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REVIEWPAPER

Latest Advances in PCMs (Phase Change Materials) for Thermal Regulation Applications: A Survey

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***Abstract*—Phase change materials have a wide range of possible uses, including thermal energy storage and temperature adjustment. This research classifies PCMs into three distinct types: organic, inorganic, and eutectic. It also details their usage, side effects, and advantages. Researchers examine PCMs' latent heat, thermal conductivity, density, and melting point, among other thermophysical characteristics, with a focus on ways to enhance them, such as by including metal foams for enhanced heat transmission. Furthermore, macro, micro, and nano encapsulation methods are presented as the main techniques to make the PHM migration impossible, raise the PHM stability, and make the integration into the real-world system easier. The combination of numerical modeling advancements, phase transition monitoring, and experimental methods has demonstrated that PCMs could be widely applied in the insulation of buildings, thermal energy storage, and even the cooling of high-tech equipment. This review has indicated the need for future research directed toward the scalability, durability, and smart integration of PCMs to be able to exploit their full potential in being part of the sustainable energy solutions.**

Keywords—Thermal Conductivity, Phase Change Materials (PCMs), Thermal Energy Storage, Renewable Energy Systems, Sustainable Energy Solutions.

I. INTRODUCTION

Renewable energy sources have been becoming more popular since the 1980s, and a lot of different groups have backed this trend [1]. The huge investment in renewable energy technology is driven by a number of factors, not the least of which is the depletion of traditional fuel sources. Polycrystalline solar cells with efficiency levels in the area of 47% [2], a figure that was thought to be impossible a decade ago, and wind turbine blades reinforced with polyester or epoxy are two more remarkable advancements.

A rise in the need for urbanized structures is a natural consequence of urbanization, which is characterized by its relentless expansion. But the building industry's energy use is a big societal problem now, limiting society's capacity to be sustainable [3]. Heating, ventilation, lighting, hot water supply, and home appliance use account for the vast majority of a building's total energy use, as do heat conduction [4], convection, and radiation [5].

As a result of supply and demand being intermittent and discontinuous, thermal energy management can be challenging and lead to low utilization efficiency [6]. In the last several decades, phase transition materials have found useful applications in thermal management [7]. Reversible phase transitions allow PCMs to store a great deal of heat in a compact volume, while conventional heat storage technologies lose the heat as latent heat. Because of PCMs, thermal management techniques have progressed into a reliable method of capturing thermal energy; these methods are renowned for their simplicity, ease of operation, and high energy storage density.

PCM a substance that can change its physical state (from liquid to solid, for example) and store thermal energy by absorbing or releasing huge quantities of latent heat [5]. Materials with this property may absorb, store, or release heat without altering their temperature in response to changes in their surrounding environment [8]. In the 1970s, this type of material was initially found and put to good use.

A. Structure of the Study

The paper is organized is as follows: The properties of phase transition materials, such as organic, inorganic, and eutectic techniques, are discussed in Section II. Next, Section III details the thermophysical properties of the PCMs in metal foam, density and thermal conductivity and stability. Further, Section IV explains Encapsulation strategies in PCMs, including microencapsulation, microencapsulation and nanoencapsulation. Section V reviews the existing literature on thermal regulation in PCMs. Finally, Section VI concludes the review and gives future directions.

II. CHARACTERISTICS OF PHASE CHANGE MATERIALS

PCMs and latent heat storage are two methods that materials might put the energy that they gain or lose as they change phases to use [9]. The main concept behind phase-shift energy storage is that energy can be taken in and then released. The melting point is an important limit for how much heat something can absorb or give off. The process of charging and draining is almost isothermal, which means that the temperature doesn't change much. This means that less heat is lost and the store medium's volume grows. Show the PCM categorization in Fig. 1.

