EXPERIMENTAL STUDY ON PORTABLE COLD STORAGE BOX WITH PHASE CHANGE MATERIAL PACKAGES

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With the popularization of green concepts and the rapid growth of cold chain logistics demand, developing efficient cold chain technology is a focus. Currently, most research is concentrated on simulating the cooling performance of cold storage boxes under constant temperature conditions, whereas experimental investigation of cold storage boxes under dynamic temperature conditions remains insufficiently explored. In this paper, the impact of phase change material (PCM) packaging layout on the cooling performance of the cold storage box, internal temperature distribution, and practical application effects was studied. The variation of temperature inside the box under different numbers and placement positions of PCM packages was analyzed through experiments, and its applicability was verified under dynamic ambient temperature conditions. The results indicate that the temperature increase inside the box was reduced with an increased number of phase change packages, while top-mounted packages were found to effectively reduce cover heat leakage and significantly extend the cooling time. During the 35 h transportation process from Shanghai to Beijing, in the best case studied, the temperature inside the box could be maintained below 7.7 ℃, and the temperature increase rate was observed to vary synchronously with ambient temperature fluctuations. In addition, the thermal retention test demonstrated that the cold storage box could maintain thermal stability for up to 47.3 hours under extreme cold conditions in Harbin. Generally, this study provided a theoretical basis for optimizing cold chain transportation equipment.

Key words*: cold storage box; phase change material package; dynamic temperature variation*

1. Introduction

In recent years, green and environmentally friendly concepts have been widely promoted, drawing significant attention to cold chain logistics due to its critical role in transportation and preservation [1-2]. As living standards improve rapidly, the demand for fresh food and beverages has grown substantially. To meet this trend, the application of advanced cold chain logistics technologies and equipment must be accelerated to support industry development. With the continuous expansion of the cold chain market, governments worldwide have implemented policies to foster the growth of the cold chain logistics industry. Globally, the cold chain logistics market was projected to surge from $160 billion in 2018 to $585.1 billion in 2026, with a compound annual growth rate of nearly 10% during this period. In China, low-temperature cold chain transportation has been identified as a key development pathway for the domestic industry. The refrigeration system played a vital role in maintaining the desired temperature of refrigerated spaces. Currently, the primary technology used in highway refrigerated transport is diesel-powered mechanical vapor compression refrigeration [6]. However, the method was associated with high energy consumption, low efficiency, and elevated equipment costs. Therefore, the exploration and widespread adoption of new cold chain logistics technologies were essential for achieving low-carbon and environmentally friendly practices, enhancing transportation efficiency, and ensuring sustainable development [7-8].

In cold chain logistics, temperature control was regarded as one of the core elements for ensuring product quality and maintaining market competitiveness [9]. Therefore, precise temperature regulation has become a critical focus in the advancement of cold chain logistics technology. Studies indicate that most refrigerated pharmaceuticals and fresh fruits and vegetables should be stored within a strictly controlled temperature range of 2 - 8° C. Phase change refrigeration technology, which relies on phase change materials (PCMs), could be employed to regulate temperatures effectively. PCMs were characterized by high latent heat, excellent temperature uniformity, and reusability [10,11], making them a promising solution for enhancing transportation flexibility and extending distribution routes. Consequently, they were considered vital for modern cold chain transportation systems [12].

Du et al. [13] investigated the refrigeration performance of a portable cooling box integrated with a phase change material (PCM) thermal energy storage module. Through experimental validation, the effects of PCM module position, PCM melting point, and insulation material on cooling time were numerically analyzed. A comparison was made between two insulation materials: polyurethane and vacuum insulation panels. The results demonstrated that cooling performance was significantly influenced by PCM module configuration, PCM melting point, and insulation material type. The maximum cooling time of 46.5 hours was achieved, along with discharge efficiency and depth reaching 90.7% and 99.4%, respectively, indicating strong potential for cold chain applications. Wang et al. [14] examined PCM applications in refrigeration systems. Under UK climate conditions, energy savings of up to 8% were obtained by using PCM to subcool refrigerant. When a PCM-based heat exchanger was employed as a pre-condenser, a 6% improvement in system COP was observed. Alok K. Ray et al. [15] evaluated the cooling performance of PCM-based portable vaccine transport boxes with different geometries. At 45° C ambient temperature, the cylindrical configuration maintained internal temperatures 4.03% lower than the rectangular design after 17 h. Under 30° C conditions, the cylindrical box demonstrated 8.7% higher cooling efficiency and 20.4% longer cooling time compared to its rectangular counterpart. Huang et al. [16] developed a PCM-based insulated box for temperature-controlled transport (2-8° C). Through configuration optimization and pretreatment methods, 72 h operation was achieved under extreme temperature variations. Using a PCM with 5° C phase transition temperature, temperature maintenance was extended from 1 h to over 80 h while keeping internal temperatures stable at 4-5° C. However, water as PCM exhibited 1-2° C supercooling effects. Experimental results showed good agreement with theoretical predictions.

