



Experimental Study to Enhance the Insulation Proficiency of a Medical Carrier Box Using Phase Change Materials

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ABSTRACT

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phase change material, vaccine carrier box, cold chain, thermal energy storage, latent heat storage, cold thermal energy storage

The experiment in this paper explores the application of PCMs in the transportation box of vaccines to enhance the preservation of temperatures under extreme heat (43 °C). They experimented with four different configurations that differed in the quantities of ice packs and phase change material (PCM). The findings reveal that PCM layers have great benefits in improving cold chain operations and improving the retention time of vaccines in the optimal storage temperature (2–8 °C), and its application in the transportation of vaccines in a hot environment is a promising application. Case A utilized ice packs alone in varying numbers (4, 6, 8, and 10). Case B covered a 2 kg system, ensuring a 5 mm PCM layer on the base and exterior walls of the carrier, and included ice packs. In cases C and D, the amount of PCM was increased to 3.95 and 5.9 kg, forming two layers of 10 and 15 mm thickness, respectively, in addition to ice packs. The results showed that retention time was enhanced using an increasing number of ice packs; however, this effect was further supplemented through the utilization of PCM. Case A-4 reached a maximum retention time of 13.66 hours (10 ice packs). Case B-4 improved by using PCM to 16.75 hours, Case C-4 increased this time to 17.91 hours, and Case D-4 increased the required range retention time to 18.58 hours. The results indicate enormous potential for enhancing cold chain logistics using PCM in hot climates.

1. INTRODUCTION

Vaccination is among the most costly and vital strategies of the World Health Organization (WHO), as the organization aims to maintain the effectiveness of the vaccine during transportation and storage [1]. The WHO's focus on this strategy has intensified following the COVID-19 pandemic, which highlighted transportation challenges and underscored the need to deliver vaccines to areas with hot climates. Vaccines are typically stored and transported in a vaccine box that maintains a specific temperature range [2]. Generally, the temperature range for storing and transporting the vaccine is (2–8) °C [3, 4]. The process of transporting vaccines from production sites to recipients is called the cold chain. Transporting products via a cold chain reduces losses and extends product life [5]. This chain consumes a lot of energy and fuel due to its reliance on mechanical refrigeration systems. Due to the continuous increase in greenhouse gas emissions, it is necessary to adapt to modern technologies, such as thermal energy storage (TES) technologies [6]. TES technology is considered a type of renewable energy [7]. It is a technology that uses a certain amount of materials to store thermal energy at a high or low temperature [8]. TES technologies are classified into (latent heat storage (LHS), sensible heat storage (SHS), and chemical heat storage), with LHS technology being the most widespread because it has a larger storage capacity [9]. The material used in LHS

technology is a phase change material (PCM) that can absorb heat during phase change (solid-liquid) [10]. Cold energy storage (CTES) technology is one of the most important TES technologies currently used as an effective means of regulating energy supplies [11]. CTES technology addresses energy instability in terms of time, space, and density, and improves energy efficiency [12]. A PCM-based cold chain offers advantages over mechanical refrigeration systems in terms of lower cost and energy consumption [13]. PCM absorbs the heat transferred from the external environment into the insulated containers, thus ensuring efficient temperature control [14].

Several studies have been conducted investigating the addition of PCMs to the carrier box used in the cold chain. Anand et al. [15] studied a numerical method to increase the thermal performance of cold storage boxes by increasing the storage time of frozen products inside. Used eutectic PCMs with a melting point of -49.8 °C. The operational design of this work is built on the ambient temperature of 20 °C. The results showed that the product storage time increased by about 30% when the internal PCM mass value increased by about 10% of the total mass.

The effect of the geometric shape of the vaccine carrier box with the addition of PCM on the retention time was the scope of work of many researchers. Geng et al. [16] studied refrigerated vaccine storage boxes using PCM bottles. The researchers compared the cooling performance of a cubic box

(0.490 m³) with a cuboid cold box of the same size (0.71 × 0.425 × 0.39) m³. This study revealed that when a fully loaded (100%) medical sample was stored at an ambient temperature of 43 °C, the storage time for the sample was 66% shorter compared to an ambient temperature of 13 °C and 11.4% shorter than when unloaded. Devrani et al. [17] studied experimental and numerical effects of the geometrical shape and PCM on the performance of the vaccine carrier box. The researchers adopted a new design (cylindrical shape). Ameliorated the new design by using PCM. It used a heat transfer mathematical model (CFD). The data results showed an improvement in the performance of the vaccine box in terms of vaccine storage time by about 17% compared to the original design.

The study of box insulation materials, in addition to PCM, was within the scope of the study. Du et al. [18] studied the cooling thermal performance of the carrier cold box (0.430 × 0.285 × 0.345) m³. Studied the effect of carrier cold box insulation materials, the melting point of PCM, and the location of PCM on the cooling time of thermal storage boxes. Used two different materials, portable boxes (polyurethane (PU) and vacuum-insulated panels), five types of PCM with 2, 3, 4, 5, and 8 °C melting points. The results of the study conclude that the vacuum box panel with a configuration of PCM type (melting point at 2 °C), 20% at the top and 20% on each of the box side walls, offered the longest cold storage time for 46.5 hr. Yin et al. [19] developed a vaccine transport incubator using paraffin/silicon dioxide gel with an extruded polystyrene (XPS) sheet to cover the incubator wall. A square box of equal dimensions (60 × 60 × 60) cm³ was used. Results showed a 99-fold increase in incubator retention time using PCM compared to incubator isolation alone.

Improving the properties of PCM and its melting points is of interest. Zhao et al. [20] studied numerically the suitable properties of PCM that can increase the thermal performance of the thermal storage application. The researchers mixed a solution of tetradecane (TD) and lauryl alcohol (LA) as the base liquid. Moreover, they added graphite (EG) to a mixture of TD-LA to improve the thermal conductivity. Used a cubic cold storage box with dimensions of (200 × 95 × 55) mm³. The results showed that the longest time to maintain (2–8) °C in the cold storage box of the vaccine (no sample inside) was about 47.73 h. Nie et al. [21] studied experimentally the portable box used as a cold chain logistics with interior dimensions (0.35 × 0.22 × 0.25) m³. The study was focused on using PCM (Organic paraffin, RT 5) with two additives (graphene and fumed silica). Experiment data proved that the charging time of the cold box was reduced by 6.25%, and the temperature was maintained at the recommended temperature for 11.5 hours. Liu et al. [22] suggested loading BPCMGs in a superabsorbent polymer (SAP) to create a highly efficient cold storage box. BPCMGs consisting of SAP and eutectic KCl-NH₄Cl with a melting point of (-21 °C) can be used to develop the isolation performance of the vaccine box. The result showed that the cold box storage was able to maintain the storage temperatures without a sample inside the box for up to 21.44 hours. However, in the case of aquatic or biological samples, the storage time reaches 16.37 hours. Xing et al. [23] developed a new composite PCM consisting of a mixture of an organic and an inorganic salt. PCM solutions containing sodium formate, potassium chloride, and water with various weights were studied. The researchers used this compound inside a cold box with a size of (0.203 × 0.179 × 0.116) m³.

The experimental data presented that the payload temperature could be kept below -18 °C for over 10 hours. Liu et al. [24] developed a PCM called 6-PCM5, consisting of 0.1% potassium sorbate, 6% glycine, and 1.5% mannitol by weight, and has a melting temperature (-5.78 °C), enthalpy of fusion (292.64 J/g), and thermal conductivity (0.6017 W/(m·k)). This material was used in the cold storage of a portable cold box, and the cold storage performance of the box was compared when using 6-PCM5 with ice. The results showed that the cold storage time using PCMs continued to 22.83 hours at a temperature of (0–3) °C. Geng et al. [16] conducted a study of experimental and numerical methods on a highly adjustable ester PCM. Used it in cold storage boxes to improve the preservation time of goods used in foam boxes. Lauric acid (LA) and polyethylene glycol 200 (PEG 200) are selected as raw materials, and a polyethylene glycol laurate (PLE). The results showed that the center and bottom regions of the foam box managed to sustain temperatures below 0 °C for 2.97 and 3.25 hours.

