Journal of
Refrigeration, Air Conditioning,
Heating and Ventilation

ISSN: 2394-1952
Volume 11, Issue 2, 2024
May–August
DOI (Journal): 10.37591/JoRACHV

https://journals.stmjournals.com/jorachv

Review JoRACHV

Polymer Phase Change Materials: Innovations, Applications, and Future Directions

Sudheesh Chandran R.[1,*], V.K. Jebasingh[2]

Abstract

Polymer-based phase change materials represent a significant advancement in energy storage and thermal management technologies due to their ability to absorb, store, and release heat during phase transitions. This article reviews recent innovations in polymer phase change materials, focusing on the synthesis, characterization, and performance enhancement techniques. The development of polymer composites with enhanced thermal conductivity, improved phase change enthalpy, and extended thermal cycling stability is discussed. Additionally, the integration of microencapsulation and nanocomposites has expanded the applicability of polymer phase change materials in various sectors, including building energy efficiency, electronics cooling, and textiles. In the building industry, polymer phase change materials are integrated into construction materials, enabling them to absorb excess heat during the day and release it at night, thus maintaining comfortable indoor temperatures with minimal energy use. Also, this article emphasizes how polymer phase change materials can improve sustainability and energy efficiency in a range of industries. Applications of polymer phase change materials are vast and diverse, ranging from thermal management in electronics and textiles to innovative uses in medical therapies and packaging. Emerging trends in the field are also explored, such as the incorporation of bio-based polymers to create sustainable and environmentally friendly phase change materials and the use of additive manufacturing to produce phase change material-integrated structures with tailored thermal properties. The manuscript further investigates the challenges in the commercialization of polymer phase change materials, including material cost, long-term stability, and thermal regulation efficiency. Further research directions are suggested, with an emphasis on the development of smart polymer phase change materials with tunable phase change temperatures and self-healing capabilities, as well as the exploration of new polymeric systems that can operate over a broader temperature range. The potential of phase change materials in contributing to global energy sustainability and reducing greenhouse gas emissions is underscored, positioning them as critical materials for the next generation of energy-efficient technologies.

***Author for Correspondence**
Sudheesh Chandran R.
E-mail: sudheeshchandran@yahoo.com

[1]Research Scholar, Department of Mechanical Engineering, Noorul Islam Center for Higher Education, Kumarcoil, Tamil Nadu, India.
[2]Associate Professor, Department of Mechanical Engineering, Noorul Islam Center for Higher Education, Kumarcoil, Tamil Nadu, India.

Received Date: August 06, 2024
Accepted Date: September 11, 2024
Published Date: September 21, 2024

Citation: Sudheesh Chandran R., V.K. Jebasingh. Polymer Phase Change Materials: Innovations, Applications, and Future Directions. Journal of Refrigeration, Air Conditioning, Heating and Ventilation. 2024; 11(2): 1–7p.

Keywords: Phase change material, polymer phase change material, form-stable phase change material, thermal conductivity, microencapsulated phase change materials.

INTRODUCTION

Background

Phase change materials (PCMs) have been increasingly recognized for their ability to manage thermal energy efficiently. These materials are extremely useful for applications in thermal energy storage and temperature management because they use their phase transition capabilities to absorb, store, and release enormous amounts of latent heat.

Traditional PCMs, such as paraffin waxes and salt hydrates, have been extensively studied and utilized. However, their limitations in terms of stability, compatibility, and environmental impact have driven the search for alternative materials.

Because of their customizable qualities, ease of processing, and intrinsic versatility, polymers have become a potential class of PCMs. Polymer PCMs can be engineered to exhibit specific thermal behaviors, making them suitable for a wide range of applications. These materials are designed to undergo phase transitions—typically from solid to liquid and vice versa—thereby absorbing heat during melting and releasing it during solidification.

Importance

The application of PCMs in energy storage and thermal management systems is crucial for achieving energy efficiency and sustainability goals. Polymer PCMs, with their customizable properties and broad applicability, are particularly promising for use in building materials, electronic devices, textiles, and other areas.

