMs, with high latent heat and medium-to-high temperature suitability, are ideal for concentrated solar power and industrial waste heat recovery but face phase separation and supercooling issues. Metallic/alloy PCMs have excellent thermal conductivity and high volumetric energy density but are costly with relatively low latent heat, currently used mainly

in aerospace and other specialized fields.

(2) **Technical Bottlenecks and Research Gaps:** The PCM field faces multi-dimensional challenges: Firstly, lack of unified international thermophysical property testing standards leads to 10–20% deviations in key parameters (thermal conductivity, latent heat) across studies, undermining material selection and system design reliability. Secondly, nano-enhanced PCMs (NEPCMs) improve thermal conductivity but face high costs, nanoparticle aggregation, latent heat loss, and insufficient hybrid nanofiller synergistic research. Thirdly, encapsulation technologies struggle to balance low cost and high reliability: raw materials account for over 60% of microencapsulation costs, shape-stabilized composite encapsulation has limited adsorption capacity, and phase transition volume changes cause encapsulation failure. Lastly, composite PCM preparation is complex and lacks reproducibility, hindering practical application.

(3) **Future R&D Directions and Breakthrough Paths:** Efforts should focus on performance optimization, cost control, and safety/sustainability. At the material level, prioritize developing synergistic flame-retardant and thermal-conductivity enhancement technologies for organic PCMs, long-term anti-phase-separation/anti-supercooling solutions for inorganic PCMs, and high-latent-heat, low-corrosion PCMs for medium-to-high temperatures to fill material gaps. Technologically, establish international thermophysical property testing standards and authoritative databases, and leverage AI for PCM screening, performance simulation, and process optimization to reduce costs. From a sustainability perspective, develop a full PCM LCA system, biodegradable composite PCMs, and smart encapsulation technologies for greener, longer-lasting energy storage systems.

(4) **Application Prospects and Industrial Value:** As core thermal energy storage and management materials, PCMs have broad prospects under the "Dual Carbon" goals. With improved performance, cost reduction, and standardization, PCMs will play a critical role in building energy efficiency, renewable energy integration, and industrial waste heat recovery, enabling energy structure transformation and efficient utilization, supporting a low-carbon, sustainable energy system.

In the foreseeable future, with national energy

strategy progression and energy storage industry development, heat transfer enhancement technologies will continue to advance, and phase change energy storage technology will gain increasing attention and application.

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