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Review on Thermal Energy Storing Phase Change Material-Polymer Composites in Packaging Applications †

Tejashree Amberkar * and Prakash Mahanwar

Department of Polymer and Surface Engineering, Institute of Chemical Technology, Mumbai 400019, India; pa.mahanawar@ictmumbai.edu.in

* Correspondence: tejuamberkar@yahoo.co.in

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Abstract: Thermally sensitive food and pharma packages are maintained at desired temperatures using refrigeration systems. These systems are powered by non-conventional energy resources. They provide uneven cooling in large containers. Interruption in their functioning during supply chain activities increases their energy requirements. Studies revealed that using phase change material (PCM)-polymer composites in refrigeration systems and packaging containers curtailed energy utilization for maintaining a consistent temperature. These composites maintain a temperature around its phase change temperature by absorbing or releasing latent heat. This review discusses different designs of PCM-polymer composites that maintain the temperature of big shipments and small containers.

Keywords: phase change material; thermal energy storage; latent heat

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1. Introduction

Temperature-controlled packaging is a high-growth sector with a predicted compounded annual growth rate of 18.14% until 2026 [1]. The surge in demand is mainly expected to result from temperature-controlled vaccine packages, biologics, and small e-commerce packages. During the COVID-19 pandemic, the increased demand for temperature-controlled packaging is for biopharma products. The traditional methods for controlling shipment temperatures involve active and passive temperature control methods. Active systems consist of cooling arrangements facilitated by electricity or fuel. The excessive use of these systems results in the consumption of high amounts of non-renewable energy, which ultimately impacts the environment in the long term. One more disadvantage of active systems is temperature excursion during transport activities. These activities, such as transferring goods to carriers at the shipping dock or airport, improper handling of goods by unskilled labor, schedule changes, excessive or low amounts of coolant, mechanical damage, etc., can vary temperatures beyond the decided limits. Such disrupted supply chain systems can spoil food and lifesaving pharma products, such as vaccines and biologics.

On the other hand, passive systems are more energy-efficient and environmentally friendly for storing temperature-sensitive products than active systems. Passive systems use coolants, such as ice packs, gel packs, and PCMs, along with insulation material to maintain the required temperature. PCMs can absorb, store, or release latent heat while undergoing phase transition and maintain the product in the predetermined temperature range. PCMs incorporated in refrigerated active packaging systems have maintained temperatures at the desired levels for as long as ten days in the absence of electricity [2]. PCM-incorporated refrigeration systems have also shown reduced temperature fluctuations. This reduced power demand results in energy savings. PCMs in conjunction with insulators can be used in mobile vaccine, food, and e-commerce containers. These passive containers can be charged once in the phase transition temperature range and can be used for a couple of hours without electricity. PCM-incorporated shippers decrease the cost of smaller shipments and achieve optimum performance. To understand the workings of PCM-incorporated packaging systems in detail, this paper is divided into two sections. The first section is dedicated to innovations using PCMs in increasing the refrigeration efficiency of large container shipments. The second section provides information about recent developments in small container packages.

2. Large Container Shipments

Refrigerator vehicle trucks are commonly used for transporting thermally sensitive goods in every part of the globe. However, variations in temperature across different territories and times of the day increase the power requirements of refrigeration. Higher temperature variation between the external and internal walls of the container increases the number of compression cycles and reduces its operation time. Such a working style necessitates frequent replacement of the compressor. Refrigerants used in compressors are greenhouse gases; thus, the increased use of compressors poses a significant risk of greenhouse gas leakage in the environment. Further, a significant amount of energy is spent on operating refrigerators with high temperature gradients between external and internal environments. Increasing the efficiency of refrigerator systems will be helpful for the environment. PCMs used in the walls of large shipment containers, such as refrigerated trucks and bulk pallet shippers, have increased energy efficiency by significant levels. The placement of PCM cold plates for trucks is as shown in Figure 1. Many researchers observed improvements in the thermoregulation of packaged goods by incorporating PCM plates in big shippers. Thus, PCM-incorporated bulk shippers are commercialized and used for transporting thermosensitive products. Though the initial investment cost for these shippers is high, the assembly has proven to be cost-effective for long-term usage over conventional shippers. PCM RT 5 was inserted into cold storage plates [3]. Each cold plate carried 126 kg of PCMs. Nineteen of such cold storage plates were placed on the roof, and one was placed in the upper part of the front wall side of the refrigerated container, with dimensions as per ISO 40. The container was insulated with 100 mm of polyurethane foam. The refrigerant passed through the fin tube to charge the PCMs. It took 6 h to fully charge a PCM-stored cold storage plate to its phase transition temperature. After that, it maintained the temperature below 12 °C for 14 long hours without using a diesel-run refrigeration system. This system was more expensive than diesel-run refrigeration systems due to the high cost of PCMs. However, its operation cost was 61.9% less than conventional systems. This means that the initial high-cost payback is 0.58 years. The container was flexible to use on the road and rail tracks.