Transporting vaccines is an arduous task that demands a good cold chain system that does not fail to stabilize the temperature, especially in hot climates. With the increase in the distribution of vaccines all over the world, cold chain technologies have to be developed through innovations. The inclusion of PCMs in vaccine carrier boxes is one of the opportunities since it has shown itself to be a good means of enhancing temperature retention.

Phase Change Materials

The PCMs have gained immense popularity due to their capacity to maintain and discharge thermal energy of phase changes. These are very useful in the regulation of temperatures in the cold chain systems. Other studies, like Anand et al. [15] and Ghosh et al. [7], analyzed various types of PCM, i.e., organic and eutectic material, to improve the thermal performance of the cold storage boxes. In particular, the paraffin wax, based on its and its desirable melting point, has been extensively experimented on and has been discovered to increase the retention time of low-temperature products. Nevertheless, such research usually targets the concept of PCM performance in ideal or moderate conditions, creating a knowledge gap when it comes to the issue of PCM performance in extreme-hot conditions, such as the ones that appear when making use of vaccine transportation. Our research fills this gap and examines the possibility of using paraffin wax PCM today, along with ice packs together, and conducting research in a high-temperature setting (43 °C).

Phase Change Material Shape and Geometry

The shape and the arrangement of the material in the container are also important factor that determines the performance of PCM. Overall, the authors have addressed the application of various PCM arrangements (in terms of layers and encapsulated shapes) to maximize energy storage and transportation rates [18, 22]. In a study by Devrani et al. [17], a cylindrical-shaped vaccine box that can be improved with PCM was shown to be better than the conventional cubic ones. Nevertheless, such improvements still do not eliminate the necessity of further investigation of the correlation between the PCM shape and retention time later in light of different ice and PCM amounts. The research analyzes the various PCM thicknesses and configurations to have a greater insight into their interactive effect on the cold chain performance.

Insulation Materials and Thermal Performance

The thermal loss in cold storage boxes can also be minimized by the use of PCM; however, the insulation material is equally important. Such materials as PU, polyethylene (PE), and polypropylene (PP) are often used, and Yin et al. [19] and Liu et al. [24] illustrated that the layering of insulation materials is a process that considerably increases temperature retention. Nevertheless, PCM and insulation in the case of high-temperature conditions are scarcely studied, and the insulation material has very few studies. PCM is used, along with these insulation materials, to investigate the topic of the effects of their synergy and how this time of retention may be extended under real-world conditions.

Hybrid Systems of Phase Change Material and Ice

The hybrid cooling technique, consisting of PCM and the use of traditional cooling techniques (ice packs), has attracted attention in recent research. Liu et al. [22] and Xing et al. [23] have analyzed the two-dimensional program of applying both PCM and ice to extend cooling periods. The results are usually not mentioned in the performance of such systems in hot temperatures, even though promising outcomes have been published, but these studies usually fail to experiment with different amounts of PCM in combination with different ice pack arrangements. In our study, we have made the only attempt at filling these gaps as we have experimented with various masses of PCM and different numbers of ice packs with the main aim of ensuring the maximum retention time in temperatures reaching up to 43 °C.

Previous studies have focused on the composition and melting points of PCMs with the geometries of vaccine carrier boxes and their insulation materials. Most studies were conducted under moderate ambient conditions and did not address the combined effect of the two types of PCM. This study addresses these gaps. This study aims to evaluate the combined effect of two different types of PCMs, namely paraffin wax (RT31) with a melting range of 29–34 °C and ice water, in different quantities and compositions, on the retention time of a temperature range of 2–8 °C inside a vaccine carrier box at an ambient temperature of 43 °C to simulate hot climates. Four experimental cases were studied: ice only, ice with different amounts of PCM (2, 3.95, and 5.9 kg), such that a layer of thickness 5, 10, and 15 mm is applied respectively on the outer walls and base of the vaccine carrier box. All cases were studied with four ice pack configurations: 4, 6, 8, and 10. The innovation in this study is the hybrid devices (ice-paraffin wax), which improve thermal stability and extend cold chain retention times for vaccine transport under hot climate conditions, thus extending the shelf life and efficacy of vaccines and providing more sustainable solutions.

2. EXPERIMENTAL WORK AND SYSTEM

This study was conducted to investigate the experimental effect of adding PCMs to the vaccine carrier box on its thermal performance.

2.1 Environment temperature (temperature outside the vaccine carrier box)

All experiments were conducted at 43 °C, the external ambient temperature that is the boundary condition for testing

the vaccine carrier box, according to WHO specifications. Therefore, the thermal chamber (116 cm (L) × 100 cm (W) × 100 cm (H)) was made of 6 mm thick acrylic glass due to its heat retention capacity and low thermal conductivity, as shown in Figure 1. Six ceramic heaters and four 1-meter-long strip heaters were distributed inside the thermal chamber to provide sufficient heat to maintain a temperature of 43 °C during the experimental work. A voltage regulator (model SCR) and a control system (model SCT-1000) were used to maintain a constant temperature environment inside the thermal chamber.

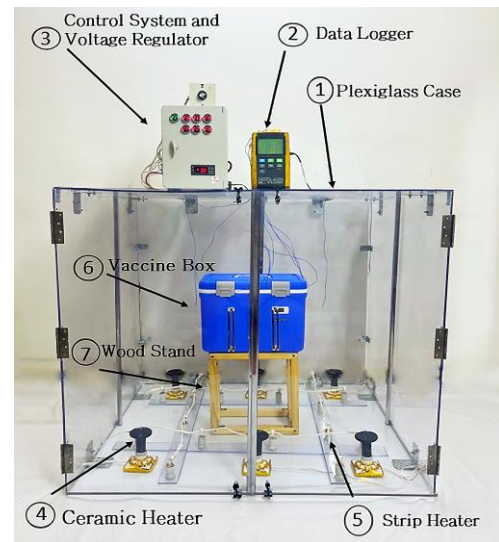


Figure 1. Thermal chamber with vaccine carrier box inside

2.2 Payload sample

Ampoules of medical-grade distilled water (2 ml) were used as the test loads. The distilled water ampoule holder made of acrylic glass with dimensions of (22.5 cm × 10 cm × 5.5 cm) was manufactured in such a way that all ampoules are exposed to the internal environment of the vaccine carrier box. It accommodates 40 ampoule tubes.

2.3 Vaccine carrier box

A vaccine carrier box produced by (BIOBASE) was chosen, model (BJPX-15L), and size (15L) as shown in Figure 2, with external dimensions (425 mm × 262 mm × 305 mm) and internal dimensions (363 mm × 203 mm × 244 mm), and a wall thickness of 23 mm. The vaccine cold box wall consists of three layers (PU, PE, and PP). Table 1 shows the thickness of each layer and its thermal specifications [25].



Figure 2. The vaccine carrier box was used in all experimental cases

Table 1. Thermal specifications of the three materials that make up the vaccine box

Material	Location	Thickness (mm)	Thermal Conductivity (W/m ² ·K)	Specific Heat (kJ/kg·K)	Density (g/cm ³)
Polyethylene (PE - HD)	External	2	0.51	2.7	0.95
Polyurethane (PU)	Middle	19	0.05	2	4.5
Polypropylene (PP)	Internal	2	0.22	2	0.9

2.4 Phase change material

Paraffin wax was selected, produced by Rubitherm Company, model (RT31), with a melting temperature of 29–34 °C, and has the specifications mentioned in Table 2.