Roberto Fioretti et al. [17] investigated a novel technology for enhancing the thermal performance of refrigerated box enclosures through phase change material (PCM) integration. The proposed solution was evaluated using both experimental and numerical approaches. Initial prototype testing was conducted under controlled laboratory conditions, followed by field evaluation under actual summer conditions in Ancona, Italy. Compared to conventional designs, peak heat transfer rates were reduced by 5.55% and 8.57% on two test days, demonstrating significant performance improvement. Chen et al. [18] developed a novel composite PCM consisting of hydrophobic fumed silica and dodecane. This material was found particularly suitable for cold thermal energy storage (TES) applications due to its low thermal conductivity. The composite containing 85 wt% dodecane exhibited excellent energy storage capacity and shape stability, showing good agreement between experimental and numerical results in refrigeration system applications. Sophie Burgess et al. [19] systematically evaluated PCM configurations in packaging containers through combined experimental and numerical analysis. Among three tested layouts, optimal performance was achieved when PCM was distributed along the top, bottom, and long side walls, yielding a threshold time of 15.8 hours with 80% discharge efficiency. M. A. Ben Taher et al. [20] addressed temperature fluctuation issues during loading/unloading operations in refrigerated transport. Through PCM integration with refrigeration systems, energy savings of 35-65% were achieved when maintaining temperature stability during door openings.

Through literature review, it has been found that most studies focus on the properties of phase change materials, as well as the cooling time and depth of release in cold storage boxes under constant temperature conditions. However, there was relatively little research on the practical application of PCM in cold storage boxes under dynamic temperature environmental conditions. In addition, the importance of the layout of the PCM package on the temperature distribution inside the cold storage boxes had not been thoroughly analyzed in the literature. Moreover, there was a lack of analysis and research on practical transportation conditions, with most focusing on the cooling performance of the box under high-temperature conditions and relatively less research on the thermal retention performance of the box under low-temperature conditions. In this study, experimental investigations were conducted to test the cooling time and temperature distribution inside the cold storage boxes with varying PCM package numbers and arrangements, and the impact of the PCM package on cooling performance. The cooling performance and thermal retention performance of the cold storage boxes were tested under dynamic temperature conditions.

2. Test program

2.1 Experimental equipment

Experimental investigations were performed using a dedicated cold chain cold storage box. The internal chamber dimensions measured 355 mm (length, L) × 355 mm (width, W) × 355 mm (height, H). The wall thickness was maintained at 50 mm. The insulation materials consisted of vacuum insulation panels combined with rigid polyurethane foam. Phase change material (PCM) with a 5° C phase transition point was selected and encapsulated into standardized packages. The PCM packages were fabricated with dimensions of 355 mm (L) × 355 mm (W) × 23 mm (thickness). Fig. 1 shows the photograph of the box and PCM packages.

Fig.1 Photograph of the cold storage box and phase change material (PCM) packages

A temperature-controlled chamber capable of simulating diverse environmental conditions was employed for testing. The cold storage box was placed inside the chamber, where ambient temperatures were systematically varied to evaluate its performance under simulated transportation and storage scenarios. Temperature readings were recorded at 1-minute intervals from all measurement points following test initiation. Fig. 2 displays the photograph of the temperature-controlled chamber and data acquisition equipment.

Fig.2 Photograph of the temperature-controlled chamber and data acquisition equipment

2.2. Experimental steps

In the early stage of the experiment, phase change material (PCM) packages were preconditioned at 0° C for 24 h to achieve complete thermal energy storage. The cold storage box was initialized at ambient temperature before testing. The experimental procedure commenced when the internal temperature reached 2° C, with continuous monitoring until the temperature exceeded 8° C. The observed time interval was operationally defined as the cooling time. All tests were conducted in compliance with national standard testing protocols. For comprehensive thermal monitoring, fifteen temperature sensors were strategically distributed throughout the box, as illustrated in Fig.3. This configuration ensured representative sampling of spatial temperature variations during operation.