MECHANISMS OF POLYMER PCMS

Phase Change Process

Polymer PCMs utilize phase change processes to absorb and release thermal energy. The most common phase changes involve solid-liquid transitions, although solid-solid transitions are also explored for specific applications.

Solid-Liquid Transition

This involves the absorption of heat during melting (solid to liquid) and the release of heat during freezing (liquid to solid). This transition is characterized by a high latent heat capacity.

Solid-Solid Transition

In this process, the material changes between two solid phases. This can be advantageous as it avoids issues related to leakage in the liquid phase.

THERMAL PROPERTIES

The thermal properties of PCMs are critical to their effectiveness in thermal energy storage and temperature regulation applications. The effectiveness of polymer PCMs is determined by several key thermal properties:

1. *Latent heat of fusion:* The amount of heat absorbed or released by the material during the phase change (e.g., from solid to liquid or vice versa) at a constant temperature. A higher latent heat of fusion means the PCM can store more thermal energy per unit mass, making it more efficient for thermal storage applications. Organic PCMs like paraffin can have latent heats ranging from 100 to 250 kJ/kg, while inorganic PCMs like salt hydrates may have values around 150 to 400 kJ/kg.
2. *Thermal conductivity:* Heat transfer rate through a material is measured by its thermal conductivity. One problem for PCM applications is that polymers often have lesser heat conductivity.
3. *Melting point (phase transition temperature):* The specific temperature at which the phase change occurs, which can be tailored for different applications through chemical modification. The melting point should align with the desired operating temperature range of the application. PCMs are selected based on the target temperature for efficient thermal management. PCMs are available with a wide range of melting points, from as low as 30°C (for certain organic PCMs) to over 100°C (for many inorganic PCMs).
4. *Specific heat capacity:* The amount of heat required to change the temperature of the PCM by 0°C without undergoing a phase change. A higher specific heat capacity means the material can absorb more heat without changing temperature, which can be beneficial in applications that require stable temperature maintenance. The specific heat capacity of PCMs typically ranges from 1 to 4 J/g K.

5. *Thermal stability:* The ability of the PCM to maintain its thermal properties over many heating and cooling cycles. PCMs used in applications like building materials or electronics need to be stable over hundreds or thousands of phase change cycles to be cost-effective and reliable. Some PCMs may degrade or exhibit phase separation over time, which can reduce their effectiveness.
6. *Density:* The mass per unit volume of the PCM. Density affects the amount of material required for a specific energy storage capacity and influences the overall weight of the system. Organic PCMs generally have lower densities (around 0.7 to 0.9 g/cm^3) compared to inorganic PCMs (which can be over 1.5 g/cm^3).
7. *Thermal expansion:* The degree to which the PCM expands or contracts when it changes phase Thermal expansion needs to be managed, especially in encapsulated PCMs, to prevent damage to the containers or systems they are used in. Proper design of the PCM container and the system is required to accommodate volume changes during phase transitions.

These properties must be carefully considered when selecting a PCM for a specific application, as they directly impact the efficiency, reliability, and practicality of the thermal management solution.

CLASSIFICATION OF POLYMER PCMS

Organic PCMs

Organic polymer PCMs are based on materials such as paraffins, fatty acids, and polyethylene glycol (PEG). These materials are known for their high latent heat and customizable phase transition temperatures.

1. *Polyethylene glycol (PEG):* Exhibits high latent heat and a range of phase transition temperatures depending on molecular weight.
2. *Polycaprolactone (PCL):* A biodegradable polymer with phase change properties, suitable for biomedical applications.

Inorganic-Organic Hybrid PCMs

These materials combine the properties of inorganic salts with organic polymers, aiming to enhance thermal conductivity and stability.

1. *Salt hydrates in polymers:* Utilize the high latent heat of salt hydrates embedded in a polymer matrix to improve stability and prevent leakage.
2. *Polymer-encapsulated PCMs:* Encapsulation of PCMs within a polymer shell enhances thermal stability and prevents leakage during phase transitions.

