Eutectic Mixtures of High Molecular Polyethylene Glycol 6000 and Low Molecular Polyethylene Glycol 600 Combined with Water as An Alternative Phase Change Material (PCM) in Portable Cold Storage

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Abstract. The increasing demand for energy-efficient cold storage solutions, particularly in the transport of perishable foods, has led to the exploration of phase change materials (PCMs) as alternatives to conventional refrigeration methods. This study investigates the use of eutectic mixtures of polyethylene glycol (PEG) 600 and PEG 6000 combined with water as PCMs in portable cold storage. The eutectic mixtures were prepared in a 50:50 weight ratio and their performance compared against traditional cold storage using distilled water and no PCM. Key metrics such as storage duration within optimal temperature ranges (-2°C to 5°C) and temperature homogeneity were evaluated. The results indicate that the PEG 6000 eutectic mixture achieved the best temperature stability, mai taining critical temperatures for up to 4.67 hours, outperforming PEG 600, water, and systems without PCM. However, the temperature uniformity within the sto age was suboptimal, with a standard deviation of around 2°C, indicating poor thermal conductivity of the materials.

Keywords: Phase change material, PEG 600, PEG 6000, Cold storage, Eutectic mixtures.

1 INTRODUCTION

Over the past few years, shopping habits have undergone a significant transformation, particularly in the aftermath of the COVID-19 pandemic [1]. The shift from traditional retail business models to home-tohome distribution has redefined the global marketplace, setting new standards for convenience and accessibility [2]. The rise of e-commerce and direct-to-consumer deliveries was driven largely by the need for safety and social distancing. As a result, the distribution of goods, especially perishable food items, has faced new challenges. One key issue lies within the supply chain, as maitaining the quality and safety of perishable products like fruits and vegetables requires careful temperature control.

Historically, refrigerated trucks have been the reliable method for transporting perishable goods over long distances, due to their ability to maintain at precise temperature. However, this approach comes with significant drawbacks, including high

M. A. Muflikhun et al. (eds.), *Proceedings of the 10th International Conference on Science and Technology (ICST 2024)*, Advances in Engineering Research 268,
https://doi.org/10.2991/978-94-6463-772-4_5

energy consumption and expensive upfront costs, which can lead to higher product prices [3]. Additionally, it also causing air pollution resulted by engine refrigeration system. This is especially concerning for fruits and vegetables in the developed country, where the majority of waste occurs during the supply chain, with only 10% of the waste happening after the products reach consumers [4].

One promising solution is the integration of phase change materials (PCMs) into cold storage systems. PCMs have the unique ability to store and release thermal energy within a narrow temperature range, making them effective for maintaining stable conditions inside cold storage [5]. This capability ensures that perishable goods are kept at optimal temperatures for longer periods, improving the efficiency and versatility of portable cold storage. Water remains the most commonly used due to its low cost, availability, and high latent heat. However, water's melting point, around 0°C, is close to the optimal storage temperature for fruits and vegetables, between -2°C and 5°C [6]. As a result, a large volume of water is needed to maintain these temperatures, reducing the available storage space in portable cold storage. To address this issue, salt water-based PCMs have been developed in recent years to achieve lower melting points [6], [7], [8]. However, salt water comes with significant downsides, such as its low thermal conductivity and also corrosive nature limits the selection of PCM container materials designed to enhance thermal performance. Additionally, the fact that it does not biodegrade can impact the environment after certain cycles [7].

On the other hand, water-based eutectic PCM consists of water and polyethylene glycol (PEG), can create a biodegradable and food grade PCM [8]. This mixture created eutectic PCM with eutectic melting point of -20ºC [9]. Additionally, PEG comes in various molecular weights, allowing different of thermal properties after mixing. Research conducted by Abdolmaleki et al [10] found that PEG with different molecular weights alters the eutectic melting point of the PCM. The study concluded that by lowering the melting point of the PCM, the energy consumption of freezers can be reduced, improving the overall efficiency of the storage system.