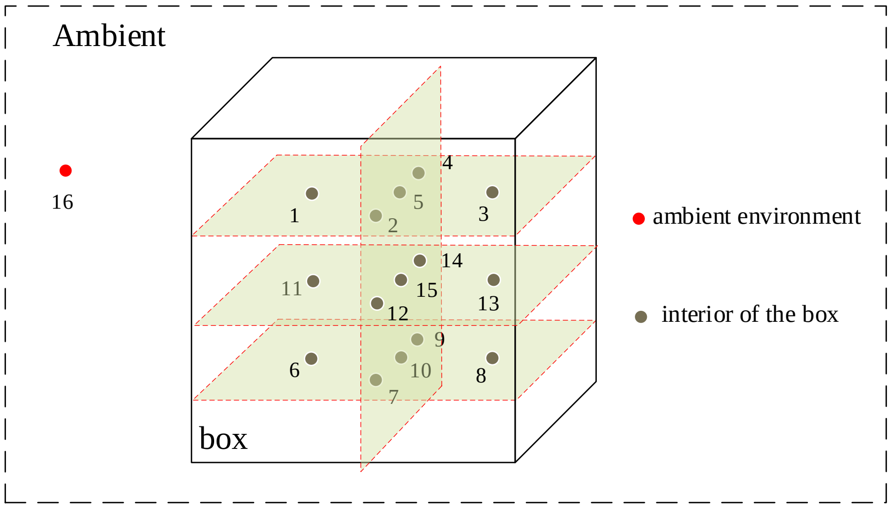

Fig. 3 Arrangement of temperature sensors

Table 1 shows the arrangement and number of PCM packages. The placement and number of PCM packages have a crucial impact on the temperature inside the refrigerator, which is an important component of the cooling source inside the box. In Case 1, no PCM packages were placed inside the box. Case 2 and Case 3 each contained one PCM package, while Case 4 and Case 5 were equipped with two. Case 6 was loaded with three PCM packages. The cold storage box was placed in a constant-temperature environment at 25° C. The cooling time and internal temperature distribution of the box were tested under different arrangement configurations.

Table. 1 Arrangement and number of the PCM packages.

Configurations	Top	Bottom	Surrounding
1	0	0	0
2	1	0	0
3	0	1	0
4	1	1	0
5	0	0	2
6	1	1	1

This study investigated the impact of ambient temperature on the cooling performance of cold storage boxes. The hourly temperature variation curves for the hottest and coldest days in different regions were retrieved using DeST software and applied as test conditions. DeST software is used to simulate a building environment and HVAC system, with a built-in meteorological data generation module [21]. Additionally, to evaluate the actual temperature variation inside the box during transportation, a simulated route was established: from Shanghai to Beijing via Jiangsu and Shandong. The departure from Shanghai was set at 08:00, with arrival in Beijing at 21:00 the following day. Table 2 shows the transportation route and time consumption.

Table. 2 Transportation route and time consumption.

Transportation Route	Shanghai	Jiangsu	Shandong	Beijing
Time	5h	15h	12h	3h

Moreover, PCM packages exhibit heat release during phase transition from liquid to solid. To evaluate the thermal retention characteristics of cold storage boxes with PCM packages in cold environments, the experimental protocol involved: 1) preconditioning the PCM packages and box at a constant 8° C environment for 24 h to achieve complete heat storage, followed by 2) keeping in a -25° C constant-temperature environment for cooling.

2.3 Uncertainty analysis

The measurement uncertainties in this experimental study were attributed to both random variations during the measurement process and the inherent precision limitations of the instrumentation. These uncertainties can be calculated by the Bessel formula and non-statistical methods.

The test uncertainty, ΔX, is determined from

$$\Delta X = \sqrt{\frac{{S_X}^2}{n} + {\Delta_{instrument}}^2} \quad (1)$$

where S_X is the standard deviation determined by the Bessel formula, n is the number of measurement points, and $\Delta_{instrument}$ is the instrument error.

The Bessel formula is expressed as follows

$$S_X = \sqrt{\frac{\sum_i^n (xi - x)^2}{n-1}} \quad (2)$$

The temperature uncertainty of the box was determined to be within a narrow range of 0.086 - 0.23° C, demonstrating that the measurement dispersion was within acceptable limits with high measurement accuracy.