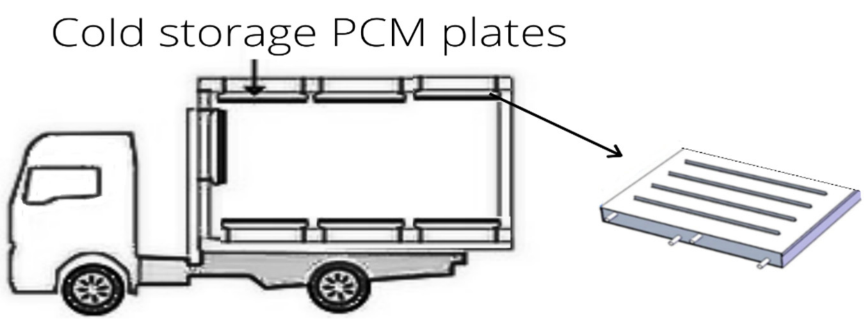

Figure 1. Placement of PCM plates in a truck.

A truck with two chambers filled with different PCMs was constructed [4]. The compartments had PCMs with phase transition temperatures of 2.34 °C and −15 °C. The compartments maintained the phase change temperature without an external power supply for 9.2 h and 6.2 h, respectively. A six-ton truck was equipped with six thin PCM cold plates [5]. Each plate consisted of 35 kg of PCMs. The cooling performance of three different PCMs was tested. The E26 PCM performed superiorly. It provided a high melting time of 17,200 s at a truck speed of 81 km per hour and 18,400 s for a stationary truck. The moving truck increased heat transfer and reduced melting time. The PCM maintained the temperature for a 491 km distance at a 110 km per hour truck speed. Thus, it helped in minimizing the use of refrigeration systems. Radebe and Huan reported that PCM eutectic plates with a salt-water solution could be incorporated into trucks transporting agricultural goods for temperature maintenance [6]. The use of PCMs maintained the temperature inside of the truck to the desired level, thus preventing the degradation of agro products.

Principi et al. [7] used PCMs in two ways to lower energy consumption. The team had incorporated PCMs with a phase transition temperature of 35 °C near the outer boundary of the refrigerated truck. The PCM layer acted as a thermal buffer and prevented solar heat from reaching the inner surface of the truck. The maximum time delay for the heat to reach the interior was 4.3 h. It allowed 8.57% less heat to reach the truck's interior than the control reference. Heat reduction curtailed the refrigerator's energy requirement for maintaining the interior temperature; this is the reason for the efficient energy consumption of the PCM-incorporated heat exchanger refrigerator. During the OFF time of the compressor, the heat was absorbed by the PCMs to liquefy at 5 °C. During the ON time, the heat released by the PCMs was absorbed by evaporator outlet air. Therefore, during the OFF time of the compressor, the PCMs maintained the temperature longer. The PCM freezing process increased the start time of the compressor. The summation of these two effects resulted in a lower number of compressor cycles and increased the duration of the operation. This change in the cycles' working reduced the energy demand of the compressor by 16%. Fioretti et al. [8] studied the effect of adding PCM panels near the outer boundary of the cold room. The thermal testing carried out on the prototype helped to determine the PCM's performance in actual reefer containers. In this test, PCM panels along with polyurethane foam sheets were enclosed within metal sheets, and their thermal performance results were compared with the reference control sample. The reference panel did not contain PCM sheets. The arrangement of the prototype panel can be better understood using Figure 2. When these panels were attached to cold room walls on external sides, the resultant heat reduction saved energy by 4.7%.