Fig. 1. PCM Classification

A. Organic Phase Change Materials

Organic PCM can change states by absorbing and letting go of heat, going from solid to liquid or liquid to solid. These materials are mostly composed of paraffin waxes or fatty acids. In terms of energy storage, chemical stability, and safety, they are head and shoulders above the competition. During the melting process, the heat release is followed by solidification; at present, these materials are being explored for thermal management within the building insulation, textile, electronic cooling, and renewable energy system areas. Besides, the noncorrosive nature of these materials, coupled with the very large melting temperature ranges, not only makes them versatile but also enables easy integration into various types of technologies.

- **Paraffins:** One group of PCMs that is known for its chemical stability is paraffins, which are organic compounds [10]. Because it doesn't undergo significant changes during the phase transition, paraffin continues its effectiveness for many cycles. Eliminating supercooling is possible with paraffin since it melts at a constant temperature, which manages to eliminate supercooling.
- **Non-Paraffins:** There is a threefold difference in price between paraffin and nonparaffin PCMs [11]. Alcohols, glycols, non-paraffin fatty acids, acidic esters of these acids, and other such compounds are known as PCMs.

B. Inorganic Phase Change Materials

PCMs based on inorganic materials can have thermal instability, and this is especially true when the materials are subjected to repeated phase transformations. Consequently, the phase change characteristics, along with the PCM's efficiency, get worse gradually.

- **Microcapsules:** The prevention of PC microcapsules from supercooling is done by using large sizes for them. This suggests that bigger capsules might not be as likely to experience supercooling [12]. Large PCM microcapsules may require reevaluation for building applications due to changes in mixing-related interactions and distributions.
- **Salt Hydrates:** The salt hydrates, amongst the inorganic PCMs, are probably the most studied for their heat-conserving properties. Encasing PCMs and avoiding leakage or unwanted interactions include substances such as titanium dioxide, calcium carbonate, zinc oxide, and polystyrene [13]. Using a sol-gel procedure, they may be manufactured in varying quantities and pH levels, which allows researchers to study the effects of varied circumstances on encapsulating approaches.

C. Eutectic Phase Change Materials

Eutectic combinations exhibit certain characteristics that improve sustainability, comfort, and energy efficiency across several industries. The main reason they are the best phase-change materials is that their melting points are very low. Among these, binary systems have the lowest melting points.

- **Organic-organic Phase Change Materials:** Organic–organic eutectic PCMs are produced by mixing two organic compounds, for instance, fatty acids or paraffins, to get the desired melting point. The chemical stability being excellent and the toxicity being low are their main advantages that make it safe and trustworthy for various applications. Insulation, textiles, energy storage systems, and similar applications make extensive use of them despite their low thermal conductivity because of their many desirable characteristics, such as their low environmental effect and ease of handling.
- **Organic-inorganic Phase Change Materials:** Creating organic-inorganic eutectic PCMs means mixing organic parts with inorganic salts or hydrates to get the right heat performance. The combination outperforms the flourish of an origin in two respects: heat conductivity and energy densification. Despite the advantages, these materials might experience problems such as phase separation or incompatibility, which require careful formulation and stabilization techniques to make them reliable in the long run.
- **Inorganic-inorganic Phase Change Materials:** Inorganic-inorganic PCMs are used for most thermal management and precise melting temperature control tasks. They are made up of two or more inorganic pairs, like metal salts or salt hydrates. Such materials give rise to significant thermal storage capacity alongside very good heat conduction, which renders them suitable for heat storage and high-temperature applications to a large extent. Though there are some drawbacks like corrosion and supercooling that can occur, which imply that measures like protective coatings and usage of g additives to improve stability and performance need to be addressed in the long run.

Table I presents the classification table, including the advantages, challenges, and applications of all categories.