3. Results and analysis

3.1 Cooling performance

Fig. 4 shows the temperature variation process inside the box (from 2° C to 8° C) under different PCM package arrangement configurations at an ambient temperature of 25° C. As demonstrated, the temperature increase rate decreases with increasing number of PCM packages. Specifically, in all cases, the temperature elevation from 2° C to 5° C was completed within 5 h, indicating rapid initial warming characteristics.

The box exhibited optimal thermal performance when equipped with two or three PCM packages (Case 4, Case 5, Case 6), maintaining an average internal temperature between 5° C and 7.5° C for the longest time. This phenomenon was attributed to the latent heat release mechanism. Increasing the number of PCM packages enhances the latent heat released, significantly retarding the warming rate. However, when the temperature rises above 7.5 ℃, the proportion of the liquid phase in PCM packages gradually increases. Therefore, the available cooling capacity was reduced, leading to accelerated temperature elevation within the box. A near-linear temperature increase pattern was observed in both Case 2 and Case 3. This phenomenon was primarily caused by the lower number of PCM packages, which resulted in significantly reduced thermal resistance between the interior and exterior of the box. Consequently, heat transfer was preferentially conducted through these lower-resistance pathways, leading to rapid temperature elevation inside the box.

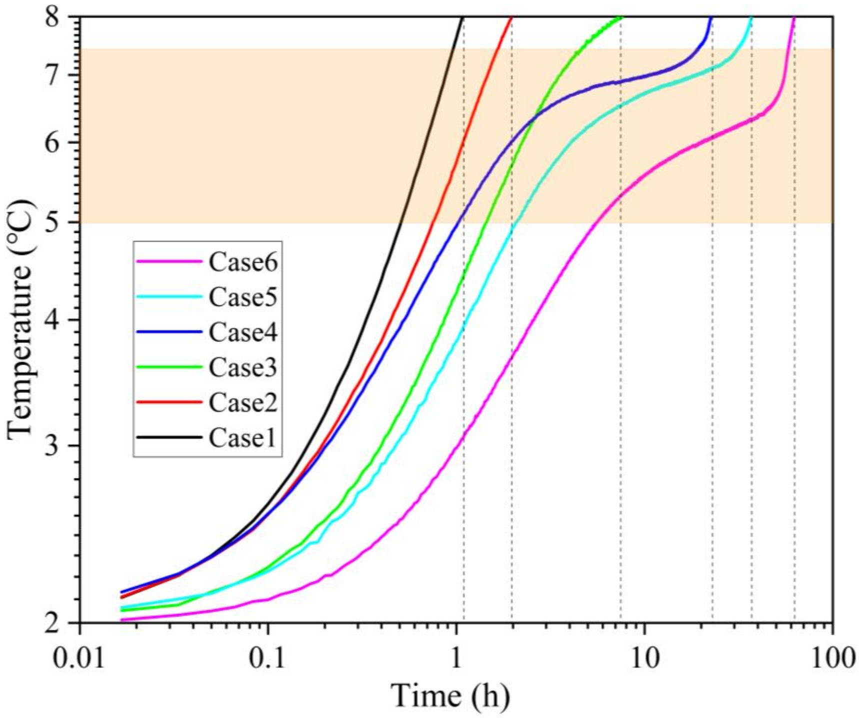

Fig. 4 Variation of average temperature inside the box under different configurations

Fig. 5 shows the cooling time of repetitive experiments under different configurations. Three sets of repeated experiments were conducted for each configuration to validate the reliability of the experimental data. The difference between the maximum and minimum cooling times under the same configuration was the experimental error. The maximum error for Case 4 was 1.5 h. It should be noted that the cooling time was affected by the placement of the PCM packages. Both Case 2 and Case 3 were configured with one PCM package, and the difference in cooling time was 5.6 h. Similarly, Case 4 and Case 5, each containing two PCM packages, exhibited a more substantial 14.4 h cooling time discrepancy. The main reason was that both Case 3 and Case 5 have a PCM package placed at the top of the box. The low-density hot air accumulated in the upper region of the box, ensuring complete phase transition of the top-positioned PCM package with consequent latent heat release. Additionally, this configuration enhanced the lid sealing effectiveness, significantly reducing direct hot air infiltration.

In addition, to reduce investment costs, the appropriate number of PCM packages could be selected based on transportation or storage time in practical applications. In general, the transportation and storage time of the box was within 24-72 h. To verify the applicability of the box, Case 6 was considered the best case studied for later experimental research.