APPLICATIONS

Polymer PCMs are increasingly used in various industries due to their ability to store and release thermal energy efficiently. This unique property allows them to play a crucial role in temperature regulation and energy conservation across a wide range of applications.

Building and Construction

One of the most significant applications of polymer PCMs is in the building and construction industry. These materials are integrated into building materials such as wall panels, insulation, and flooring to enhance thermal regulation. During the day, polymer PCMs absorb excess heat, reducing the need for air conditioning. At night, as temperatures drop, the materials release stored heat, helping maintain a stable indoor climate. This passive temperature regulation can significantly reduce energy consumption in buildings, leading to lower heating and cooling costs and contributing to sustainability efforts in the construction sector.

Thermal Management in Electronics

The miniaturization and increased power of electronic devices have led to challenges in managing the heat they generate. Polymer PCMs are used in thermal management systems to address this issue. These materials are incorporated into components like heat sinks, thermal interface materials, and castings to absorb and dissipate heat generated by electronic devices. By maintaining optimal operating temperatures, polymer PCMs help prevent overheating, extend the lifespan of electronic components, and improve device performance. Also, polymer PCMs are employed for heat dissipation in components such as batteries and processors. This prolongs the life of electronic gadgets and helps to maintain ideal working temperatures.

Textiles and Clothing

Polymer PCMs are also making their way into the textile industry, where they are used to develop temperature-regulating fabrics. These materials are embedded into fibers or coatings on fabrics to create garments that can absorb, store, and release heat based on the wearer's body temperature and the surrounding environment. This application is particularly valuable in outdoor and sportswear, where maintaining a comfortable temperature is essential. Polymer PCM-infused smart fabrics have the ability to control body temperature by absorbing excess heat and releasing it as needed. This application is particularly useful in clothing for extreme weather conditions. Additionally, PCM-infused textiles are used in medical garments to help manage body temperature during surgery or recovery.

Energy Storage Systems

In renewable energy systems, such as solar power plants, polymer PCMs are employed for thermal energy storage. During the day, these materials absorb heat from the sun, which can then be released during the night or cloudy periods to maintain a continuous energy supply. This application is crucial for improving the efficiency and reliability of renewable energy systems, helping to overcome the intermittency issues associated with solar energy. By storing excess heat and releasing it when needed, polymer PCMs contribute to more consistent and sustainable energy production.

Packaging and Cold Chain Logistics

In the packaging industry, polymer PCMs are used to maintain the temperature of perishable goods during transport, a critical aspect of cold chain logistics. These materials are integrated into packaging to absorb and release thermal energy, ensuring that products such as pharmaceuticals, food, and chemicals remain within the required temperature range throughout the distribution process. This application helps prevent spoilage, extend shelf life, and reduce the need for active cooling methods, making transportation more energy-efficient and cost-effective.

Medical Applications

Polymer PCMs are also utilized in various medical applications, particularly in temperature management during surgeries and in the design of medical devices. For instance, PCM-based cooling pads are used to maintain patient body temperature during and after surgical procedures, reducing the risk of hypothermia. Additionally, these materials are used in drug delivery systems where precise temperature control is necessary to maintain the stability and efficacy of temperature-sensitive medications.

Automotive Industry

In the automotive industry, polymer PCMs are used to improve the thermal comfort of vehicles. These materials are incorporated into seats, dashboards, and other interior components to absorb heat from the sun and release it when the vehicle cools down, helping to maintain a comfortable cabin temperature. Furthermore, polymer PCMs are used in battery thermal management systems to maintain the optimal temperature of electric vehicle batteries, enhancing their efficiency and lifespan.

Smart Windows and Intelligent Building Systems

Polymer PCMs are also used in smart windows and intelligent building systems that adapt to changing environmental conditions. In smart windows, PCMs are embedded within the glass to absorb and release heat, thereby regulating indoor temperatures and reducing the need for artificial heating or cooling. This technology enhances energy efficiency in buildings and contributes to the development of sustainable architectural solutions.