TABLE I. CLASSIFICATION OF PHASE CHANGE MATERIALS

Category	Sub-Type	Advantages	Challenges	Applications
Organic PCMs	Paraffins	High chemical stability, reliable over multiple cycles.	Lower thermal conductivity.	Building insulation, textiles, and electronics cooling.
	Non-Paraffins	Environmentally friendly options.	Higher cost (3× more than paraffins).	Thermal energy storage, temperature regulation.
Inorganic PCMs	Microcapsules	Lower risk of supercooling.	Uneven distribution during mixing in buildings.	Building materials, controlled heat release.
	Salt Hydrates	High heat storage capacity.	Potential for leakage; phase instability.	Solar energy storage, heating/cooling systems.
Eutectic PCMs	Organic–Organic	Low toxicity, eco-friendly, stable.	Lower thermal conductivity.	Textiles, insulation, energy storage.
	Organic–Inorganic	Enhanced energy density and thermal conductivity.	Risk of phase separation, compatibility issues.	Advanced thermal management systems.
	Inorganic–Inorganic	High latent heat & excellent conductivity.	Corrosion and supercooling issues.	High-temperature heat storage, industrial use.

III. Thermophysical Properties of Phase Change Materials (PCMs)

PCMs, a new type of thermal energy storage material, have become very popular lately because of big changes in the area. Improving the heat conductivity of PCMs is often done by adding highly conductive nano-additives.

A. Properties of PCMs Embedded with Metal Foam

Heat absorption, storage, and release capabilities are fundamental to several thermal energy storage-dependent applications. One order of magnitude more heat conductivity is displayed by metal foams in comparison to PCMs [14]. Furthermore, the metal foam's inner structure is very porous and disorganized, which speeds up the phase shift process without significantly lowering PCMs' ability to store heat. Because the foam joints are spread out, PCMs may melt and harden more evenly.

1) Effective Thermal Conductivity

Composite PCMs may experience an enhancement in their effective thermal conductivity through the incorporation of metal foam, which possesses exceptional thermal conductivity and a porous architecture. Predicting the thermal conductivity of phase change materials (PCMs) embedded within metal foam presents a challenge due to the intricate pore structure. An entirely new model is needed to explain the phase distribution of PCMs made from metal foam structures. The streamlined model of heat movement came with a blank sub-model. Using the equivalent thermal resistance method, the formula for effective thermal conductivity was then found. Using the TPS method, the thermal characteristics of four different porosity levels of copper-foam/paraffin have been taken into account. Among these characteristics are the thermal capacity, thermal diffusivity, and effective thermal conductivity. After inserting copper foam into paraffin, the results demonstrated a 25-fold improvement in effective heat conductivity compared to pure paraffin.

2) Convection

The ability of PCMs to move heat better could be greatly improved by using a metal foam that is good at conducting heat. A novel approach to improving convective thermal transfer can be achieved by using metal foam in small heat exchangers. This happens because the metal foam has a lot of surface area compared to its volume, and its passageways are twisted, which makes flow mixing better. Unfortunately, the metal foam prevents natural convection from reaching the liquid regions of the PCMs. PCM has a low thermal expansion ratio, is very thick, and has a high flow resistance; thus, buoyancy-driven velocities can't achieve the major convection.

B. Properties of PCMs on the basis of Density and Thermal Conductivity

A lot of progress has been made on renewable technology in the last several years as the globe moves away from dangerous and ecologically destructive ways of obtaining energy, such as fossil fuels. Energy systems that rely on wind and solar power, for example, are notoriously unreliable and unpredictable. Combining these energy-gathering methods with other current technologies allows them to be used and made available more extensively, which is essential for maximizing their potential.

1) Melting Point and Latent Heat of Fusion (Hfit)

DSC and DTA are two calorimetric methods that can be used to find the melting point and latent heat of fusion [15]. Equation (1) can be used to determine the latent heat of fusion for an n-component mixture. It does this by taking into account both the latent heat of each element and the difference in heat between their solid and liquid states:

$$H_f = \sum_{i=1}^{n} \left(H_f\right)_i \left(\frac{T_m}{T_i}\right) + T_m \sum_{i=1}^{n} x_i (C_{p,l,i} - C_{p,s,i}) \ln\left(T_m/T_i\right) \tag{1}$$

The mole fraction is x_i, the specific heat is C_pThe melting point of the element is T_i, and the melting point of the mixture is T_m.