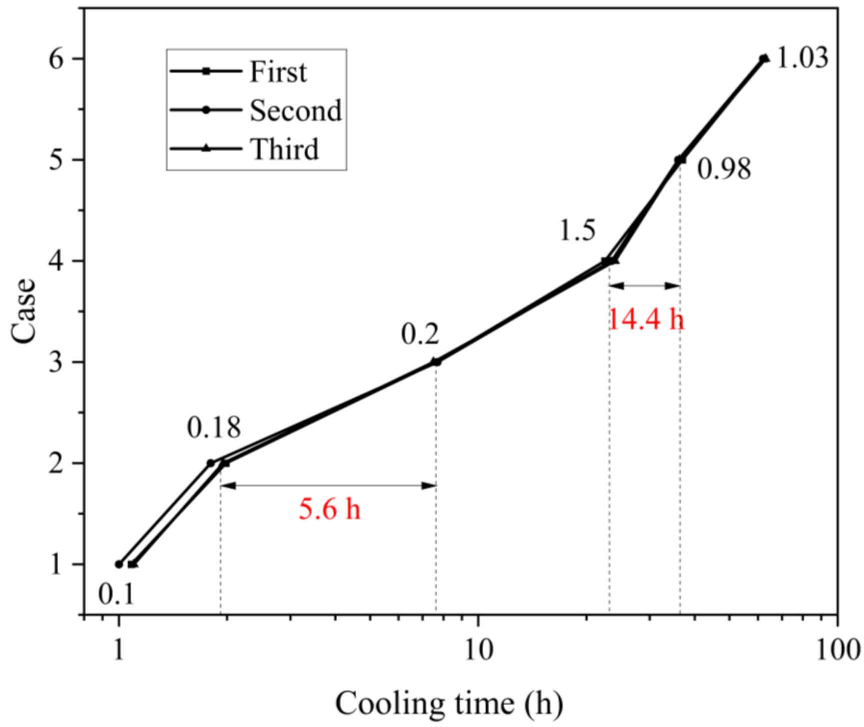

Fig. 5 Cooling time of repetitive experiments under different configurations

3.2 Effect of supply air temperature

Fig. 6 shows the average temperature variations across upper, middle, and lower cross-sections under different configurations. In Case 1 (without PCM package), the temperature distribution exhibited a vertical gradient: upper > middle > lower sections. Case 2 and Case 4 demonstrated similar temperature distribution patterns, with faster warming rates observed in the upper regions compared to the lower sections. Case 3 and Case 5 shared identical temperature distribution characteristics, maintaining consistently lower temperatures in the upper regions. This phenomenon was attributed to potential heat leakage at the box lid, which was effectively mitigated by top-positioned PCM packages in these configurations. In best case studied, uniform temperature distribution initially, but above 7° C, the upper section became progressively warmer. This transition occurred due to complete PCM melting without releasing any cooling capacity, allowing thermal stratification of less dense warm air. Notably, Case 4, Case 5, and Case 6 exhibited identical temperature escalation patterns, featuring an initial rapid increase followed by a slow increase.