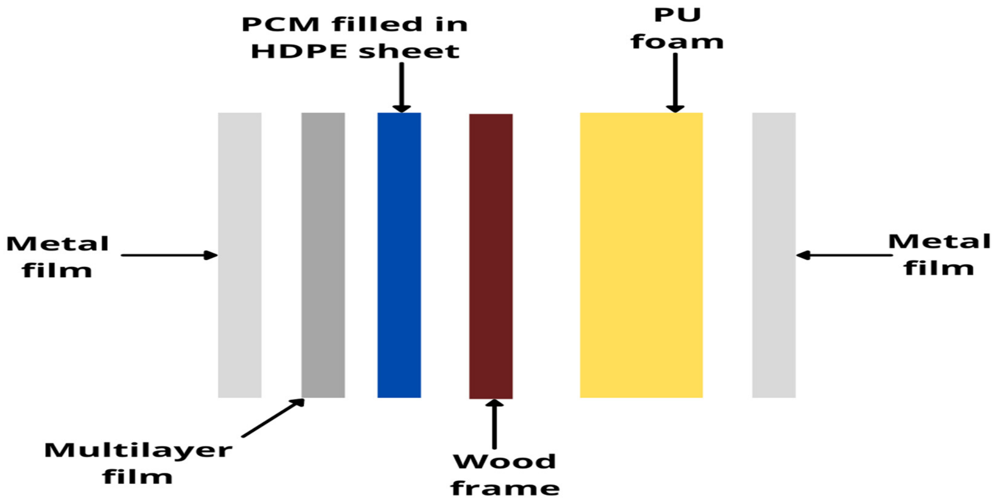

Figure 2. PCM panel.

The transport air conditioning systems' efficiency levels were improved by using serrated fins on the air side and perforated straight fins near the PCM [9]. The discharging performance is the indicator of the temperature maintenance of the system. The designed device had a discharging depth of more than 97% and could cool down the environment in seconds. The compactness and high heat transfer performance of the system will be beneficial for use in reefers. A compact PCM-incorporated air conditioner (AC) design was created for space-sensitive transportation refrigeration systems [10]. The assembly consisted of rectangular straight perforated fins in PCM chambers. Air channels with serrated fins were positioned orthogonally to the PCM chamber. Both the chamber and channel were periodically connected to the clapboard to provide a compact structure. The structure provided emergency cooling at a rate nine times higher than conventional AC systems and reduced temperature fluctuation to a lower value of 2.56 °C compared to 4.3 °C for conventional systems.

3. Small Container Packages

PCMs or microencapsulated phase change materials (MPCMs) are filled in rigid containers or flexible pouches. These PCM slabs can be used with or without insulation material in small containers to maintain the temperature of packaged products without electricity. These assemblies can be better understood using Figure 3.