2) Density

According to Vegard's law, Equation (2), the molar volume and molar fraction of the individual elements are stated to be in a straight-line relationship. The density of metal alloys in liquid form may be determined using this method:

$$\rho_l = \sum_i x_i M_i (\sum_i x_i \sqrt{\frac{M_i}{\rho_{li}}})^3 \tag{2}$$

The formula for the molar fraction and molar mass is given by x_i and ρ_l , respectively, where M_i denotes the liquid density.

3) Solar Water Heater

Solar water heaters are gadgets that use the sun's energy to heat water for different uses in homes, businesses, and factories. Among the main benefits of this heating method are lower electric bills, using green energy sources, and lower carbon footprint. This system of solar water heater uses a nearly evacuated tube solar collector to gain solar energy. Evacuated-type solar collectors with nanofluid in many ways outperform traditional collectors, among which are the increase in heat transfer rates, the better absorption and the excellent thermal conductivity of the nanofluid.

C. Temperature Regulation and Stability of the Composite PCM

Renewable energy sources need to be developed to satisfy power needs and reduce dependence on fossil fuels, and need to continuously deliver electricity, too [16]. There is a problem when some natural energy sources, like the sun and wind, aren't always available.

1) Indoor Temperature Regulation

The execution of the numerical simulations enabled the assessment of PCM-GBs' capacity to modulate interior air temperature and enhance thermal comfort. Everything about the PCM's melting and solidifying process, PCM-GBs' ability to attenuate temperature variations, and the preservation of the specified range of thermal comfort levels were accurately recreated from the experimental data. Taken as a whole, these findings demonstrate how crucial PCM is for managing indoor temperatures during hot and cold spells [17]. The PTC materials prevent the peak temperature from reaching its maximum. Thus, they delay the appearance of the peak, minimize the effect of variations, and keep the indoor air reasonably stable and rewarding. This is a significant part of the process of making energy use more efficient and, at the same time, keeping the room temperature within the desired limits.

2) Thermal Stability of the Composite PCM

The TGA was used to test how stable the hybrid PCM was at high temperatures. Example S8's (the composite PCM) TG curve is seen in Fig. 2. As can be shown, the composite PCM reaches its initial breakdown temperature of around 894 °C and 885 °C at heating rates of 5 and 10 K/min, respectively. At temperatures above 900°C, its decomposition rate accelerates. Used XRD to study the breakdown products in the composite PCM (S8) leftover material following the TG test (heated over 950°C). The three chemicals displayed in Fig. 3 are the primary byproducts of decomposition: MgO, Na2MgSiO4, and K2MgSiO4. After reaching 850°C, research on the breakdown of Na2CO3 revealed that it begins to dissolve at a sluggish rate. After reaching a temperature of 900°C, the gradual breakdown of K2CO3 begins. To add, there are two phases in the breakdown of Na2CO3 and K2CO3: (1) A2CO3 (l) = A2O (s) + CO2 (g); (2) A2O (l) = 2A (g) + ½ O2 (g), where A is either Na2CO3 or K2CO3. This leads us to believe that at very high temperatures, byproducts of breakdown such as Na2O and K2O may react with SiC and MgO. Thus, Na2MgSiO4 and K2MgSiO4 have been generated by the process. Still, further research into the chemical interaction that occurs during degradation is required [18]. Approximately 850°C is the maximum temperature that this composite has the potential to withstand, according to the preliminary thermal stability research that was mentioned before. One important area for future research is the material's stability over time and how quickly it degrades when broken down.

