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Review on thermal energy storing phase change material-polymer composites in packaging applications †

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Abstract: Thermally sensitive food and pharma packages maintained at desired temperature with refrigeration systems. These systems are powered by non-conventional energy resources. They provide uneven cooling in large containers. Interruption in their working during supply chain activities increases their energy requirement. Studies revealed that use of phase change material (PCM)-polymer composites in refrigeration systems and packaging containers curtailed the energy utilization for maintaining consistent temperature. These composites maintain temperature around its phase change temperature by absorbing or releasing latent heat. This review has discussed different designs of PCM-polymer composites which maintain the temperature of big shipments as well as 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 predicted compounded annual growth rate of 18.14% till year 2026 [1]. The surge in demand is expected mainly from temperature-controlled vaccine packages, biologics and small e-commerce packages. During the period of COVID 19 pandemic, high requirement of temperature-controlled packaging is from biopharma products. The traditional methods for controlling temperature of shipment involve active and passive temperature control methods. Active systems consist of cooling arrangement facilitated by electricity or fuel. Excessive use of these systems consumes high amount 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. The activities like transferring goods to carriers at shipping dock or airport, improper handling of goods by unskilled labor, schedule changes, use of excessive or low amount of coolant, mechanical damage, etc. can vary temperature beyond decided limits. Such disrupted supply chain systems can spoil food and lifesaving pharma products like vaccines and biologics.

On the other hand, passive systems are more energy efficient and environment friendly for storing temperature sensitive products as compared to active systems. Passive systems use coolants such as ice packs, gels packs and PCMs along with insulation material to maintain required temperature. PCMs can absorb, store or release latent heat while undergoing phase transition and maintain product in predetermined temperature range. PCMs incorporated in refrigerated active packaging systems have shown to maintain temperature at desired level for as long as 10 days in absence of electricity [2]. Low temperature fluctuation in PCM incorporated refrigeration systems have low power demand which results in energy saving. 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 range of phase transition temperature and used for a couple of hours without electricity. PCM incorporated shippers reduce the cost of smaller shipments and achieve optimum performance. To understand the working of PCM incorporated packaging systems in detail this paper is divided in two sections. First section is dedicated to innovations using PCMs in increasing 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. But variation in temperature across different territories and time of the day increases the power requirement of refrigeration. Higher temperature variation between the external and internal walls of the container increases the number of compression cycles and reduces its time of operation. Such working style requires frequent replacement of the compressor. Refrigerants used in compressors are greenhouse gases and more use of compressors pose significant risk of greenhouse gas leakage in the environment. Also, high amount of energy is spent for operating refrigerators with high temperature gradient between external and internal environments. Increasing efficiency of refrigerator systems will be helpful for the environment. PCM 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 improved thermoregulation of packaged goods with incorporation of PCM plates in big shippers. Thus, PCM incorporated bulk shippers are commercialized and used for transporting thermosensitive products. Though the initial cost of investment for these shippers is higher, the assembly proved as cost-effective in long term usage over conventional shippers. Amount of 126 kg of PCM RT 5 with temperature of melting 5 ^{0}C inserted in cold storage plate consisting of aluminium finned tube [3]. The refrigerant passed through the fin tube to charge PCM. 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 PU foam. It took 6 hours to fully charge the PCM stored cold storage plate to its phase transition temperature. After that it maintained temperature below 12 ^{0}C for 14 long hours without using diesel run refrigeration system. This system cost higher than diesel and refrigeration system due to the high cost of PCM. But, its operation cost is 61.9% lesser than conventional systems. This means that the initial high cost payback in 0.58 years. The container is flexible to use on road and rail tracks.