This research investigates the use of PEG 600 and PEG 6000 as primary materials, selected for their availability and affordable compared to other molecular weights. These materials were then combined with water in a 50:50 weight ratio for use in portable cold storage applications. This ratio was chosen based on findings by Huang and Nishinari [9] which identified the eutectic point of the PEG-water mixture as optimal for cold storage. The performance of these PEG-water mixtures as PCMs was compared with standard portable cold storage units without PCM and with units using only water as the PCM. The results of this comparison aim to highlight the effectiveness of PEG as a potential solution for enhancing the energy efficiency and temperature control of portable cold storage systems.

2 MATERIALS AND METHOD

In this research, three primary materials were employed to create eutectic mixtures designed to achieve a lower melting point than any of the individual components. PEG 600, with a molecular weight between 570 and 630 g/mol and a melting point ranging from 15 to 25ºC, was combined with distilled water. Likewise, PEG 6000, which has a molecular weight of 5000 to 7000 g/mol and a melting point of 58ºC, was also mixed

with distilled water. Both mixtures were prepared in a 50:50 weight ratio to form eutectic solutions. In addition to investigating performance of these eutectic solutions, the tests conducted with the portable cold storage operating without any PCM, with pure distilled water used as PCM, and with the newly developed eutectic mixtures as PCM, as shown in the Table 1.

Table 1. PCM variations in the experiment.

PCM Mixture	Distilled Water (wt%)	PEG600 (wt%)	PEG6000(wt%)
1	-	-	-
2	100	-	-
3	50	50	-
4	50	-	50

The experiment employed a commercial polystyrene box with dimensions of 345 mm x 255 mm x 285 mm, specifically designed as a portable cold storage unit to assess the effectiveness of different phase change materials (PCMs) in preserving temperature stability for fruits and vegetables at optimum temperature ranges from -2 to 5 ºC. The objective was to determine which PCM materials would provide the most reliable and efficient cooling solution for these applications. High-density polyethylene (HDPE) packs were used, each to encapsulate PCMs, weighing 200 grams and measuring 110 mm x 90 mm x 30 mm.

To monitoring the temperature monitoring throughout the experiment, a sophisticated data acquisition system (DAQ) was implemented. The DAQ NI-9213 model, which supports 4 type-T thermocouples, was employed to capture temperature data at various points in and around the portable cold storage. The thermocouples were positioned to monitor both the internal conditions and ambient temperature. Specifically, three thermocouples were placed at varying heights in the center of the cold storage to track temperature homogeneity in the portable cold storage. Additionally, a single thermocouple was dedicated to measuring the ambient temperature outside the cold storage box, providing an environment condition during experiment. This illustration of the setup can be seen from Fig. 1.

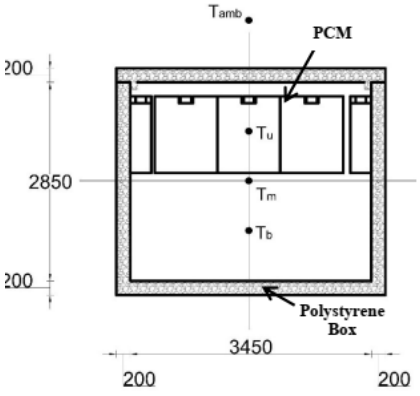

Fig. 1. Experimental setup of portable cold storage.

Before conducting the actual tests, it was essential to precondition both the insulated cold storage unit and the PCM packs. This step was critical to ensure all components were exposed to the same low-temperature environment. The preconditioning process involved placing the cold storage, along with the PCM packs, inside a chest freezer for 24 hours. This long duration allowed the PCMs to reach their phase change temperatures and the box to be uniformly cooled. Once preconditioned, the cold storage unit and the PCM packs were removed from the freezer and exposed to ambient enviro mental conditions to start the testing phase. The primary goal of the experiment was to compare the thermal performance of the insulated box under four different scenarios. First, tests were conducted with the cold storage unit operating without any PCMs to establish a baseline for natural thermal loss. Next, distilled water was used as the PCM to assess its cooling performance, given its common use due to its availability, low cost, and high latent heat capacity. Finally, the newly developed eutectic mixtures of PEG 600 and PEG 6000 fused with water were introduced as the PCM to evaluate their performance in maintaining stable temperatures over time. These eutectic mixtures were expected to offer improved energy efficiency and longer cooling durations compared to distilled water alone, due to the melting point of both eutectic mixtures lower than distilled water.