Table 2. The thermal specifications of a phase change material (RT31)

Parameter	Value
Melting Temperature	(29 °C–34 °C) Main peak (31 °C)
Congeeing Temperature	(34 °C–29 °C) Main peak (31 °C)
Heat storage capacity ±7.5%	165 kJ/kg
A combination of latent and sensible heat in a temperature range of 23 °C to 28 °C	46 Wh/kg·K
Specific heat capacity	2 kJ/ kg·K
Density solid (at 15 °C)	0.88 kg/L
Density liquid (at 45 °C)	0.76 kg/L
Heat conductivity (for two-phase)	0.2 W/mK

2.5 Ice packs

In all experimental cases, 400 ml ice packs (160 mm × 90 mm × 30 mm) made of PE were used, as supplied by the manufacturer with the vaccine carrier box, as shown in Figure 3. It is filled with 300 ml of water. Temperature sensors were distributed inside the ice packs.

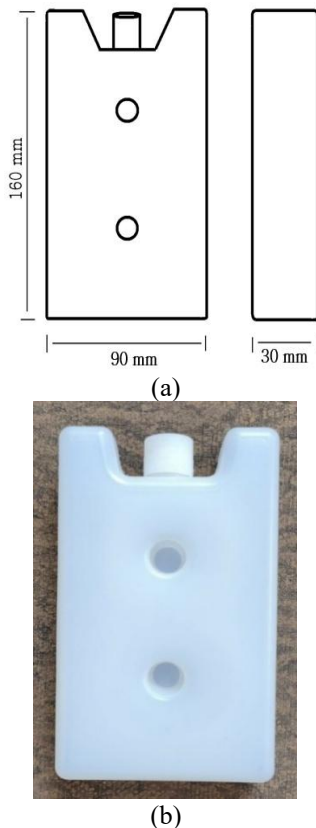


Figure 3. Ice packs used in experimental work

2.6 Validation

The thermal performance of the vaccine carrier box was verified by comparing the retention time with the data provided by the manufacturer. The results were verified, with a mean absolute error of 8.6%, as shown in Figure 4. A validation test was attempted with a boundary condition as mentioned by the manufacturer’s vaccine cold box, an outside temperature (ambient temperature) of 33.5 °C for 24 hours of testing time. Using a standard ice pack of water (2.4 kg) inside the vaccine cold box, distribute it on the inner walls of the vaccine cold box.

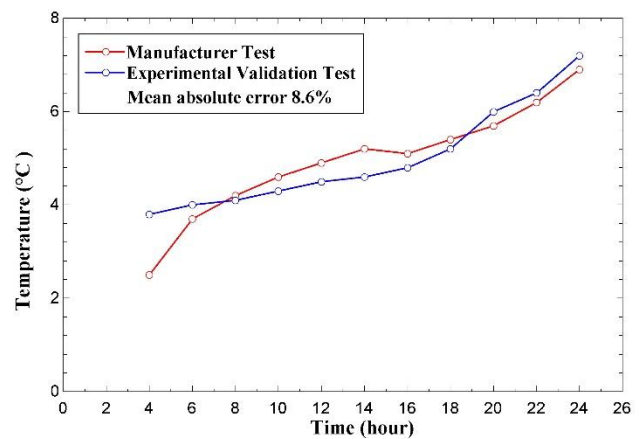


Figure 4. The percentage of error between the manufacturer's values and the experimental work

2.7 Procedure

A thermometer recorder of the type (BTM-4208SD) with 12 channels was used in all experimental works, and the thermocouple used is of the (K) type. Four sensors were placed inside the distilled water ampoules in different locations to ensure even temperature distribution across all ampoules. Four more sensors were placed inside the ice packs to measure the ice temperature, as shown in Figure 5(a). Temperature sensors were distributed at multiple points inside the vaccine cold box to measure the thermal performance of the system. The experimental data is recorded every 5 minutes. Practical experiments were conducted on the vaccine carrier box in four cases. Case A was to study the thermal performance of the vaccine box using only water ice packs. Different numbers of ice packs (4-6-8-10) (i.e., 1.2, 1.8, 2.4, and 3) kg, respectively, were used, which were arranged on the inner sidewalls of the vaccine carrier box. In cases (B, C, and D), the PCM was used on the outer wall of the box so that it was 5, 10, and 15 mm thick, which had 2, 3.95, and 5.9 kg of PCM, respectively. An area of 91.3% of the outer wall and base of the vaccine carrier box was covered by manufacturing a basin of 2.5 mm thick acrylic glass, as shown in Figure 5(b). To maintain the PCM at the required thickness using ice packs in the same order as in case A, i.e., (4-6-8-10) for both cases. Five sensors are

distributed in the PCM, two on the long wall, two on the shorter wall, and one at the base. Each of the two cases, B and C, was compared with case A to determine which of the two cases could provide the best improvement in the thermal performance of the vaccine carrier box, thus providing a clear vision of the strategy for transporting and distributing vaccines safely. Table 3 and Figures 6 and 7 show the four cases with

the number and distribution of ice packs used in each case. All experiments begin by placing ice packs, distilled water ampoules, and a vaccine box in a freezer at -10 °C for 18–24 hours. The ice packs are then placed in the appropriate order for each case, holding the distilled water ampoules inside the vaccine box, and placed in a thermal chamber at 43 °C, as shown in Figure 5(c).

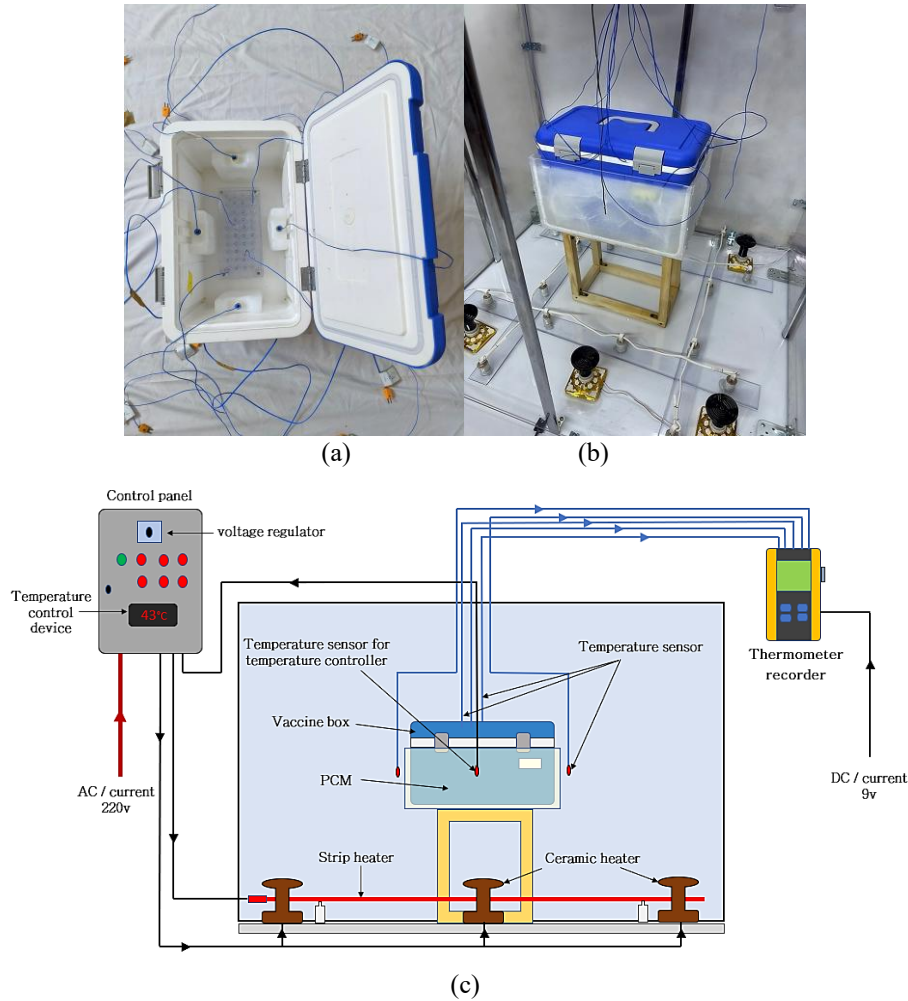


Figure 5. (a) A distribution of sensors in ice packs and distilled water ampoules (case A-1), (b) Vaccine carrier box with phase change material (PCM) inside thermal chamber, (c) Thermal chamber schematic diagram