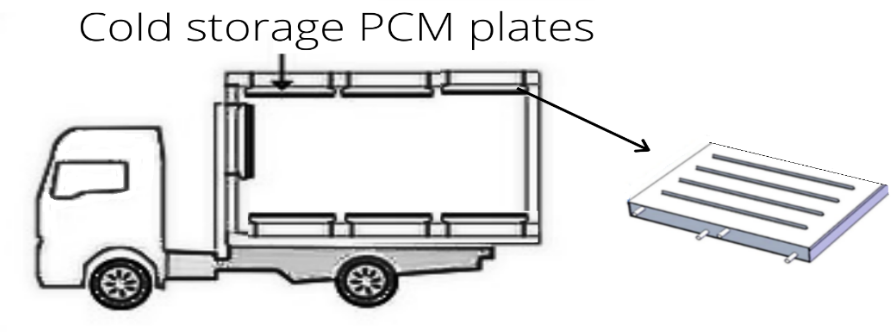

Figure 1. Placement of PCM plates in truck

A truck consisting of two chambers filled with different PCMs to give different phase transition temperatures in different chambers was constructed [4]. One compartment had phase transition temperature of 2.34 ⁰C and another had - 15 ⁰C. Both the compartments maintained phase change temperature without external power supply for 9.2 hours and 6.2 hours respectively. A six-ton truck was equipped with 6 thin PCM cold plates [5]. Each plate consisted of 35 kg PCM. Three different PCMs were tested for their cooling performance. E26 PCM performed superiorly. It gave high melting time of 17200 seconds at truck speed of 81 km per hour and 18400 seconds for stationary truck. The moving truck increased heat transfer and reduced melting time. The PCM maintained temperature for 491 km distance at 110 km per hour truck speed. It helped in reducing the use of refrigeration system. Radebe and Huan studied that PCM eutectic plates with salt-water solution can be incorporated into trucks transporting agricultural goods for temperature maintenance [6]. The use of PCM maintained temperature inside the truck to desired level preventing degradation of agro products.

Principi et al. [7] had used PCM in two ways to reduce energy consumption. The team had incorporated PCM with phase transition temperature of 35 ⁰C near the outer boundary of the refrigerated truck. The PCM layer acted as thermal buffer and prevented solar heat from reaching the inner surface of the truck. The delay in reaching the heat was maximum of 4.3 hours. It allowed 8.57% lesser heat to reach in the interior of the truck as compared to the control reference. Reduction in heat means less amount of energy required by the refrigerator to maintain interior temperature. This is the reason for the reduction in energy consumption of PCM incorporated heat exchanger refrigerator. During OFF time of compressor, the heat was absorbed by PCM to liquify at 5 ⁰C. In ON time, heat released by PCM was absorbed by evaporator outlet air. So, during OFF time of compressor the PCM maintained temperature longer. The PCM freezing process increased the start time of the compressor. The summation of these two effects resulted in reduced number of compressor cycles and increased its duration of operation. This change in cycles' working reduced energy demand of the compressor by 16%. Fioretti et al. [8] studied the effect of adding PCM panel near the outer boundary of the cold room. The thermal testing carried out on the prototype helped to determine performance of PCM in actual reefer containers. In this test, PCM panels along with PU foam enclosed within metal sheets and its results were compared with reference control sample. The reference panel did not contain PCM sheet. The arrangement of the prototype panel can be better understood from figure 2. When these panels were attached to cold room walls on external sides, the resultant heat reduction saved energy by 4.7%.

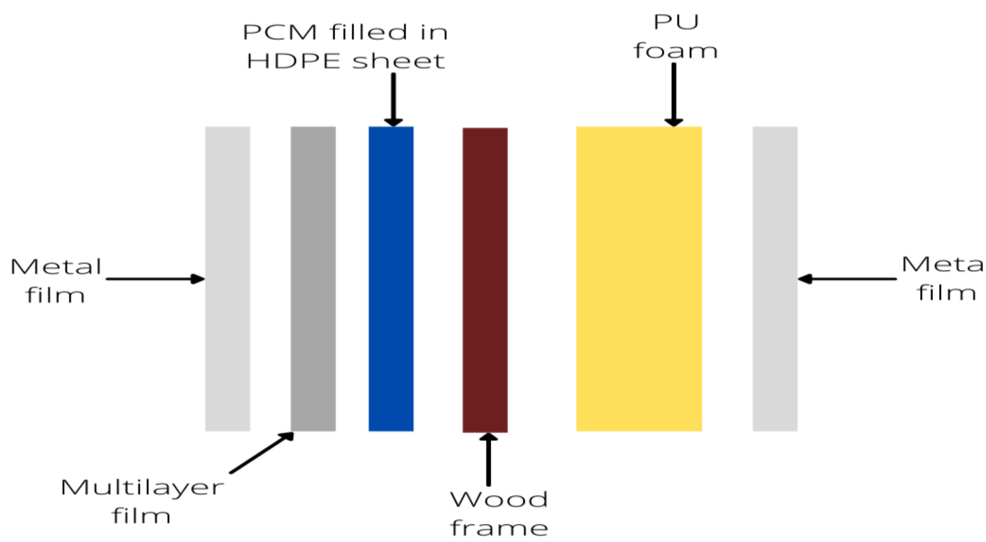

Figure 2. PCM panel

Transport air conditioning systems' efficiency improved by using serrated fins on the air side and perforated straight fins near PCM [9]. The discharging performance is the indicator of temperature maintenance of the system. The designed device had discharging depth more than 97% and has the ability to cool down the environment in seconds. The compactness and high heat transfer performance of the system will benefit its use in refers. A compact PCM incorporated air conditioner (AC) design was created for space sensitive transportation refrigeration system [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 connected to clapboard in periodic manner to give compact structure. The structure provided emergency cooling nine times higher than conventional AC systems and reduced temperature fluctuation to lower value of 2.56 ^{0}C compared to 4.3 ^{0}C for conventional system.