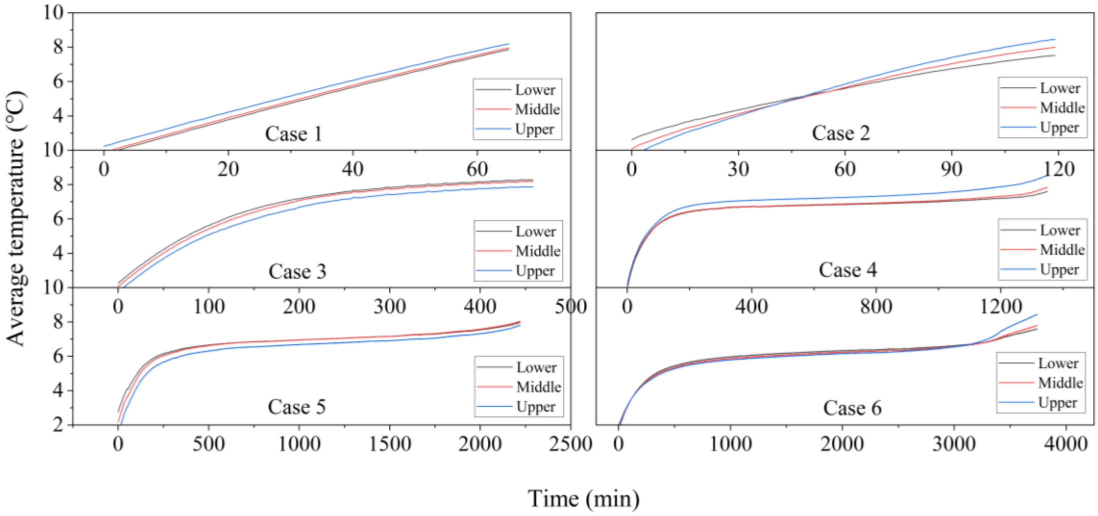

Fig. 6 Temperature distribution inside the box under different configurations

3.3 Practical application

In practical applications, cold storage boxes were subjected to dynamic ambient temperature variations during the transportation process. To evaluate the thermal performance during actual transportation, this study utilized DeST software to simulate climatic profiles of the hottest days in Shanghai and Beijing. The obtained temperature data were programmed into the temperature setting module of the temperature-controlled chamber to replicate actual operational scenarios. Fig. 7 shows the average temperature variation inside the box under dynamic ambient conditions in best case studied. Ambient temperature profiles in Shanghai and Beijing fluctuated between 26 – 38℃. The corresponding cooling times were recorded as 32.4 h and 38.1 h, representing reductions of 48% and 39%, respectively, compared to the 25° C constant temperature condition. As evidenced by the highlighted region, the warming rate of the average temperature inside the box exhibited minor fluctuations under dynamic ambient conditions.

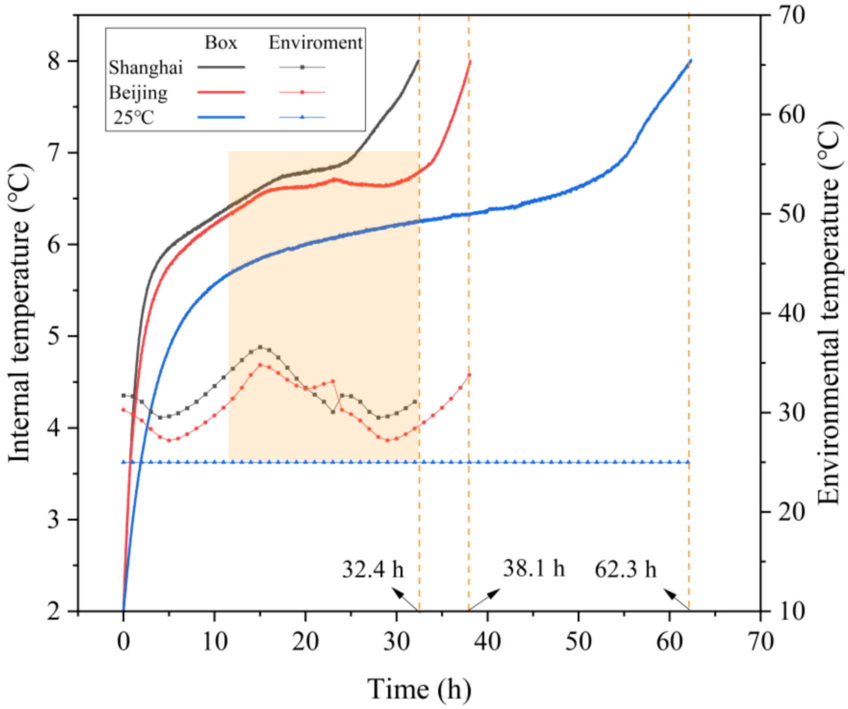

Fig. 7 Variation of the average temperature inside the box

Fig. 8 shows the climate characteristics of the hottest days in Shanghai, Jiangsu, Shandong, and Beijing. The temperature parameters were extracted according to the transportation timeline (It has been highlighted in Fig. 8 in order), exhibiting fluctuations within the 26–38° C range. From these data, the dynamic temperature variation curve characteristic of cold storage box transportation routes was extracted and subsequently employed as the control parameter for the thermal chamber in follow-up experimental validation.