Table 3. The number of cases with ice packs and their distribution for each case

No.	Case	Description	Experimental	Number of Ice Packs	Ice Mass (kg)	Location of Ice Packs			
						Long Wall 1	Long Wall 2	Short Wall 1	Short Wall 2
1	Case A	Ice packs without PCM	A-1	4	1.2	1	1	1	1
			A-2	6	1.8	2	2	1	1
			A-3	8	2.4	3	3	1	1
			A-4	10	3	3	3	2	2
2	Case B	Ice packs with a PCM thickness of 5 mm (2 kg)	B-1	4	1.2	1	1	1	1
			B-2	6	1.8	2	2	1	1
			B-3	8	2.4	3	3	1	1
			B-4	10	3	3	3	2	2
3	Case C	Ice packs with a PCM thickness of 10 mm (3.95 kg)	C-1	4	1.2	1	1	1	1
			C-2	6	1.8	2	2	1	1
			C-3	8	2.4	3	3	1	1
			C-4	10	3	3	3	2	2
4	Case D	Ice packs with a PCM thickness of 15 mm (5.9 kg)	D-1	4	1.2	1	1	1	1
			D-2	6	1.8	2	2	1	1
			D-3	8	2.4	3	3	1	1
			D-4	10	3	3	3	2	2

Note: PCM = phase change material.

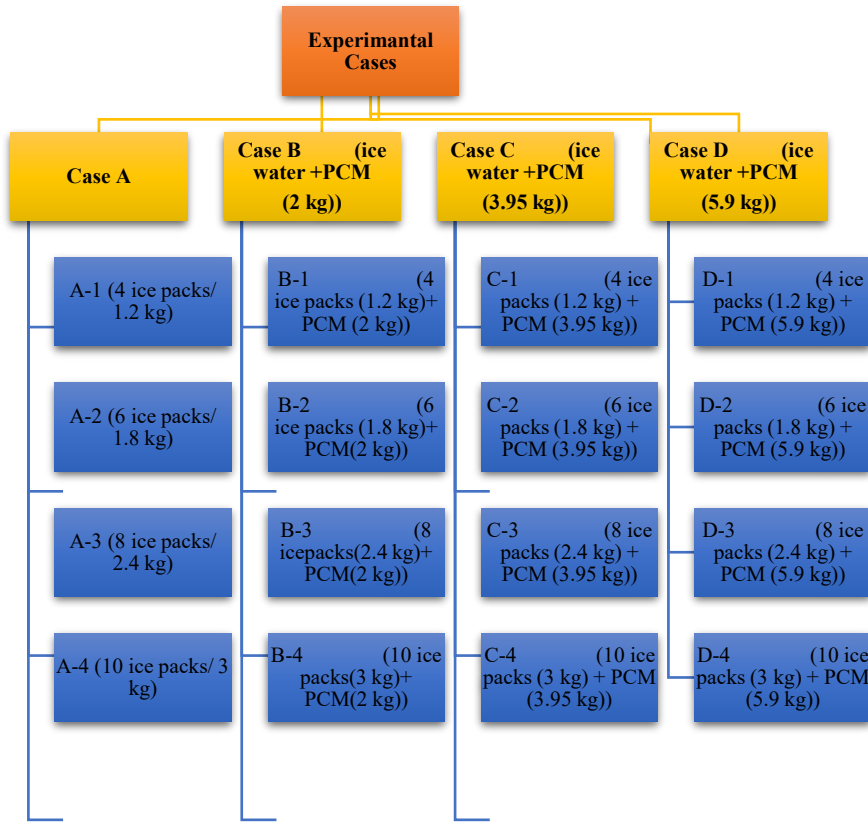


Figure 6. A diagram showing the cases studied
 Note: PCM = phase change material.

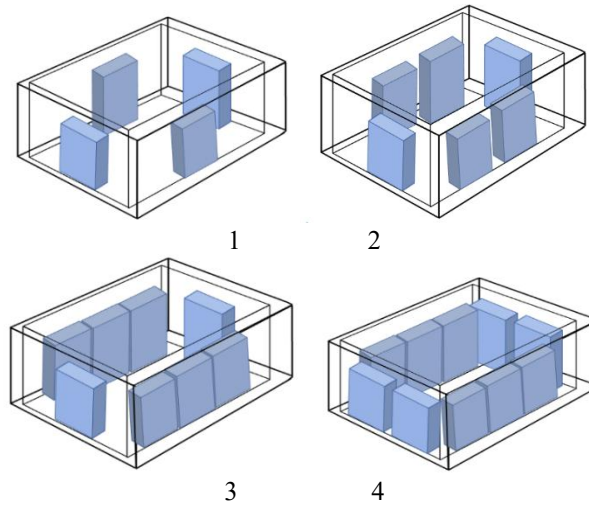


Figure 7. Ice packs distribution inside the vaccine cold box

3. UNCERTAINTY

Uncertainty analysis is performed to determine a possible error value in the measuring devices and equipment used in the study, and it can be calculated from Eq. (1) [26]:

$$U_c(y, (x_1, x_2, \dots, x_n)) = \left(\left(\frac{\partial y}{\partial x_1} \right) x_1^2 + \left(\frac{\partial y}{\partial x_2} \right) x_2^2 + \dots + \left(\frac{\partial y}{\partial x_n} \right) x_n^2 \right)^2 \quad (1)$$

where, $U_c(y, x)$ represents the uncertainty value, and (x_1, x_2, x_n) Represents the values of the independent variables. A thermometer recorder with a resolution of 0.1 °C/1 °C. Measured the temperatures in this study. Moreover, a data error of 0.1% of the total saved data is max. The uncertainty for all temperature sensors ranged from ±0.1 °C to ±0.2 °C.

4. HEAT TRANSFER RATE

The heat transfer rate for distilled water ampoules was calculated using Eq. (2) [27]:

$$Q = mcp \frac{\Delta T}{t} \quad (2)$$

where, Q represents the heat transfer rate in watts per second, m the mass of distilled water, and cp the specific heat of water (4.2 kJ/kg·k), assumed constant for all experimental work cases. ΔT The temperature difference for distilled water ampoules, and t is the time, which represents every five minutes (300 s). Table 4 shows the heat transfer rate for each case.

Table 4. The average heat transfer rate for each case

Case	Heat Transfer Rate (w/s)			
	(1) 4 Ice Packs	(2) 6 Ice Packs	(3) 8 Ice Packs	(4) 10 Ice Packs
Case A	0.82	0.34	0.13	0.044
Case B	0.275	0.082	0.06	0.055
Case C	0.208	0.08	0.057	0.045
Case D	0.152	0.066	0.047	0.038

5. RESULTS AND DISCUSSION

In this part of the paper, we report the outcomes of our experimental study, which targeted how the number of ice packs and the PCM setup had an influence on the temperature maintenance of the vaccine carrier box. The explanation of these observations is also built based on the phase change physics and the basic principles of heat transfer.

The retention time for the payload temperature range of 2–8 °C inside the vaccine carrier box at a controlled ambient temperature of 43 °C varied by different values for three cases, which are listed as:

Time of Retention vs. Ice Pack Number (Case A):

In Case A, the retention time of the vaccine carrier box in the target temperature of 2–8 °C also increased with a rise in the number of ice packs, and Case A-4 had the highest retention time, 13.66 hours. Such a trend is justified by the latent heat of fusion of the ice packs. The more ice packs one puts in the box, the higher the thermal mass in the box and the higher the quantity of heat that must be converted before the temperature can achieve its desired level. Ice is a latent heat reservoir because it absorbs heat as it melts in the summer season. The extra ice packs raise the thermal storage capacity, thus improving the duration of time the box can take to retain the desired temperature. Nevertheless, after complete melting of the ice, its capacity to absorb heat decreases, hence its plateau in the retention time in this case.