3. Small Container Packages

Majorly PCM or microencapsulated phase change material (MPCM) 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 from figure 3.

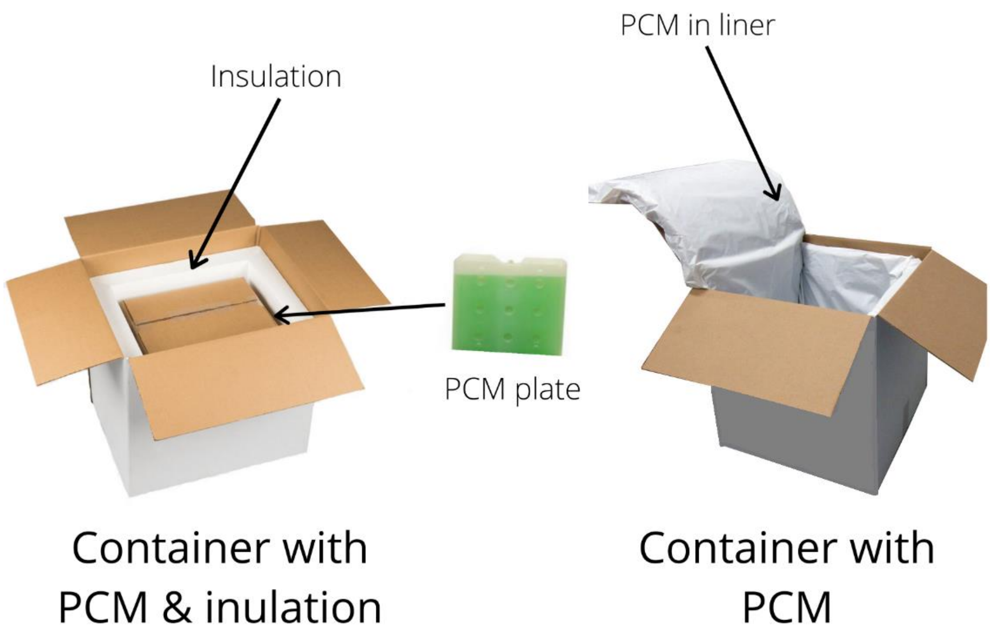

Figure 3. Small container packages with PCM plates & insulation and only PCM liners

These assemblies maintain the temperature of packaged products near phase transition temperature of PCM. The literature which studied PCM incorporated small containers' heat transfer performance is discussed in this section. RT 6 PCM was encapsulated into porous calcium silicate [11]. This shape-stabilized PCM had high melting enthalpy of 174 J/g at 8 ^{0}C and it maintained temperature of shipment for 4-9 hours in the ambient atmosphere. Sodium chloride hydrate along with nucleating agent and other additives was encapsulated in plastic brick [12]. When ice cream stored at -24 ^{0}C kept in an ambient atmosphere of 20 ^{0}C, packaging with PCM + insulation, only insulation and control sample showed temperature rise of less than 1 ^{0}C, 9 ^{0}C and 42 ^{0}C respectively in 40 minutes near the surface. This confirmed the superiority of PCM over insulation material in temperature-controlled packaging systems. Octanoic acid was microencapsulated in polystyrene shell and incorporated in chocolate shipper walls [13]. It maintained temperature for

6-8.8 hours. Yie et al. [14] prepared silica aerogel-PCM composite structure. The porous structure of aerogel was filled with microencapsulated PCM by impregnation method. This composite when combined with the insulator board increased temperature maintenance period by 99 times. Xu et al. [15] prepared a container for storing apples in temperature range 2-8 ^{0}C with PCM and insulator. Addition of PCM maintained temperature for 9.63 hours and without PCM this time was 0.77 hours. Wang et al. [16] studied thermal buffering characteristics of meat packaging with polystyrene shelled PCM microcapsules. It maintained the temperature of meat at desired level for 30 minutes. Huang and Pinolek [17] designed a container which combined polyurethane insulation, vacuum insulation panel and thermal energy storing PCM panels to maintain temperature for more than 72 hours in the range of 2-8^{0}C in varying ambient temperature range from -20^{0}C to 35^{0}C. Buska [18] designed a cup whose walls were filled with PCM to maintain beverage temperature at desired level. It helped in consuming the beverage at required temperature level for longer time with lesser amount of energy.

4. Conclusion

Due to limited fossil resources and increased need for environment 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. Contribution of traditional cooling systems such as AC, ice-water systems is contracting mainly due to its 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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