A Review on Phase Change Materials in Cold Storage Applications

Selva Kumar Chellamuthu[1] Dr.K.Chinnarasu[2] Anisha R[3] Kaleeswari T[4] Ratish P[5]
[1]Assistant Professor [2]Associate Professor [3,4,5]UG Student
[1,2,3,4,5]Department of Agricultural Engineering
[1,2,3,4,5]PPG Institute of Technology, Coimbatore, India

Abstract — The study reviews the key characteristics of PCMs, such as their high latent heat capacity, thermal stability, and ability to maintain a constant temperature during phase transitions. By integrating PCMs into the design of cold storage systems, researchers and engineers aim to enhance thermal inertia, reduce temperature fluctuations, and mitigate the impact of external temperature variations. Additionally, the study investigates various types of PCMs, including organic, inorganic, and eutectic formulations, assessing their suitability for different cold storage applications. Furthermore, the research examines the impact of PCM-enhanced cold storage on energy efficiency, operational costs, and overall sustainability. Insights into the design considerations, material selection, and practical implementation of PCM-based solutions are discussed, emphasizing the potential for significant improvements in energy consumption and environmental impact.

Keywords: Phase Change Materials (PCM), Latent Heat, Thermal Energy Storage, Phase Transition, Sustainable Energy

I. INTRODUCTION

Phase Change Materials (PCMs) represent a cutting-edge technology at the forefront of thermal energy storage and management. Rashid FL, Al-Obaidi MA, Dulaimi A, Bernardo LFA, Redha ZAA, Hoshi HA, Mahood HB, Hashim A (2023) These materials have gained widespread attention due to their unique ability to store and release significant amounts of energy during phase transitions, contributing to enhanced temperature control and energy efficiency in various applications.

At the core of PCM technology is the principle of latent heat, where the material undergoes a phase change—typically from solid to liquid or vice versa—at a specific temperature. This phase transition (Figure 1) allows PCMs to absorb or release thermal energy while maintaining a nearly constant temperature, making them invaluable in addressing challenges related to temperature fluctuations.

The versatility of PCMs finds application across diverse industries. In cold storage scenarios, PCMs play a pivotal role in stabilizing temperatures, mitigating energy consumption, and preserving the integrity of temperature-sensitive products. Mariela Vega, Paula E. Marín, Svetlana Ushak, Stan Shire(2024) Similarly, in building and HVAC systems, PCMs contribute to more efficient temperature regulation by absorbing excess heat during warm periods and releasing it when cooling is needed.

This introduction aims to set the stage for a deeper exploration into the characteristics, classifications, and applications of Phase Change Materials. As we delve further, we will unravel the intricacies of how PCMs are reshaping the landscape of energy storage and thermal management, offering sustainable solutions to pressing challenges in fields ranging from construction to logistics and beyond.

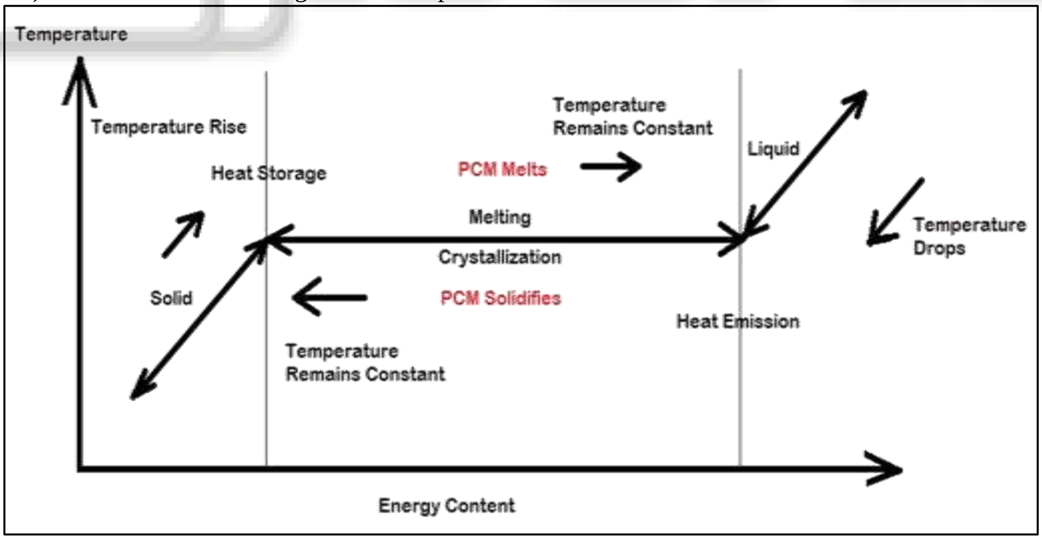

Fig. 1: Phase Change Process

II. CLASSIFICATIONS OF PCM

Phase Change Materials (PCMs) can be classified Figure 2 based on various criteria, including their origin, chemical composition, thermal properties, and applications. Here is a classification of PCMs based on different aspects:

A. *Chemical Composition*

Organic PCMs are derived from organic compounds, such as paraffins and fatty acids. They exhibit a wide range of melting points and high latent heat of fusion. Inorganic PCMs comprised of inorganic substances like salt hydrates and metallic alloys. Inorganic PCMs often have higher thermal conductivity compared to organic PCMs.