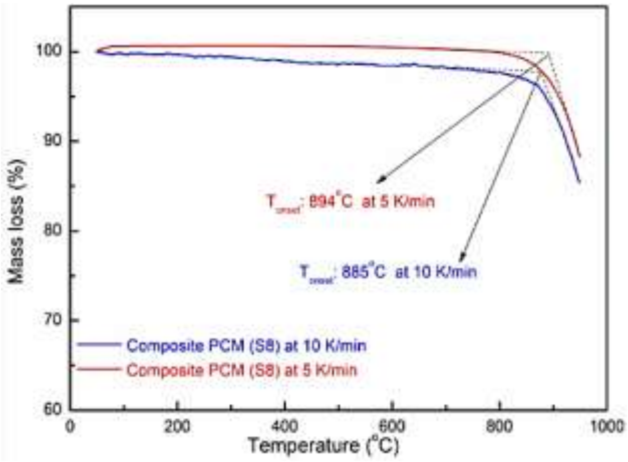

Fig. 2. TG Curve of the Composite PCM

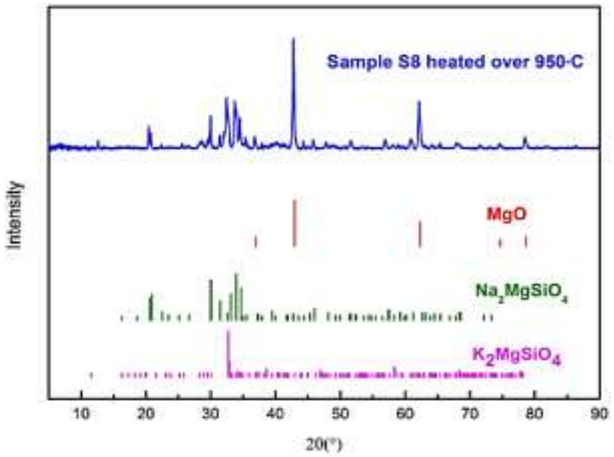

Fig. 3. XRD Patterns of composite PCM (S8) heated over 950°C.

IV. Encapsulation Techniques Applied in Phase Change Materials

The encapsulation method has the potential to make PCMs more integrated with the building structure and less prone to leakage issues. Encapsulation is a covert method of protecting a PCM from outside influences and leaks [19]. Improving the PCM's heat transfer area and thermal conductivity is essential for maintaining its function as a thermal storage material, and this process is critical for achieving that goal. Encapsulating PCM improves heat transfer efficiency, simplifies processing, and prevents leakage because to its increased surface area-to-volume ratio. There are primarily three types of encapsulations: macro, micro, and nano. Fig. 4 displays the several methods of PCM encapsulation in action.

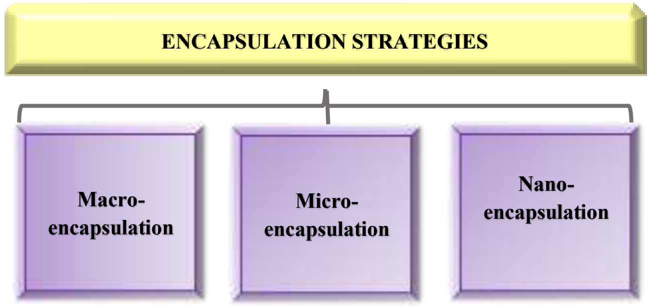

Fig. 4. Encapsulation Techniques

A. Macroencapsulation in PCMs

"Macroencapsulation" refers to the practice of enclosing and preserving a multitude of PCMs, ranging in weight from a few grams to several kilograms, within bigger structures such as spheres, panels, balls, or tubes. In addition to storing PCM, the containers that are suitable for this activity also give the PCM the mechanical support it needs. Thus, mild steel containers, tin-coated metal cans, and plastic bottles are the most preferred goods for economically viable alternatives. The corrosion problem can reach enormous dimensions if internal or external protective coatings are inadequate when mild steel is employed. The integrity of the container and the performance of the PCM are compromised by this. A certain way to help the environment is to employ PCM macroencapsulation in building projects. The geometry, thermal characteristics, and creative designs of macroencapsulated PCMs are among the many elements that affect their performance.