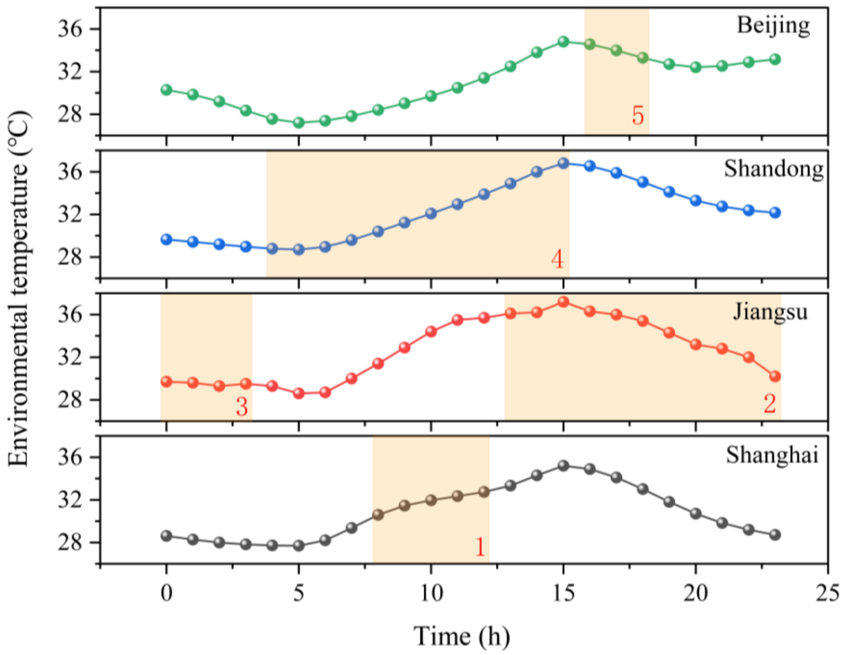

Fig. 8 Climate characteristics of different regions

Fig. 9 shows the average temperature change inside the box during transportation. The warming rate of the average temperature inside the box was affected by fluctuations in ambient temperature. When the ambient temperature decreases, the warming rate of the temperature inside the box decreases. Conversely, when the ambient temperature increases, the rate of temperature rise increases. The box maintained average internal temperatures of 6.1° C upon arrival in Jiangsu, 6.5° C in Shandong, and 7.2° C in Beijing. At the receiving location, an average temperature inside the box of 7.7° C was recorded after 35 h of transportation, confirming compliance with thermal requirements.

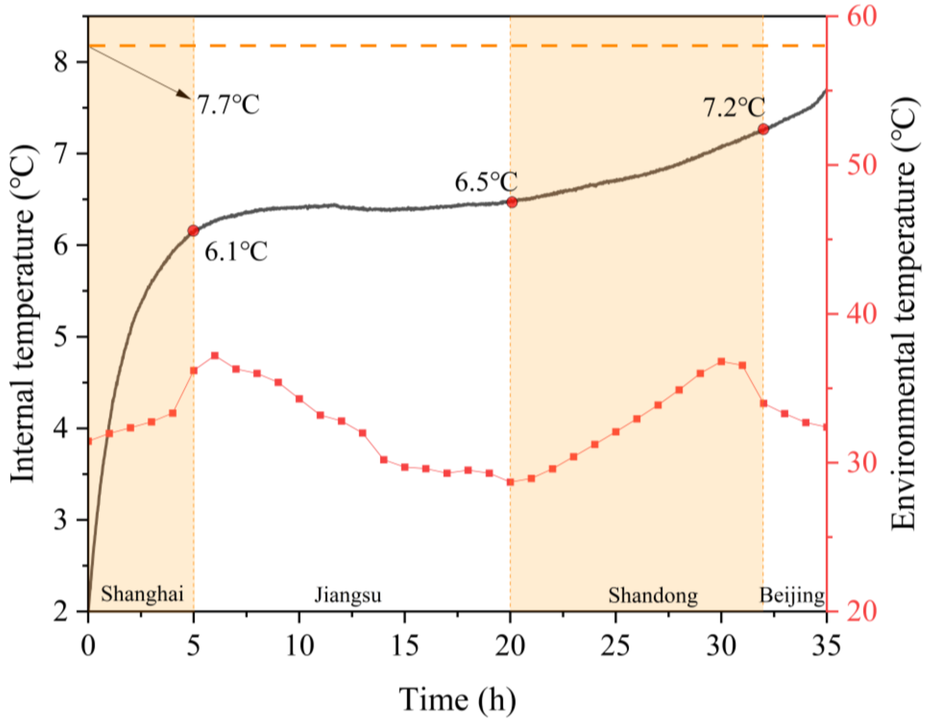

Fig. 9 Average internal temperature variations during transportation

3.4 Thermal retention performance

Fig. 10 shows the average internal temperature variations of the box under both constant temperature (-25° C) and dynamic (Harbin's coldest day) ambient conditions. The temperature on the coldest day in Harbin exhibited fluctuations within the range of -26° C to -18° C. At the initial experimental stage, a rapid decrease in the average internal temperature of the refrigerated container was observed. As the temperature approached the phase transition point, the liquid PCM gradually initiated solidification, during which a substantial amount of latent heat was released. This latent heat release resulted in a sudden deceleration of the cooling rate. Subsequently, with the progressive increase in solid PCM fraction, the available latent heat for temperature maintenance gradually diminished, leading to a corresponding acceleration in the cooling rate.