In Case A-1, as shown in Figure 8, the temperature remained within the required range for 0.4 hours. In Case A-2, the retention time increased by 16 times compared to Case A-1, which was 6.75 hours, demonstrating the significant effect of increasing the amount of water ice pack. The retention time at 2–4 °C accounted for 9.78% of the total retention time at 2–8 °C, while it accounted for 38.37% at 4–6 °C and 51.85% at 6–8 °C in Case A-2. In Case A-3, the retention time was 9.91 hours, 23 times higher than that in Case A-1 and 46.81% higher than that in Case A-2. The storage time at 2–4 °C accounted for 7.58%, while at 4–6 °C it accounted for 73.15%, and at 6–8 °C it accounted for 19.27% of the total storage time for Case A-3. In Case A-4, the storage time was 13.66 hours, representing a 33-fold increase compared to Case A-1, a 102.37% increase compared to Case A-2, and a 37.84% increase compared to Case A-3. The storage time at 2–4 °C

accounted for 6.07%, while at 4–6 °C it accounted for 77.45% of the total storage time for Case A-4. This indicates that the storage time increases with the increase in the amount of ice water in the vaccine carrier box. The prevailing storage time also falls within the 4–6 °C temperature range and increases with the increase in the ice pack value.

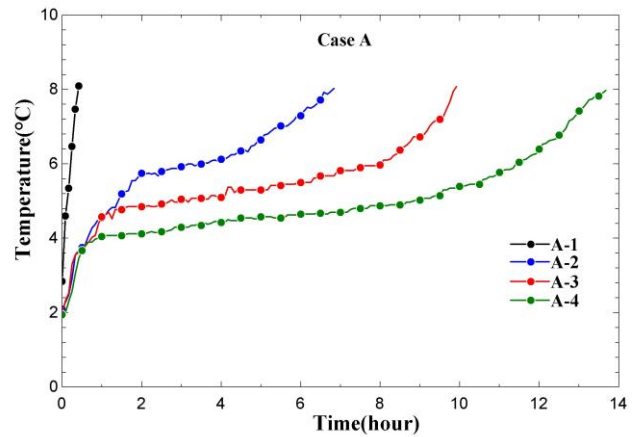


Figure 8. Retention time with payload temperature using water ice packs (Case A)

The effect of PCM on Retention Time (Case B):

In Case B, when the PCM was added (layer 5 mm thick, 2 kg), the retention time was 16.75 hours. This has been attributed to the storage capacity of the latent heat of PCM. PCM takes up a large quantity of heat during the period when it undergoes transformation between liquid and solid, without much rise in temperature. This property of retaining heat during the change of phase retards the gradual rise of the internal temperature of the box. In particular, the PCM has a melting temperature of 29–34 °C, which means that the PCM should be able to store heat provided by the outside environment and still not allow the inside temperature of the box to go over the safe range. The faster retention period in Case B than in Case A proves the role of PCM in increasing thermal stability by reducing the speed of heat uptake by latent heat retention.

In Case B, an outer layer of PCM (2 kg) with a thickness of 5 mm was used, along with an ice pack that was evenly distributed on the outer walls and base of the vaccine carrier box. In Condition B-1, the retention time was 1.08 hours within the temperature range of 2–8 °C. In Condition B-2, the retention time was 9.08 hours, a 7.4-fold increase compared to Condition B-1. In Condition B-3, the retention time increased to 12.5 hours, a 10.57-fold increase compared to Condition B-1 and a 37.66% increase compared to Condition B-2. In Condition B-4, the retention time was 16.75 hours, a 14.5-fold increase compared to Condition B-1 and an increase of 84.4% - 34% compared to Conditions B-2 and B-3, respectively. The retention time for Condition B-1 was 1.7 times higher than that of Condition A-1. The retention time of cases B-2, B-3, and B-4 was 34.51%, 26.13%, and 22.62% higher than that of cases A-2, A-3, and A-4, respectively. The retention time at 2–4 °C for cases B-2, B-3, and B-4 accounted for 9.14%, 19.28%, and 38.26% of the total retention time for each case. While the retention time in the temperature range 4–6 °C for case B-2 accounted for 55.06% of the total time for the case, the retention time at the same temperature for cases B-3 and B-4 accounted for 65.36% and 52.23% of the total time for each

case, respectively. Adding PCM to the outer walls of the vaccine carrier box in the presence of ice packs increased the retention time within the desired temperature range. This increase in retention time is attributed to the ability of PCMs to store energy as latent heat, which reduces heat transfer to the vaccine carrier box [28]. The retention time at the prevailing temperature remained 4–6 °C of the total time for each case. Figure 9 shows the temperature change with time for case B.

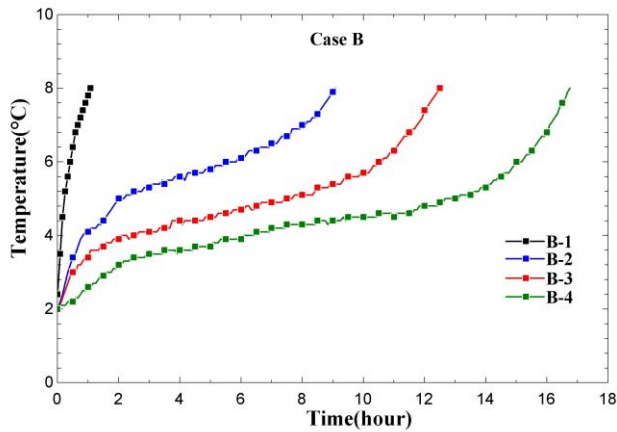


Figure 9. Retention time with payload temperature using 5 mm thick phase change material (PCM) (Case B)

Cases C and D: Increasing PCM Mass and Thickness:

In Cases C and D, when the corresponding amount of PCM was increased to 3.95 kg (10 mm thickness) and 5.9 kg (15 mm thickness), respectively, retention times became even better, 17.91 and 18.58 hours. It is possible to explain the increase in retention time due to the increase in the thermal mass of PCM. The more the PCM, the more heat is able to be stored and consumed during phase transition. The storage capacity of latent heat grows as the PCM mass of the substance, hence enhancing the capacity of the substance to defer the thermal equilibrium between the interior and outside surroundings. Nevertheless, this rate of increase in retention time is not always linear; the higher the amount of PCM added to it, the lower the rate of increase in retention time. This is not because the conductivity of heat to the overheated region will decrease when the amount of PCM in the box begins to melt, but its capacity to buffer the heat dissipated to the cooler coolant is limited in nature. This conduct is in accordance with the principle of thermal conductivity, in which the capability of the PCM to delay the heat transfer is not only dependent upon the quantity of material, but also on the thermal conductivity and absorptivity of the material and the extent of harnessed heat during the transition of state.