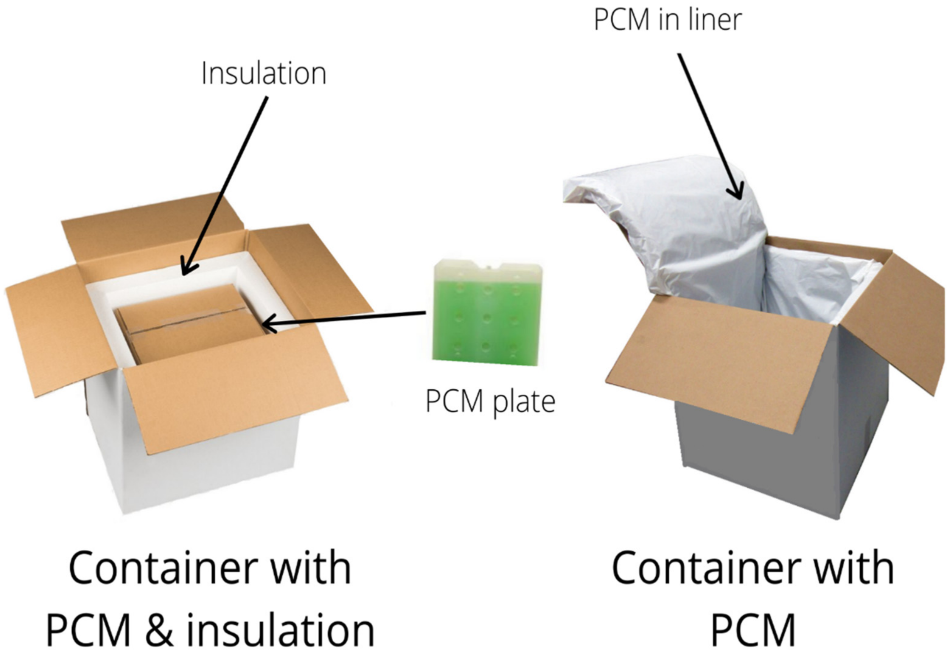

Figure 3. Small container packages with PCM plates and insulation versus PCM liners only.

These assemblies maintain the temperature of packaged products near the phase transition temperature of the PCM. The literature, in which PCM-incorporated small containers' heat transfer performance is studied, is discussed in this section. In one study, RT 6 PCM was encapsulated into porous calcium silicate [11]. This shape-stabilized PCM had a high melting enthalpy of 174 J/g at 8 °C. It maintained the shipment temperature at the desired level for 4–9 h in the ambient atmosphere. Sodium chloride hydrate, along with a nucleating agent and other additives, was encapsulated in plastic brick [12]. When ice cream stored at −24 °C was kept in an ambient atmosphere of 20 °C, packaging with PCM + insulation, only insulation, and a control sample showed a temperature rise of less than 1 °C, 9 °C, and 42 °C, respectively, in 40 min near the surface. This confirmed the superiority of PCMs over insulation material in temperature-controlled packaging systems. In another study, octanoic acid was microencapsulated in the polystyrene shell and incorporated in chocolate shipper walls [13]. It maintained the desired temperature for 6–8.8 h. Yie et al. [14] prepared a silica aerogel-PCM composite structure. The porous structure of the aerogel was filled with microencapsulated PCMs using the impregnation method. This composite, when combined with the insulator board, increased the temperature maintenance period by 99 times. Xu et al. [15] prepared a container for storing apples in the temperature range of 2–8 °C with PCMs and insulation. The addition of PCMs maintained the temperature for 9.63 h. Without PCMs, this time was 0.77 h. Wang et al. [16] studied thermal buffering characteristics of meat packaging with polystyrene-shelled PCM microcapsules. It maintained the meat temperature at the desired level for 30 min.

Huang and Pinolek [17] designed a container that combined polyurethane insulation, vacuum insulation panels, and thermal energy-storing PCM panels to maintain the desired temperature for more than 72 h within the range of 2–8 °C in varying ambient temperature ranges from −20 °C to 35 °C. Buska [18] designed a cup whose walls were filled with PCMs to maintain the beverage temperature at the desired level. It helped in consuming the beverage at the required temperature level for a longer time with less energy used.

4. Conclusions

Due to limited fossil resources and the increased need for environmentally friendly, sustainable technologies, the importance of using PCMs to reduce thermal energy waste will increase in decades to come. The culture of using PCMs in packaging is growing exponentially. PCM consumption seems to be an emerging trend in various fields, such as e-commerce packaging, food packaging, and pharma packaging. This paper provides information about different packaging systems utilizing PCMs for transporting temperature-sensitive products. The contribution of traditional cooling systems, such as AC and ice water systems, is contracting mainly due to their higher cost for smaller shipments. A steadily growing knowledge base has demonstrated that PCMs can replace traditional cooling systems and even improve their performance.

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