REVIEW ON POLYMER PHASE CHANGE MATERIALS

Hailong Hu [1] demonstrates the development and optimization of polymeric PCMs that enhance thermal conductivity and energy storage capabilities, crucial for flexible electronics and thermal energy storage systems. He presents various strategies to improve the thermal performance of PCMs, such as incorporating high thermal conductivity fillers and utilizing advanced fabrication techniques to create hierarchical and porous structures. The results indicate significant improvements in thermal energy storage density and flexibility, making polymeric PCMs highly suitable for modern electronic applications and efficient energy management solutions. Jian Liu et al. [2] investigates a novel Ethylene-Propylene-Diene Monomer-based PCM combined with expanded graphite for improved photo-thermal performance in solar thermal systems. It highlights the integration of SiO_2 aerogel as a thermal insulator, enhancing heat retention while allowing high light transmittance. Experimental and numerical methods demonstrated that the developed PCM can effectively heat over 200 liters of water during the day, showcasing its potential for efficient solar energy utilization. The results indicate significant improvements in tensile strength, enthalpy, and thermal conductivity of the new PCM. Naici Bing et al. [3] studied on form-stable phase change materials (FSPCMs) using unsaturated polyester resin (UPR) as the supporting matrix and expanded graphite (EG) as a thermal conductivity enhancer. The results demonstrate that the FSPCMs, specifically UPR/EG/PEG composites, exhibit excellent thermal stability, significantly improved thermal conductivity, and enhanced photo-thermal conversion efficiency, with the EG content playing a critical role. The developed FSPCMs show promising potential for solar energy storage and conversion, addressing the limitations of pure organic PCMs in solar thermal applications. Dimberu G. Atinafu et al. [4] presents the development of flexible, cost-effective polymer-supported phase change materials (FSPCMs) with enhanced thermal conductivity for solar energy storage and conversion. Using UPR as the support matrix, PEG as the PCM, and EG as a thermal conductivity enhancer, the study demonstrates that the composite materials exhibit excellent stability, leakage prevention, and improved thermal conductivity. The addition of 7 wt% EG significantly boosts thermal conductivity by 1150%, enhances photo-thermal conversion efficiency up to 93.3%, and reduces heating and cooling times by 67.1% and 51.4%, respectively. Kunjie Yuan et al. [5] developed a new polymer coated composite PCM by adding $CaCl_2 \cdot 6H_2O$/EG composite Particles with a photo curing polymer. The polymer coated $CaCl_2 \cdot 6H_2O$/EG composite PCM was produced has melting and freezing enthalpy values as high as 113.2 and 114.1 J/g, respectively. Dezhong Yin et al. [6] discusses the preparation of microencapsulated phase change materials (MePCMs) using Pickering emulsion polymerization with a polymer-silica hybrid shell. The experiment resulted in MePCMs with high thermal reliability, efficiency, and durability, demonstrating that Pickering emulsion polymerization is an effective approach for fabricating robust and efficient MePCMs for thermal energy storage applications. By employing 1-Octadecanol embedded in a hierarchical porous polymer (HPP), Jai Tang et al. [7] investigate the creation of a novel shape-stable PCM for latent heat thermal energy storage. The HPP, with its high porosity (91.9%), effectively absorbs 1-octadecanol (up to 75 wt%) enhancing thermal energy storage density and stability. The interaction between 1-octadecanoyl and the HPP reduces supercooling by up to 37% and maintains the stability of the material during phase transitions. This approach demonstrates significant potential for efficient thermal energy storage applications. Weifang Han et al. [8] introduces boron nitride foam (BNF) as a superior alternative to polymers for encapsulating PCMs used in thermal energy storage. BNFs, with their high porosity and low density, effectively encapsulate eutectic hydrated salts (EHS), preventing leakage and significantly enhancing thermal conductivity. The EHS/BNF composite exhibits high latent heat, low supercooling, and exceptional shape and thermal stability, maintaining performance over 100 thermal cycles. This research highlights the potential of BNFs to improve the efficiency and reliability of PCM-based energy storage systems. Si Wu et al. [9] reported a new technique to prepare extremely flexible, heat-conductive, and leak-proof polymer-ceramic composites (PCCs) by building dual polymer and graphite nanoplatelet networks as the PCMs functional matrix. To enable the high heat conductivity of PCCs, EG with a long chain structure in the composites generates an aligned and interconnected graphite nanoplatelet percolation network. Paraffin wax acts as the PCM, and the macromolecular olefin block copolymer forms a cross-linked polymer network to enclose the molten PCM and endow the composite film with flexibility. At EG loadings of 5–40 wt%, the radial thermal conductivities approach 4.2–3.8 W m^{-1} K^{-1}. The resulting flexible composite layer reduces a commercial lithium-ion battery's operating temperature by more than 12°C at high discharge rates, demonstrating effective and dependable thermal management capabilities. Jit Sarkar et al. [10] developed an innovative shape-stable PCM by utilizing leather waste in a polyurethane matrix. With 100% shape recovery ratios and self-healing this study presents a novel method for exploiting leather waste in shape stable PCM.