In Case C, an outer layer of PCM (3.95 kg) with a thickness of 10 mm was used. The retention time was (1.75, 10.91, 15, and 17.91) hours for cases (C-1, C-2, C-3, and C-4), respectively, with an increase of (3.37 times, 61.62%, 51.36%, and 31.11%) compared to cases (A-1, A-2, A-3, and A-4), and an increase of (62.03%, 20.15%, 20%, and 6.92%) compared to cases (B-1, B-2, B-3, and B-4). The retention time at 2–4 °C for case C-2 accounted for 11.47% of the total time for this

case, while the retention time for the same temperature range for cases C-3 and C-4 accounted for 22.73% of the total time for case C-3 and 49.3% of the total time for case C-4. The retention time in the temperature range 4–6 °C for cases (C-2, C-3, and C-4) accounted for (57.28%, 58.93%, and 37.24%) of the total time for each case. The retention time in the temperature range 6–8 °C for cases (C-2, C-3, and C-4) accounted for (31.25%, 18.33%, and 13.45%) of the total time for each case. The retention time in the temperature range 2–8 °C was increased by increasing the amount of PCM, as this increase leads to an increase in the amount of latent heat stored, thus reducing heat transfer to the vaccine carrier box. However, this increase in retention time was not proportional to the amount of phase change agent added, as the amount was doubled, but the retention time increased by different percentages, less than doubling. The dominant time for cases C-2 and C-3 was the time maintained at 4–6 °C, while for case C-4, the dominant time was the time maintained at 2–4 °C. Figure 10 also shows the increase in retention time for case C.

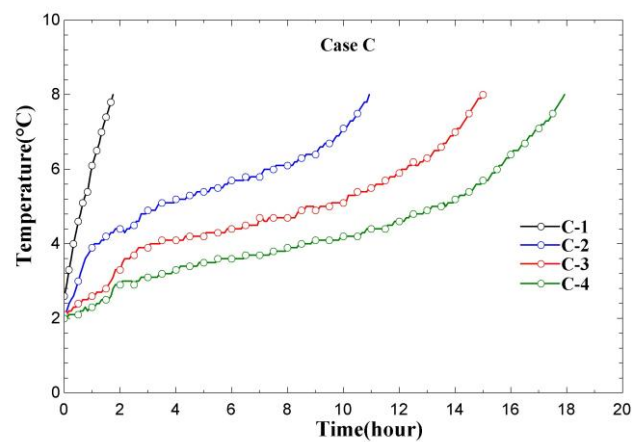


Figure 10. Retention time with payload temperature using 10 mm thick phase change material (PCM) (Case C)

In Case D, an outer layer of PCM (5.9 kg) with a thickness of 15 mm was used. The retention time was (2.33, 12.33, 16.16, and 18.58) hours for cases D-1, D-2, D-3, and D-4, respectively. The increase was 4.68 times compared to case A-1, and 80.52%, 36.06%, and 36.01% compared to cases A-2, A-3, and A-4, respectively. The percentage increases in retention time were 1.15 times, 35.79%, 29.28%, and 10.92%, respectively. However, when comparing case D with case C, the retention time increased by (33.14%, 13.01%, 7.73%, and 3.74%) for cases C-1, C-2, C-3, and C-4, respectively. The retention time at 2–4 °C for cases D-2, D-3, and D-4 accounted for (14.19%, 41.76%, and 64.58%) of the total time for each case. The retention time at 4–6 °C for case D-2 accounted for 60.82% of the total time for the case. For cases D-3 and D-4, the retention time in the 4–6 °C temperature range accounted for 45.85% and 23.73% of the total time for each case, respectively. The retention time in the 2–8 °C temperature range increased with the increase of the PCM amount, but the rate of increase remained low compared to the rate of increase in cases B and C. Figure 11 also shows the increase in retention time for case D.

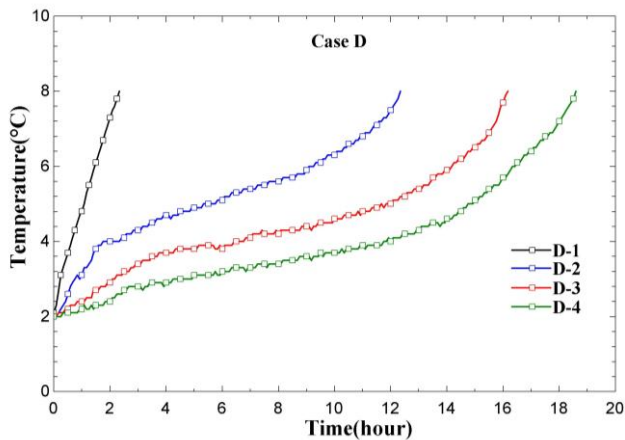


Figure 11. Retention time with payload temperature using 15 mm thick phase change material (PCM) (Case D)

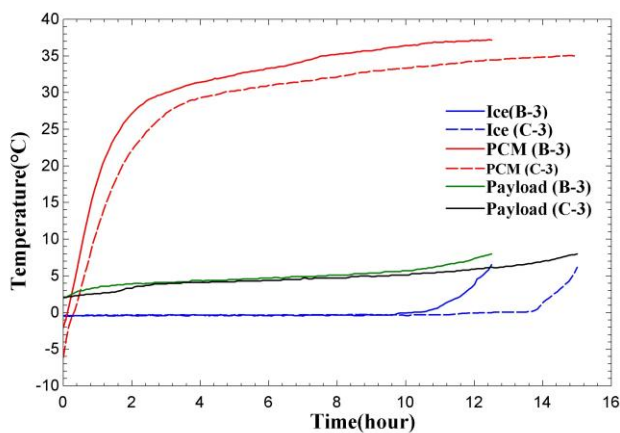
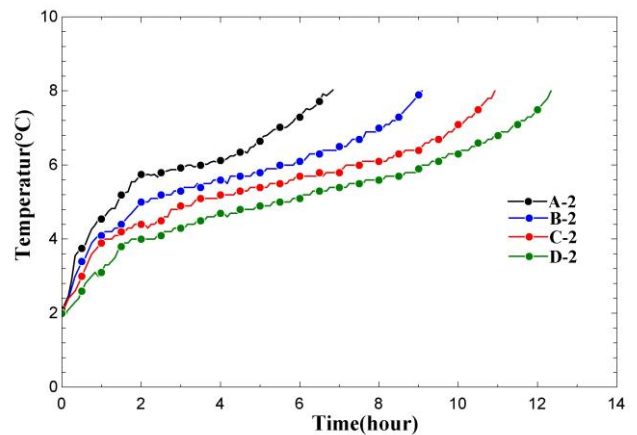


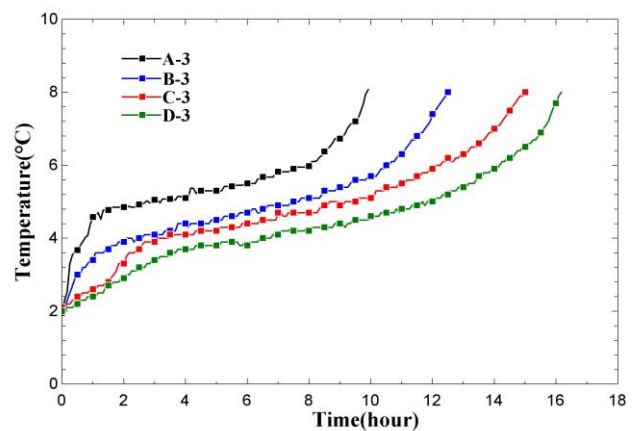
Figure 12. Temperature change for (ice, payload, and phase change material (PCM)) with time for the cases (B-3, C-3)

Using ice packs alone in case A, adding a 2 kg layer of PCM in case B, and increasing the amount of PCM in cases C and D to 3.95 and 5.9 kg, respectively. Physically, the difference in retention times between these cases is driven by how the heat energy is absorbed and delayed before reaching the payload. Ice packs can provide LHS as long as the ice remains at or below 0 °C. However, when ambient heat penetrates the box, the ice melts and loses its ability to absorb latent heat, which explains why Case A had a relatively short retention time. Case A-4 maintained the desired temperature range for 13.66 hours. The proportion of time spent within the most critical sub-range, 2–4 °C, was only 6.07%. This shows that although the temperature was maintained within safe limits, the ability to remain within the ideal range of 2–4 °C was limited. As the ice packs melted, the system moved rapidly through temperature ranges, reducing retention time. In case (B), the PCM phase changes to melt as it absorbs heat. This phase change depends on the amount of latent heat absorbed, delaying heat transfer to the box and thus increasing the retention period. However, its thermal mass is limited by the amount of PCM in the outer layer. Case B-4 was able to maintain the required temperature range for the payload for 16.75 hours and maintained 38.26% of this time within the temperature range of 2–4 °C. While the total retention time increased to (17.91, 18.58) hours for cases (C-4, D-4) respectively, the retention time in the best range 2–4 °C increased by 49.3% and 64.58% respectively, as the thermal