3 PERFORMANCE ANALYSIS

The performance of the portable cold storage was assessed by examining the duration during critical temperature period and the homogeneity temperature distribution.

3.1 Critical Temperature Period

It is generally advised that most fruits and vegetables should be stored at temperatures between- 2°C and 5°C to maintain their freshness and quality. The critical factor in ensuring proper storage is the ability of portable cold storage units to sustain temperatures within this recommended range over a prolonged period. The longer the storage unit can maintain these optimal conditions, the better it is at preserving the nutritional value, texture, and overall condition of the produce. This time period becomes crucial in applications such as transport and distribution, where maintaining stable temperatures is essential to prevent spoilage, extend shelf life, and reduce food waste.

3.2 Homogeneity temperature

Uneven temperature distribution in cold storage can cause spoilage of perishable foods in areas where the temperature is higher. The standard deviation (σ) was calculated to quantify the temperature variation within the cold storage. This calculation is defined as follows [11]:

$$\sigma = \sqrt{\frac{\sum_{i=1}^{n}(T_i - T_{avg})^2}{n}} \tag{1}$$

where Ti represents the temperature from three thermocouples placed at different vertical sections in the center of cold storage. These include the upper thermocouple (TU), the middle thermocouple (TM) and the bottom thermocouple (TB) with the n is the number of thermocouples. The average temperature ($Tavg$) is calculated by these thermocouples and defined as:

$$T_{avg} = \frac{T_U + T_M + T_B}{3} \tag{2}$$

4 RESULTS AND DISCUSSION

This section examines the effects of different phase change materials (PCMs) on the performance of portable cold storage, particularly during the critical temperature range of -2ºC to 5ºC. Fig. 2 depicts the temperature profiles over a 24-hour period, comparing the performance of various PCMs and the absence of any PCM. The graph highlights the ability of each material to maintain internal temperatures relative to the ambient environment.

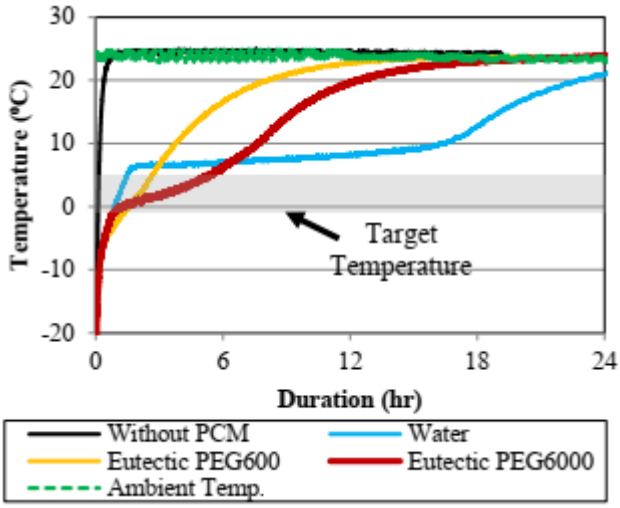

Fig. 2. Average storage temperature distribution over time.

In the absence of a PCM, the temperature inside the cold storage increases rapidly, reaching ambient conditions in less than an hour. This reflects the limited thermal capability of the polystyrene box alone, which relies purely on insulation properties and lacks the heat capacity to withstand heat offered by PCMs. When water is used as the PCM, the duration of cold storage is extended significantly before the internal temperature reaches ambient levels. While it offers the longest period before reaching ambient temperature compared to having no PCM, water is less effective at maintaining temperatures within the optimal range. Water's latent heat of fusion doesn't help regulate the temperature during the critical temperature period, diminishes its

effectiveness as PCM. The cooling effect of water begins once the critical temperature is exceeded, meaning it cannot be used efficiently. In contrast, the use of eutectic mixtures, specifically PEG 600 and PEG 6000, offers a notable improvement in maintaining temperature stability during the critical period. These eutectic PCMs delay the rise in temperature, with PEG 600 in range with the critical temperature after approximately 1.12 hours. However, the temperature rises at a rate of about 4.5ºC per hour during the critical temperature period. This indicates that while PEG 600 is more effective than water, it still faces limitations in sustaining long-term cooling. On the other hand, Eutectic PEG 6000 provides superior thermal management, reaching the critical temperature range in just 0.68 hours and offering a slower temperature increase of approximately 1.5ºC per hour during the critical period. This significantly lower rate of temperature rise during the critical phase demonstrates PEG 6000's better ability to maintain stable conditions over time.