Fig. 5 shows a model of macroencapsulation that shows the pros and cons of this method, including.

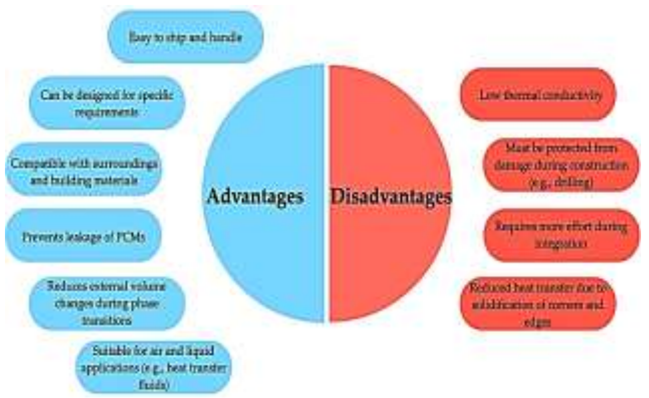

Fig. 5. Principal advantages and disadvantages of the macroencapsulation technique

B. *Microencapsulation in PCMs*

Microencapsulation is a method that involves the addition of tiny PCM particles, often measuring between 1μm and 1mm, to diverse temperature control applications that mainly need regulated temperatures between 10 and 80°C. High thermal conductivity, outstanding chemical and thermal stability, resistance to volume change, simplicity of introducing technology to construction materials, and great PCM control during phase changes are just a few of the numerous benefits of this approach. The technique also improves heat transfer due of PCM's higher surface area to volume ratio. Microencapsulation does have a few drawbacks, despite all of its benefits. The particles it contains make it hard for heat to travel through, it can damage building materials' mechanical qualities, and it's expensive to produce. Microencapsulated PCMs usually come in round or uneven shapes. Creating microencapsulated PCMs can be done in two main ways. Chemical methods use methods like the ones below, as shown in Fig. 6:

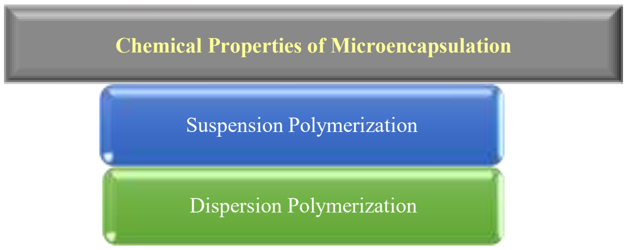

Fig. 6. Microencapsulation Chemical Properties

- **Suspension Polymerization:** Microcapsules' surface properties and form are affected by a combinatorial transition that includes particle coalescence, break-up, secondary nucleation, and monomer diffusion.
- **Dispersion Polymerization:** Controls the reaction duration, stabilizer concentration, initiator concentration, and monomer concentration to achieve the desired particle properties.

C. *Nanoencapsulation in PCMs*

The process of nanoencapsulation is integrating large amounts of PCM particles with nanometric dimensions, usually from 1 nm to 1 μm. When the size of the particles becomes so small that, in relation to their volume, they have very large surface areas, thus causing a more enhanced efficiency of heat transfer. Chemical procedures such as microencapsulation, in situ dispersion, emulsion techniques, suspension polymerization, and interfacial polymerization can also produce nano emulsions. A more modern method of encapsulating PCMs, nano-encapsulation, aims to solve problems including better heat transmission, stability during charging and discharging cycles, protection against leakage, and higher dependability [20]. Nano-encapsulation is a coating technique that makes use of nanoparticles, which are known as the core or active substance, encased in a secondary material called the matrix or shell to produce nano capsules, thereby creating a new product. The core contains the active ingredient, whereas the shell protects the core from the environment. The barrier can be either short-lived or lasting, and the center is usually liberated by diffusion or other means, such as pH or shear, which gives control over the movement to the right place at the right time. Nanotechnology has attracted much interest in the field of PCMs as a method for enhancing their thermophysical properties and life cycles.