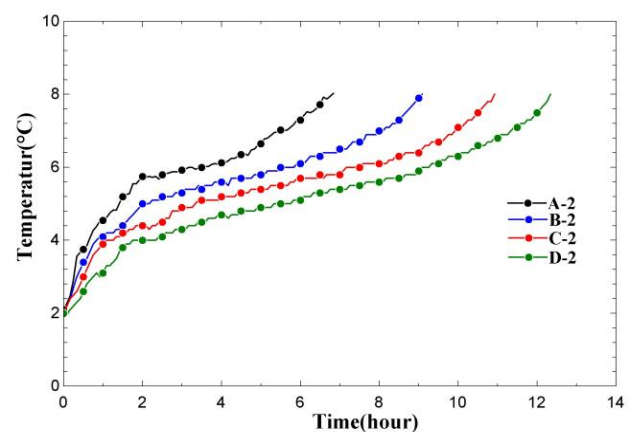
performance of the vaccine carrier box was better than cases A and B. This increased performance is due to the integrated performance between the PCM and the ice, as the PCM stores thermal energy and reduces its transfer within the box, while the ice absorbs heat from the areas surrounding the payload. Increasing the amount of PCM also leads to an increase in the amount of stored energy (increase in the mass of the PCM, thus increasing the amount of latent heat absorbed) [15]. Figure 12 also shows a comparison between Cases B-3 and C-3 in terms of the change in temperature of the load, ice, and PCM with retention time.



(a)



(b)



(c)

Figure 13. (a) Comparison between cases (A-2, B-2, C-2, and D-2), (b) Comparison between cases (A-3, B-3, C-3, and D-3), and (c) Comparison between cases (A-4, B-4, C-4, and D-4)

Figures 13 and 14 also show a comparison between the four cases in terms of the increase in retention time. Table 5 shows the retention time for each condition along with the retention percentages for the temperature range 2–4, 4–6, and 6–8 °C of the total time for each condition. Overall, Cases (B, C, and D) demonstrate that combining sensible and LHS mechanisms provides the most effective passive thermal control, especially in high ambient temperatures, making it the most robust solution for last-mile vaccine transport. The results demonstrate the ability of PCMs to store large amounts of heat in the form of latent heat, in addition to their ability to delay heat transfer, which improves retention time and thus improves cold chain performance and provides economical and cost-effective solutions for transporting temperature-sensitive medical products.

Temperature Distribution of Cases B, C, and D:

In every instance of PCM (B, C, and D), it was noted that the temperature inside the box showed the greatest consistency between 4–6 °C. The reasoning behind this is that, PCM absorbs heat in the process of phase change (melting) and is useful in the maintenance of the temperatures to be in the recommended pair of temperatures that are recommended when storing a vaccine. The external heat further enters, and the PCM starts melting, storing latent heat, and the internal temperature takes a longer time to reach temperatures above 6 degrees Celsius. It is possible to explain the prevalent retention at the 4–6 °C temperature range by the fact that the PCM phase change temperature level stabilized it and kept the temperature within that range longer. The more PCM is incorporated, the higher the amount of heat that can be absorbed by the system, which in turn increases the amount of time the phase transition takes to reach the desired temperature.

Regarding heat transfer, Figure 15, the thermal performance of the vaccine carrier box was evaluated in the four cases. In case A, the rate of heat transfer to the load in cases (A-1, A-2, A-3, and A-4) was (1.52, 0.82, 0.34, and 0.13) w/s, respectively. Due to the increased thermal mass and broader internal surface area coverage, which slows internal temperature rise, there should be an inverse relationship between ice volume and the exchange of heat. Average exchange rates during Case B (B1, B2, B3, and B4) were 0.275, 0.082, 0.06, and 0.055 w/s, respectively. The amount of PCM placed on the outer wall of the vaccine carrier box improved

insulation by reducing the heat transferred into the box and thus reducing the heat transferred to the distilled water ampoules. While increasing the amount of PCM in case C led to a slight improvement in the performance of the thermal box, as the heat transfer rate to the distilled water ampoules decreased, the heat transfer rate for cases C-1, C-2, C-3, and C-4 was 0.208, 0.08, 0.057, and 0.045 w/s, respectively. The gains resulting from adding more PCM continued to decrease as the heat transfer rate (0.152, 0.066, 0.047, and 0.038) for cases (D-1, D-2, D-3, and D-4), respectively. The decrease in the percentage of improvement in thermal performance with increasing the amount of PCM is due to the fact that the PCMs do not prevent the flow of heat into the box, but rather store it temporarily. After a certain amount, the rate of conduction through the walls remains almost constant, so the effect is limited to prolonging the period of phase change only. Therefore, we do not notice a significant improvement in the thermal performance of the box after adding an amount of PCM, which affects the rate of heat transfer to the distilled water ampoules.

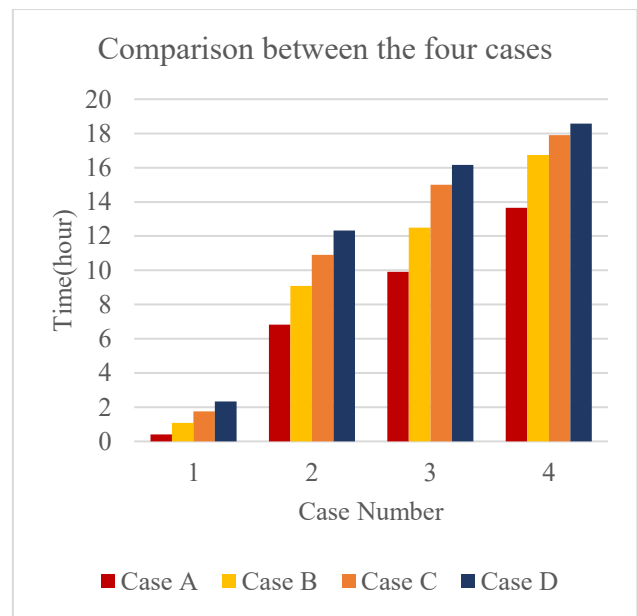


Figure 14. Comparison between the four cases

Table 5. The retention time and percentage retention at various temperature ranges for each case

Cases	Experimental	Retention Time 2–8 °C (h)	Temperature Retention Rate Over Total Time (%)		
			2–4 °C	4–6 °C	6–8 °C
Case A	A-1	0.4	-	-	-
	A-2	6.75	9.78%	38.37%	51.85%
	A-3	9.91	7.58%	73.15%	19.27%
	A-4	13.66	6.07%	77.45%	16.47%
Case B	B-1	1.08	-	-	-
	B-2	9.08	9.14%	55.06%	35.7%
	B-3	12.5	19.28%	65.36%	15.36%
	B-4	16.75	38.26%	52.23%	9.5%
Case C	C-1	1.75	-	-	-
	C-2	10.91	11.48%	57.28%	31.25%
	C-3	15	22.73%	58.93%	18.33%
	C-4	17.91	49.3%	37.24%	13.45%
Case D	D-1	2.33	-	-	-
	D-2	12.33	14.19%	60.82%	24.99%
	D-3	16.16	41.76%	45.85%	12.39%
	D-4	18.58	64.58%	23.73%	11.69%