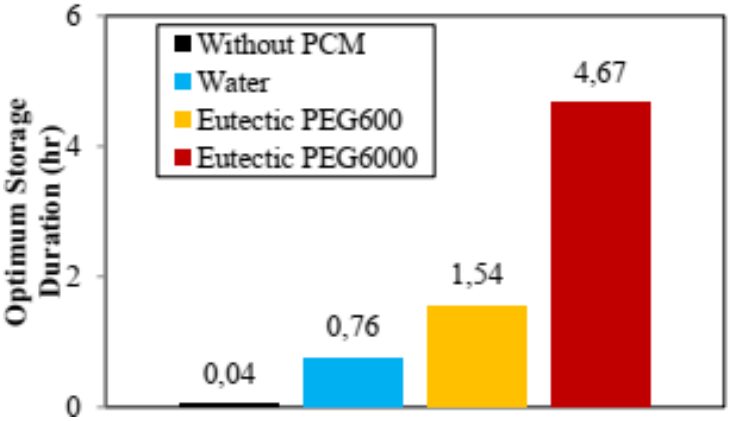

Fig. 3. Storage duration at critical temperature period of -2°C – 5 °C.

The data in Fig. 3 further illustrating the duration which the cold storage can maintain the desired temperatures using different types of the PCM. Without any PCM, the polystyrene box, relying solely on its insulation properties, can only sustain the critical temperature range for a brief period of 0.04 hours. This highlights the limitations of passive insulation without active temperature regulation. And then, as previously mentioned, the water PCM depends primarily on sensible heat rather than latent heat of fusion, which reduces its efficiency in comparison to eutectic PCMs. Consequently, when distilled water is used as the PCM, the cold storage's ability to sustain optimal temperatures shows only a slight improvement compared to having no PCM at all, extending the duration to 0.76 hours. Eutectic PEG mixtures, which have lower melting points, show a substantial increase in cooling duration. PEG 600 extends the cold storage time beyond water, maintaining internal temperatures for up to 1.54 hours. This reflects the higher heat-absorbing capability of PEG 600 compared to water, as it can regulate the internal temperature longer before it begins to rise.

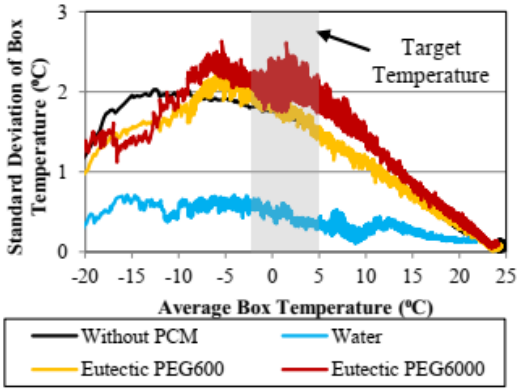

Fig. 4. Standard deviation of storage temperature at critical temperature.

The eutectic PEG 6000 mixture offers the most remarkable results, keeping the critical temperature range for up to 4.67 hours, around six times longer than water. This extended cooling duration, coupled with the slower rise in temperature, makes PEG 6000 an ideal choice for scenarios requiring prolonged cold storage, particularly when presser ing the freshness and quality of perishable goods during transport.

However, despite its superior ability to prolong the cooling duration, eutectic PEG 6000 does present some challenges regarding temperature uniformity, as described in Fig. 4. The data indicate that PEG 6000 has a standard deviation of ±2ºC, which meansthat the temperature disparity within the cold storage is less homogeneous than that of other PCMs. This variability due to lower thermal conductivity of the material and may pose a concern when storing perishable foods that require precise temperature control to prevent degradation. In contrast, water, though less effective at maintaining low temperatures over an extended period, offers the lowest temperature variation, with a standard deviation of only ±0.45ºC.