V. Literature Review

The critical review points out that the performance of thermal regulation has been greatly improved by the recent developments in PCMs. Improvements in thermal management systems have resulted from studies that combine numerical simulations with experimental validation and from research that use comprehensive analytical methods.

Yuksel et al. (2025) focus on the impacts that the incorporation of PCM in a mosque building envelope would have on thermal comfort, energy use and CO2 output during the hottest summer months in Yalova/Turkey, which is in the 'Csa' Koppen-Geiger climate zone. The configurations that involved the use of 30 mm thick PCM (InfiniteRPCM25C) with a melting temperature of 25°C were: introducing it into the walls, the dome and both elements at the same time [21].

Song et al. (2025) introduce a sheath whose stiffness can be adjusted, inspired by a multi-layer wave spring structure, and made of thermoplastic material. A water-based heating/cooling technique that is active is used, in which the hot/cold water flows through the silicone tubes that are coiled around the VS sheath, allowing for quick temperature control. The selection of structural parameters of the VS sheath using the orthogonal design method has been done to improve the stiffness in the rigid state and to decrease the maximum stress in the flexible state during 90° bending [22].

Ki et al. (2024) objective is not only to reduce the free energy needed for the heterogeneous nucleation between the liquid metal and its substrate to the minimum but also to demonstrate a fast solidification path utilizing the copper backbone structure. Their method has shown an eco-friendlier thermal buffering effect as compared to the droplet-shaped LM/PDMS composites, which is seen through the spread of crystallization even at almost room temperature. The interconnected LM's thermal percolation and the excellent wetting properties between the LM and the CuGa2 intermetallic layer are the factors that make the porous-shaped LM/PDMS a strong contender for passive thermal management solutions [23].

Zhu et al. (2024) present a study that introduces a new measurement arrangement that combines in-situ resistance measurement and the wafer curvature method to simultaneously acquire the common parameters of resistance, reflectivity, and stress. Furthermore, an upgraded source measure unit module and a self-created multi-channel expansion module are drafted for fast batch testing, which make it possible to carry out simultaneous accurate multi-channel resistance measurements. The experiments with Ge2Sb2Te5, various batches of Sn15Sb85, and Ge2Sb2Te5/Sb7Se3 validated the system's performance, and the proposed system's capability to capture the complex phase transition systems' subtle behavior during crystallization was proven [24].

Zhou et al. (2024) study focuses on the temperature-induced crystalline phase transition behavior of iPP, first exploring the specific conditions for temperature-induced phase transition. Based on the determined conditions for temperature-induced phase transition, further research was conducted on the performance changes of iPP after constant-temperature phase transition treatment. The study indicated that as the temperature of the constant-temperature phase transition treatment was elevated, the transition from β phase to α phase became more complete along with an increase in melting temperature and no substantial influence on the crystalline properties [25].

Deng et al. (2023) a long-term mission of an autonomous underwater vehicle by creating a very efficient power system that uses ocean temperature gradients. created a hybrid energy harvesting system that enhances the performance of thermal gradient energy systems through the use of PCMs for buoyancy management and electrical storage. This system allows UUVs to operate more efficiently. The mechanism for converting hydraulics into electricity was prototyped [26].

Wang and Dai (2022) Using the genetic algorithm, it is possible to get a perfect combination of phase change material properties, according to the experimental optimization findings. The algorithm also produces more regulation hours and greater contribution rates than the PSO solution strategy. Finally, this proves that a genetic algorithm is the best way to deal with PCM room temperature in construction, allowing us to achieve the aims of better temperature and economy while keeping the reference value constant [27].