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Natural PCMs are obtained from natural sources, such as fatty acids from plants or animals. Synthetic PCMs are produced through chemical synthesis, including paraffins, salt hydrates, and other artificial materials.

B. Thermal Properties

H.M. Teamah (2024) High Temperature PCMs are designed for applications requiring phase change at elevated temperatures, such as solar thermal energy storage. Low Temperature PCMs are suited for applications with phase change occurring at lower temperatures, such as refrigeration and cold storage.

C. Phase Transition Range

Narrow Range PCMs exhibit phase change within a specific temperature range, suitable for applications with precise temperature control requirements. Wide Range PCMs undergo phase transition over a broader temperature range, providing flexibility in various applications.

D. Application Specific

In Building applications, PCMs used for thermal regulation in buildings, enhancing energy efficiency and comfort. Ali Uysal, Ali Keçebaş, Muhammet Kayfeci (2023) In Electronics cooling, PCMs applied for cooling electronic devices and preventing overheating.

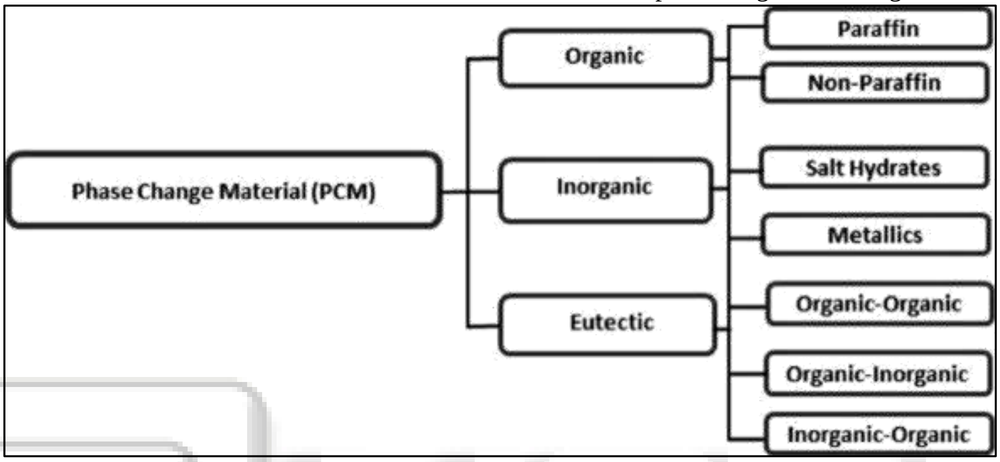

Fig. 2: Classification of PCMs

For Textile Industry, PCMs are integrated into fabrics for temperature-regulating clothing. In Cold storage, PCMs employed in refrigeration and cold chain applications to stabilize temperatures.

III. SELECTION CRITERIA

Temperature Range: Identify the specific temperature range required for the cold storage application. PCMs have different melting points, and choosing one with a phase transition temperature within the desired range (Table 1) is crucial for effective temperature control.

Consider the latent heat of fusion, which indicates the amount of thermal energy absorbed or released during the phase change. Higher latent heat values generally lead to better thermal storage capacity, enabling PCMs to store more energy per unit mass.

Bogdan Marian Diaconu, Mihai Cruceru, Lucica Anghelescu (2024) Evaluate the thermal conductivity of the PCM, as it influences the rate at which heat is transferred during the phase change process. Higher thermal conductivity helps in distributing heat more efficiently, reducing temperature fluctuations in the storage environment.

Assess the PCM's ability to undergo repeated phase transitions without significant degradation. Lunxiang Zhang, Xinran Xia, Yuan Lv, Fan Wang, Chuanxiao Cheng, Shi Shen, Lei Yang, Hongsheng Dong, Jiafei Zhao, Yongchen Song (2023) A durable PCM with good cycle stability is essential for long-term and reliable performance in cold storage applications.

Ensure that the chosen PCM is compatible with the materials used in the cold storage system, including containers, pipes, and any other components. Compatibility issues can lead to material degradation or performance issues.

Consider the density and volume expansion characteristics of the PCM, as these factors can impact the design and storage capacity of the system. Some PCMs may experience volume expansion during the phase change, which must be accommodated in the storage design. Evaluate the cost-effectiveness of the PCM, considering both initial investment and long-term operational costs. Additionally, assess the availability of the chosen PCM in the required quantity for the application.

Consider the environmental sustainability of the PCM. Bio-based or eco-friendly PCMs derived from renewable resources might align with sustainability goals and reduce the overall environmental impact of the cold storage system.

The below table (Ali Uysal, Ali Keçebaş, Muhammet Kayfeci (2023)) comprises of properties of available different Phase Change Materials.