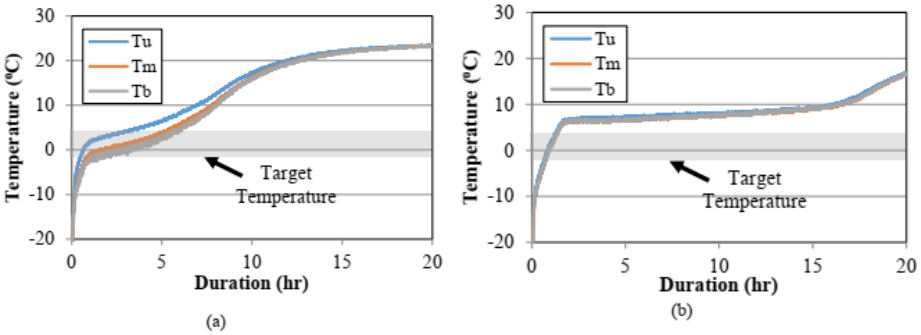

Fig. 5. Cold storage temperatures at different height over time with (a) eutectic PEG6000 (b) water.

To further analysis the problem, temperature at different heights were presented over time in the Fig. 5. In the system using PEG 6000 as the PCM, all sections initially

experience a rapid temperature rise from approximately -20°C. However, as the temperature increase begins to decelerate, a clear temperature disparity emerges between the different sections. The upper section (Tu) becomes significantly warmer than the middle and lower sections, with a temperature difference of about 2°C between the upper and middle sections (Tm), and 3°C between the upper and lower sections (Tb). This suggests uneven heat distribution, with the upper section warming faster than the other parts of the cold storage. This disparity becomes more pronounced as the system approaches steady temperature, showing that PEG 6000 leads to a non-homogenous temperature distribution within the cold storage.

In contrast, when water is used as the PCM, the temperature across all sections remains much more consistent over time. The temperature disparity between the upper, middle, and lower sections stays below 1°C. This indicates a much more uniform heat distribution across the cold storage when using water as the PCM. Despite the water maintaining temperature at higher temperature than optimum temperature of fruits and vegetables, water's performance in maintaining homogeneous temperature makes it suitable for perishable items with higher temperature is needed.

5 Conclusions

In this study, the analysis highlights the varying effectiveness of different PCMs in sustaining the critical temperature range of -2ºC to 5ºC in portable cold storage. The following conclusions can be drawn:

1. Without a PCM, the storage unit's reliance on passive insulation alone leads to a rapid rise in temperature. By introducing PCM, the performance improves from 0.04 hours without PCM to 0.76 hours when water is used as the PCM at its optimal temperature. However, the performance was still limited, as this duration relied on water's sensible heat rather than its latent heat.
2. Eutectic PCMs, particularly PEG 600 and PEG 6000, show significant improvements in thermal regulation. Eutectic PEG 600 provides better temperature capacity than water, but PEG 6000 proves to be the most effective, maintaining the critical temperature for up to 4.67 hours, making it an ideal choice to preserve fruits and vegetables during transport, which requiring extended cooling.
3. However, the analysis also reveals a trade-off between cooling duration and temperature disparity within cold storage. PEG 6000, while offering longer cooling times, has greater temperature variability (±2ºC) during critical temperature period, which may be problematic for fruits and vegetables due to narrow storage temperature. In contrast, water, despite its shorter cooling period,
   ensures more consistent temperature distribution with a lower variation of ±0.45ºC.

Future research should investigate modifying the PEG and water ratio to achieve an optimal balance to more stable temperature periods during critical temperature. A detailed study of these mixtures at various concentrations could identify ideal formulations that improve cooling time while ensuring consistent and lower temperatures. Furthermore, examining the effect of PCM quantity and melting point on

the cooling duration while minimizing the required PCM volume.

Nomenclature

T : temperature (ºC)
ΔT : temperature difference (ºC)
σ : standard deviation/temperature disparity of cold storage (ºC)
n : the number of temperature points

Subscripts

avg : average
U : upper
M : middle
B : bottom

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