Under constant temperature conditions, the internal temperature change curve was smooth, and it took about 36.4 h for the average temperature inside the box to drop from 8 ℃ to 2 ℃, which is a decrease of 41.6% compared to the 25 ℃ condition. Under the coldest day dynamic temperature conditions in Harbin, the internal temperature variation curve fluctuates due to environmental temperature fluctuations, and the thermal retention time could reach 47.3 h.

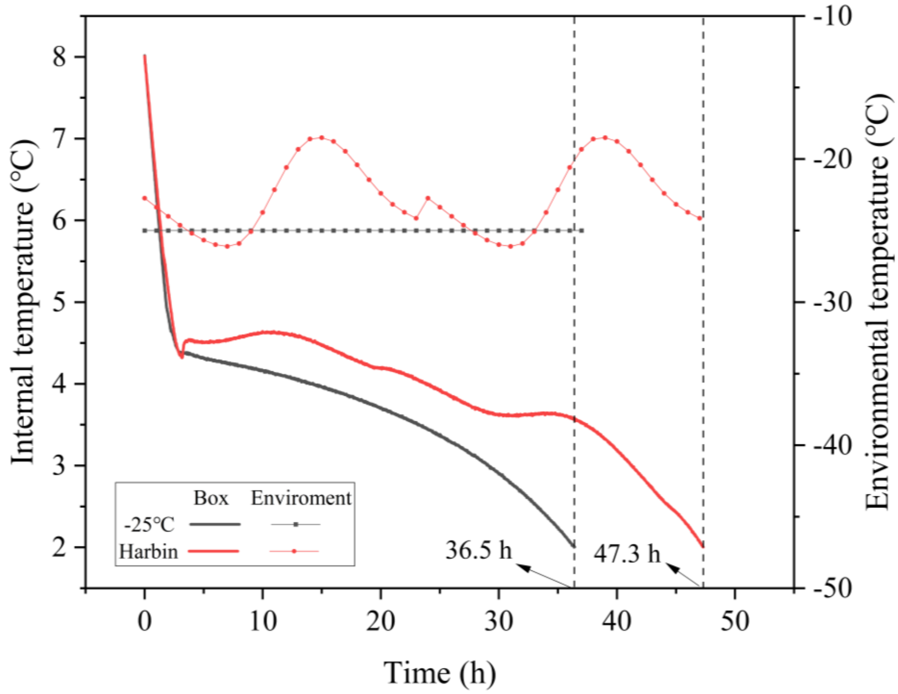

Fig. 10 Average internal temperature variations under low-temperature conditions

4. Conclusions

To promote the green development of cold chain transportation and improve the economy and practicality of cold storage boxes, this study explored the influence of the number and layout of PCM packages on the cooling performance, temperature distribution, and practical application effects of cold storage boxes. Additionally, the heat retention performance of the cold storage box under low-temperature conditions was tested. These investigations provided critical data support for the optimization of cold chain transportation equipment. The principal findings are summarized as follows:

1) The arrangement of PCM packages significantly affects cooling performance. The internal temperature increase rate was effectively decelerated with increased PCM package number. Placing a PCM package at the top could reduce heat leakage at the cover, thereby extending the cooling time of up to 14.4 h (Case 5 compared to Case 4).

2) The temperature distribution was related to the placement of the PCM package. In the absence of PCM packages, a vertical thermal gradient was observed with higher temperatures in the upper regions. This distribution pattern was effectively reversed when PCM packages were top-mounted (Case 3 and Case 5),

while multiple PCM packages (Case 6) achieved more uniform temperature distribution.

3) Variations in ambient temperature directly govern the rate of internal temperature change within the box. The box was transported from Shanghai to Beijing, and the temperature inside the box was maintained at 2-7.7 ℃ within 35 h.

4) The cold storage box demonstrated excellent thermal retention performance, maintaining stable temperatures for 36.4 h under constant -25° C conditions. Notably, under extreme cold climate conditions simulating the coldest regional days, the cold storage boxes could achieve a heat retention effect of 47.3 h.

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