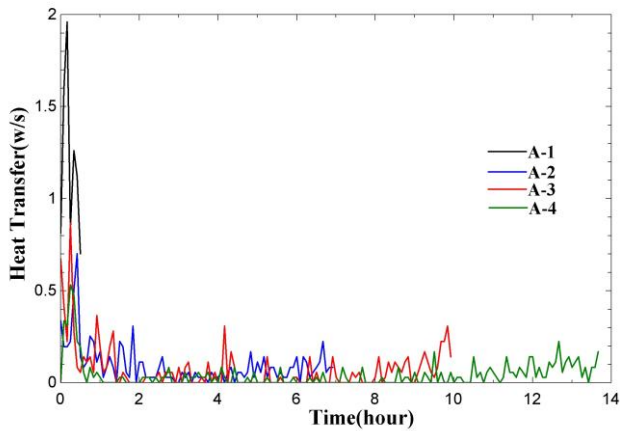


Figure 15. Heat transfer with time for Case A

The rates of heat transfer (HTR) are determined as follows:

The rate of heat transfer that was computed in each case indicated an overall decrease in the speed of heat transfer with the increase in the mass of PCM. Indicatively, Case A had a mean rate of heat transfer at 0.82 W/s using 4 ice packs, and Case D had low heat transfer at 0.038 W/s using 5.9 kg of PCM. This reduction in the rate of heat transfer as the temperature is experienced in the PCM can be attributed to the thermal insulation effect of the PCM layer. By receiving the energy on the phase change, the PCM absorbs heat when the temperature drops into the box, therefore, minimizing the total amount of heat transferred to the inside payload. The more PCM that has been added, the higher the thermal resistance of the system and hence the slower the internal temperature is going to rise. Nevertheless, the first degree of enhancement in thermal performance decreases when the storage capacity of the PCM is filled up.

Discussion: The Tradeoff between PCM Mass and Portability.

The greater the writings of PCM in the vaccine carrier box, the greater its mass. Thicker layers of PCM (i.e., 15 mm in Case D) have a much greater ability to retain heat by absorbing a larger quantity of heat during the phase change process. This, however, leads to the mass being heavier, and thus the increase in mass leading to the heavier box might be a challenge to transport, especially where one needs to use manual handling and mobility as important considerations, especially in field conditions.

The retention time of Case D was a maximum of 18.58 hours with a PCM of 5.9 kg (thickness of 15 mm). Although this is quite a large improvement in the performance of the cold chain, the additional PCM weight increases the weight of the box and hence may become more difficult to handle. This problem is particularly relevant in cases when vaccines should cover long distances, where weight has a direct influence on the effectiveness of logistics and physical stress in the work of employees.

Finding the Sweet Spot

To strike a balance between retention time and portability, we may say about a rule-of-thumb of using PCM in vaccine carrier boxes:

To infer increased retention duration (greater than 15 hours) it is generally successful to use 3–5 kg of PCM (about 10–15 mm thick). This gives an ideal ratio in which PCM can hold

sufficient latent heat to lengthen the cold chain without significantly weighing it.

To ensure it is portable, the sweet spot is approximately 2–3 kg of PCM (5–10 mm thin), which is enough to hold the internal temperature in the 2–8 °C range in 12–16 hours and have a portable weight.

The idea here is to pick the PCM mass that has a minimum mass and greatly meets the desired retention time of the area, given the normal temperature conditions, in addition to making the carrier box as light as possible to be transported.

This guideline is an expedient solution that helps to strike the right balance between cold weather and the restrictions of weight encountered in the field logistics, leaving the box portable while bringing decent results in disparate conditions.

Ecological and economic Concerns

The PCM-enhanced vaccine carrier box will normally be more expensive than traditional ice pack-based systems or mechanical refrigeration systems with regard to the material costs and system design. Nevertheless, such initial expenses are compensated in the long term. The PCM system is able to be reused (up to 100 or more cycles) and makes an inexpensive, long-life solution compared to mechanical refrigeration, which needs to be energy-fed and has a higher maintenance cost. In addition, as it efficiently lowers the use of electricity and mechanical refrigeration, PCM-based solutions would help decrease CO₂ emissions, and a more sustainable and environmentally-friendly rate would be offered. In places where access to power is limited, the PCM system proves to be very cost-effective in energy consumption and carbon footprint, where every re-use cycle would greatly reduce energy consumption as well as the emission of greenhouse gases.

6. CONCLUSIONS

In this work, the thermal behavior of a vaccine carrier box with the use of PCM, along with the ice packs, was investigated. The outcomes indicated that the temperature retention time increased significantly with increasing the PCM layer thickness between 5 mm in Case B and 15 mm in Case D, with an interval of 16.75 hours to 18.58 hours, respectively. The ice-USB-PCM hybrid system demonstrated superior thermal performance and therefore maintained the most crucial 2–4 °C temperature range better. These findings imply that the ice and PCM layers may be used together to prolong the shelf life of the vaccines, and so this system can be an alternative to the common method of refrigeration using mechanical means, particularly in hot areas. Four configurations were implemented to analyze the thermal performance:

1- Case A implemented ice packs. Based on 10 ice packs, the temperature remained between 2 and 8 °C for 13.66 hours in Case A-4.

2- Case B implemented ice packs with a 2 kg (5 mm thick) outer layer of PCM surrounding the base and outer wall. In B-4, the retention period increased by 22.62% compared to Case A-4, reaching 16.75 hours. Furthermore, the temperature range 2–4 °C covered 38.26% of the period, indicating improved thermal control. This increase is attributed to the LHS in the PCM, which delays internal load heating by absorbing external heat during phase change.

3- Case C implemented ice packs with a 3.95 kg PCM layer

(10 mm thick). The retention period was extended to 17.91 hours using the same 10 ice packs and PCM layer in Case C-4, representing a 31.11% increase over Case A and a 6.92% increase over Case B. In this case, improved temperature control, with 49.3% of the period falling within the 2–4 °C range.

4- The final case (Case D) had a 5.9 kg PCM layer (15 mm thick). Thermal performance was improved, with retention time increasing to 18.58 hours, representing a 37.99% increase over case A-4, a 12.53% increase over case B-4, and a 5.24% increase over case C-4, respectively. With 64.58% of the period falling within the 2–4 °C range.

5- The rate of heat transfer to the payload is inversely proportional to the amount of PCM, as it decreases with increasing amounts of PCM.

Despite the increased retention time, the percentage of increase gradually decreased with each case due to thermal saturation of the PCM and the phase change of the ice, where ice absorbs most of the heat in the stages before the onset of PCM melting. These results indicate that more ice packs increase retention, but the PCM significantly improves thermal efficiency by storing latent heat. The D-4 is the most efficient for the field transportation of medical products for more than 18 hours without the need for mechanical refrigeration systems.

We found higher retention times by use of PCM and ice packs (up to 18.58 hours in Case D) than in the past studies regarding cold chain performance in extreme heat. Nevertheless, they have performed their experiments in moderate temperature conditions that are not the same as our experimental that is recreating high ambient temperatures of 43 °C. The dramatic rise of retention time observed in Case D (18.58 hours) indicates a great improvement compared to these studies. That jump is novel, and this is why it is important: PCM used with ice packs can allow extending the cold chain performance far beyond what it used to be possible, which can serve as a developer of a more green solution to the challenge of vaccines and hot weather, where energy consumption is considered a life-or-death issue. This not only enhances the effectiveness of vaccinations but also minimizes the use of energy-consuming refrigeration that costs more to operate and has a higher environmental impact.

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NOMENCLATURE

m	mass of distilled water, kg
CP	specific heat, J. kg ⁻¹ .K ⁻¹
ΔT	temperature difference, °C
t	time, s
Q	heat transfer, W/s

Abbreviation

WHO	World Health Organization
PCM	phase change material
TES	latent heat storage
SHS	sensible heat storage
CTES	cold thermal energy storage
SCR	silicon controlled rectifier
PU	polyurethane
PE	polyethylene
PP	polypropylene
Uc	uncertainty