The most recent developments in PCM technology for thermal management, including their applications, integration techniques, and performance gains, are illustrated in Table II. The results conclude that heat management by employing PCMs could be achieved via both numerical and experimental means of optimization.

TABLE II. RECENT ADVANCES IN PHASE CHANGE MATERIALS FOR THERMAL REGULATION APPLICATIONS

Author & Year	Application Area	PCM Type	Integration Method	Main Outcomes	Innovations
Yuksel et al. (2025)	Mosque building envelope (thermal comfort & energy efficiency)	InfiniteRPCM25C (30 mm, 25 °C melting point)	Walls, dome, and both combined	Improved thermal comfort and reduction in energy consumption & CO_2 emissions during peak summer	Comparative evaluation of PCM placement zones for optimal building performance
Song et al. (2025)	Stiffness-tunable thermoregulating sheath	Thermoplastic material-based PCM	Active thermal regulation using hot/cold water through helical silicone tubes	Fast thermal regulation; stiffness enhancement and stress reduction during flexion	Multi-layer wave spring-inspired structure + orthogonal design optimization
Ki et al. (2024)	Passive thermal management materials	LM/PDMS (porous-shaped with $CuGa_2$-based Cu backbone)	Composite structure for enhanced percolation & crystallization	Sustainable thermal buffering & rapid solidification near room temperature	Establishing crystallization path + reduced nucleation free energy
Zhu et al. (2024)	Phase transition monitoring & measurement systems	Ge2Sb2Te5, Sn15Sb85, Ge2Sb2Te5/Sb7Se3	In-situ resistance & wafer curvature measurement system	Accurate detection of crystallization dynamics & complex phase transitions	Multi-channel advanced resistance measurement with batch testing capability
Zhou et al. (2024)	Temperature-induced phase transition of iPP	iPP (β-to-α crystalline phase)	Constant-temperature phase transition treatment	Higher treatment temperature led to more complete phase transition & increased melting point	Determined precise conditions for temperature-induced phase transition
Deng et al. (2023)	Ocean thermal energy harvesting for UUVs	PCM-based hybrid system	Buoyancy regulation + electrical storage mechanism	Efficient energy harvesting for long-term UUV missions	Dual-function PCM system & hydraulic-to-electric conversion prototype
Wang & Dai (2022)	Building energy optimization	PCM with variable attributes	Numerical optimization via genetic algorithm	GA showed superior regulation hours & contribution rate vs. PSO	Demonstrated GA-based optimization for temperature–economy balance

VI. CONCLUSION AND FUTURE DIRECTIONS

Thermal energy storage and renewable energy systems have been utterly transformed by PCMs, a really revolutionary technology. Energy conservation, temperature maintenance, and system endurance are greatly enhanced by PCMs due to their latent heat storage and nearly heat-free phase transitions. Metal foams, novel materials, and improved encapsulation methods have all contributed to recent advancements, some of which are associated with increased stability, adaptability, and thermal conductivity. But still, there are some problems to be solved such as getting rid of the long-term material breakdown, dealing with leakage, losing compatibility with host structures, and the problem of large-scale production. Besides, it is also necessary to assess the durability, incorporate the smart technology with real-time control systems, and conduct the lifecycle evaluation when considering the large-scale application and diverse climatic and industrial scenarios. Altogether, PCMs are likely to contribute a lot in terms of being one of the main pillars of thermal management technologies; hence, supporting the world in the direction of energy efficiency and environmental sustainability.

It is pointed out that future studies are to be done on durability of PCM, thermal conductivity improvement and large-scale integration of PCM in real systems. Smart encapsulation, nano structuring and AI-driven optimization can be the ways to further enhance PCM performance. A significant step toward more environmentally friendly energy storage and heat management in a variety of contexts can be the development of low-cost PCM.

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