	Organic Paraffin	Organic Non-Paraffin	Inorganic Salt Hydrates	Inorganic Metal Eutectics
Melting Temp (°C)	-12 to 187	<150	20 – 140	30 – 125
Latent Heat (J/m3) x 106	190 – 240	140 – 430	250 – 660	300 – 800
Density (Kg/m3)	~810	900 – 1800	900 – 2200	~8000

Thermal Conductivity (W/m°C)	~0.25	0.2	0.6 – 1.2	~20
Toxicity	No	Some Are	Highly	Some Are
Corrosion	Low	Some Are	Highly	Some Are
Congruent Melt	Yes	Some Do	Most Some Do	Yes
Supercool	No	No	Most Do	No

Table 1: Properties of Phase Change Materials

IV. APPLICATIONS

Phase Change Materials (PCMs) offer versatile applications in cold storage environments, enhancing energy efficiency, temperature stability, and overall performance. PCMs play a crucial role in maintaining the required temperature during the transportation of temperature-sensitive goods, such as pharmaceuticals, vaccines, and perishable foods, within the cold chain. They help mitigate temperature fluctuations and ensure product integrity. Integration of PCMs in refrigeration systems can enhance energy efficiency by reducing the workload on traditional cooling systems. PCMs absorb and release heat during phase transitions, stabilizing temperatures and reducing the need for constant compressor operation.

PCMs can be incorporated into the building structure of cold storage warehouses to regulate internal temperatures more effectively. This leads to reduced energy consumption for cooling systems and improved temperature control for stored goods. PCMs are used in ice storage systems to store thermal energy during periods of low energy demand. The stored energy can then be released during peak demand periods, reducing the load on the electrical grid and optimizing overall energy usage.

PCMs act as thermal energy storage units, absorbing excess thermal energy during low-demand periods and releasing it when demand is higher. This application is beneficial for balancing energy loads and managing energy consumption in cold storage facilities.

Bingbing Meng, Xuelai Zhang, Weisan Hua, Lu Liu, Kunlin M (2022) PCMs are integrated into packaging materials to create temperature-regulating containers for the shipment of temperature-sensitive products. This application is particularly valuable for maintaining the quality of pharmaceuticals, biological samples, and certain food items during transit. In the food industry, PCMs can be employed for temperature-controlled storage of perishable goods. By stabilizing temperatures within refrigerators and cold rooms, PCMs help extend the shelf life of products and minimize food waste. Naeim Farouk, Abdullah Alhumaidi Alotaibi, Abdullah H. Alshahri, Khalid H. Almitani (2022). PCMs can be integrated into heating, ventilation, and air conditioning (HVAC) systems to optimize energy efficiency. They assist in reducing the overall energy consumption of HVAC systems by storing and releasing thermal energy as needed.

PCMs are available in a variety of formulations with different melting points and thermal characteristics. This allows for the selection of PCMs tailored to specific cold storage requirements, providing flexibility in design and application. Some PCMs are derived from renewable or bio-based sources, contributing to the development of environmentally sustainable cold storage solutions. The use of eco-friendly PCMs aligns with green building practices and corporate sustainability goals.

The advantages of using Phase Change Materials in cold storage applications make them a promising technology for achieving more efficient, cost-effective, and environmentally friendly solutions in various industries.

V. LIMITATIONS

While Phase Change Materials (PCMs) offer numerous advantages in cold storage applications, there are certain limitations and challenges that should be considered. PCMs have specific phase change temperatures, and their effectiveness is limited to the range defined by their melting and freezing points. In some cases, finding a PCM with the precise temperature range required for a specific application can be challenging. The thermal conductivity of some PCMs may be lower than that of traditional building materials. This can result in slower heat transfer rates, potentially affecting the overall efficiency of temperature control systems, especially in large-scale applications.

The efficiency of PCMs depends on their ability to transfer heat to and from the surrounding environment. Rashid FL, Al-Obaidi MA, Dulaimi A, Bernardo LFA, Redha ZAA, Hoshi HA, Mahood HB, Hashim A (2023) In some cases, the surface area available for heat exchange may be limited, impacting the rate at which thermal energy is absorbed or released. Depending on the specific PCM used, the weight of the storage system may increase. This can be a concern in applications where weight is a critical factor, such as in transportation or portable refrigeration.

VI. CONCLUSION

In conclusion, the study on the usage of Phase Change Materials (PCMs) in cold storage applications underscores the transformative potential of this innovative technology. Through meticulous examination of PCMs' thermal properties, cycle stability, and compatibility with existing infrastructure, we have illuminated their significant impact on enhancing energy efficiency and temperature control in cold storage systems.

The versatile applications of PCMs, ranging from cold chain logistics to refrigeration, present a promising avenue for sustainable and cost-effective solutions. The ability of PCMs to stabilize temperatures, mitigate energy consumption, and contribute to peak load management positions them as a key player in addressing the challenges faced by diverse industries, such as pharmaceuticals, food preservation, and data canter cooling.

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