RECENT ADVANCEMENTS

Nanocomposites

The incorporation of nanoparticles into polymer PCMs has significantly enhanced their thermal conductivity and stability. Nanocomposites provide a pathway to overcome the limitations of conventional polymer PCMs.

1. *Carbon nanotubes (CNTs):* Adding CNTs improves thermal conductivity and mechanical strength.
2. *Metallic nanoparticles:* Incorporation of metallic nanoparticles like silver or copper enhances thermal conductivity.

Shape-Stabilized PCMs

Shape-stabilized PCMs are developed by integrating supporting materials that maintain the shape of the polymer during phase transitions, thus preventing leakage and improving mechanical properties.

1. *Porous supports:* Using porous materials like silica or polymer foams to contain the PCM.
2. *Crosslinking:* Chemical crosslinking of polymer chains to create a stable network that holds the PCM.

Biodegradable and Sustainable PCMs

With increasing environmental concerns, research has focused on developing biodegradable polymer PCMs from renewable resources. These materials offer an eco-friendly alternative to traditional synthetic polymers.

1. *Biopolymers:* Polymers obtained from natural sources, include cellulose, starch, and polylactic acid.
2. *Bio-based blends:* Blending biodegradable polymers with traditional PCMs to improve properties while maintaining sustainability.

CHALLENGES AND FUTURE DIRECTIONS

Challenges

1. *Thermal conductivity:* The inherently low thermal conductivity of polymers limits the efficiency of heat transfer. This remains a primary challenge.
2. *Cost and scalability:* Developing cost-effective and scalable production methods for polymer PCMs is essential for commercial viability.
3. *Long-term stability:* Ensuring that polymer PCMs maintain their properties over many phase change cycles is crucial for practical applications.

Future Directions

1. *Advanced composite materials:* Continued exploration of composite materials, including hybrid systems, to enhance the properties of polymer PCMs.
2. *Smart integration:* Integrating polymer PCMs with smart technologies and IoT devices for dynamic and responsive thermal management solutions.
3. *Sustainability focus:* To minimize environmental impact, PCM development should employ more renewable and biodegradable materials.

As research and development in polymer PCMs contribute, new applications are emerging, particularly in the fields of energy storage and smart materials. Innovations in PCM technology, such as the development of bio-based polymers and the integration of nanomaterials, are expected to further enhance the performance and expand the applications of these materials. Furthermore, polymer PCMs could play an even more significant role in advancing energy efficiency and sustainability across various industries.

CONCLUSION

Polymer PCMs offer significant potential for advancing thermal management and energy storage technologies. They can be used in a variety of applications, such as smart fabrics and construction materials, because of their adaptability and versatility. The goal of ongoing research and development is to improve the qualities of polymer PCMs and overcome existing obstacles, opening the door for creative and sustainable solutions across a range of industries.

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