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THERMAL PERFORMANCE OF A PORATBLE COLD BOX USING PHASE CHANGE MATERIAL BASED COLD ENERGY STROAGE

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ABSTRACT

Cooling performance of a portable cold box for cold chain was studied in this paper. The effects of melting point of the phase change materials (PCMs), the locations of the PCMs, and the insulation material on the cooling duration time were numerically compared using the experimentally validated model.

Firstly, five distributions of PCMs inside the box (case 1: 100% of the PCMs at the top, case 2: 20% at the top and 20% on each side wall, case 3: 25% on each side wall, case 4: 20% on each side wall and 20% at the bottom, case 5: 100% at the bottom). Secondly, five different PCMs, with melting point at 2 °C, 3 °C, 4 °C, 5 °C and 8 °C respectively, were used to verify the cooling effect of the box. Finally, two different insulation materials (polyurethane, vacuum insulated panels) were compared under the same operation conditions.

It was found that different PCMs locations, melting point of the PCMs and the insulation materials leaded to different cooling duration times. The location of PCMs with 20% at the top and 20% on each side wall, the melting point at 3°C, and the vacuum insulated panel (VIP) as the insulation material could maximize the cooling duration time of the box.

Keywords:

Portable cold box, phase change material, cooling duration time

NONMENCLATURE

PCM	Phase change material
PU	Polyurethane
VIP	Vacuum insulated panel
Cp	Sample heat capacity, J kg^{-1} K^{-1}
k	Thermal conductivity, W m^{-1} K^{-1}
t	Time, s
ε	Volume fraction of a phase, %
ρ	Density, kg m^{-3}
θ	Volume fraction, %
u	Velocity, m s^{-1}
Q	Heat source, W m^{-3}
H	Specific enthalpy, kJ kg^{-1}
T	Temperature, K

1. INTRODUCTION

The demand of the fresh vegetables and fruits increases significantly in recent years [1]. Low-temperature transport can prolong the storage time of the fresh foods and drugs, and reduce the risk of the quality degradation during transportation [2-3]. It is reported that, one third of the world's fresh food products are wasted every year due to the improper storage and transport. The promising way to solve the issue is to use cold chain transport which is able to guarantee the food safety and quality [4].

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Currently, the cold chain is using mechanical vapor compression refrigeration driven by diesel engines [5]. However, diesel engines have the disadvantage of poor energy efficiency, high pollution emissions and maintenance costs [6]. Approaches have been made to improve the performance of the on-board refrigeration system. Venkatraman [7] studied the couple of a solid oxide fuel cell auxiliary power unit with a vapor absorption refrigeration system. The result showed that it was possible to couple them together for the refrigerated truck and the system performed a higher total efficiency up to 80%. Han JW simulated the temperature distribution inside the refrigeration container with and without an air duct. It showed that with an air duct at the rear of container, more uniform temperature distribution in the cargo area could be achieved [8]. Besides, the mechanical unit faces the refrigeration system failure and the refrigerant leakage risks [9].

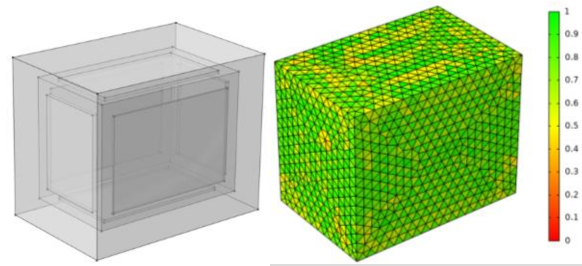
The thermal energy storage based on phase change material has the advantages of large energy density and long duration time of cooling at a specific temperature during phase change period [10]. It was found that using phase change materials on cold chain transportation could replace the on-board mechanical unit [11-12]. Fioretti R added PCM to the refrigerated container and found that the total energy consumption was reduced by 4.7% [13].

To the best of our knowledge, there is currently little research on the portable cold storage box with PCM. In this paper, a portable box using PCM was optimized numerically with an experimentally validated model. The optimized parameters including the PCM location and phase change point, the insulation materials were obtained. The achievements in this study can be used as the design guideline of the portable box for the cold chain.

2. MODEL DESCRIPTION AND NUMBERICAL METHOD

2.1 Physical model

The outer dimensions of the refrigerated box case are 430 mm (L) * 285 (W) * 345 (H), and the internal dimensions are 355 mm (L) * 215 (W) * 265 (H). Fig. 1(a) gives the physical geometry, while Fig. 1(b) shows the grid used for this simulation. The initial temperature inside the box is 0° C with an ambient temperature at 25° C.



(a) (b)

Fig 1 Physical geometry(a) and computational grids(b) of the box.

2.2 Heat transfer model

Heat transfer inside solids and liquids can be expressed as following:

$$\rho C_p \frac{\partial T}{\partial t} + \rho C_p u \cdot \nabla T + \nabla \cdot q = Q$$

$$q = -k\nabla T$$

The density and specific enthalpy of PCM are given as:

$$\rho = \theta \rho_{ph1} + (1-\theta)\rho_{ph2}$$

$$H = \frac{1}{\rho}(\theta \rho_{ph1} H_{ph1} + (1-\theta)\rho_{ph2} H_{ph2})$$

The specific heat capacity of PCM is give as:

$$C_p = \frac{\partial H}{\partial T}$$

The heat exchange mode between the box and the ambient is convective and radiant heat transfer. The external bottom surface is assumed to be adiabatic, and the emissivity of the other surfaces is 0.1.

A three-dimensional and unsteady-state numerical simulation was carried out using COMSOL Multiphysics 5.4. The time step was selected at 1800s.

2.3 Materials and methods

The total volume of the PCM is 1371750 mm^3. The five distributions of the PCM are shown in Table 1.

Table 1: Various distributions of PCM inside the box

	top	side wall	bottom
Case 1	100%	0	0
Case 2	20%	20%*4	0
Case 3	0	25*4	0
Case 4	0	20%*4	20%
Case 5	0	0	100%

The PCM used in the experiment is RT5 HC from Rubitherm Company. The thermos-physical properties of the PCMs used in simulation are shown in Table 2.

Table 2: Physical properties of PCMs

Properties	value
Density[kg*m-3]	800
Specific heat[kJ*kg*K-1]	2
Thermal conductivity[W*m-1*K-1]	0.2
Latent heat[kJ*kg-1]	220
Melting point[°C]	2,3,4,5,8

Two insulation materials of the box are compared. One is polyurethane (PU) and the other is vacuum insulated panel (VIP). Their thermal-physical parameters are shown in Table 3.

Table 3: Different insulation materials

Material	PU	VIP
Density[kg*m^{-3}]	40	170
Specific heat[kJ*kg*K^{-1}]	2	0.134
Thermal conductivity[W*m^{-1}*K^{-1}]	0.03	0.004

2.4 Grid Independence verification and experimental compare

Fig. 1(b) shows the finite element mesh that was discretized in COMSOL Multiphysics. The sensitivity analysis of grid number was conducted. Fig. 2 shows the inside temperature of the box with different grid sizes.

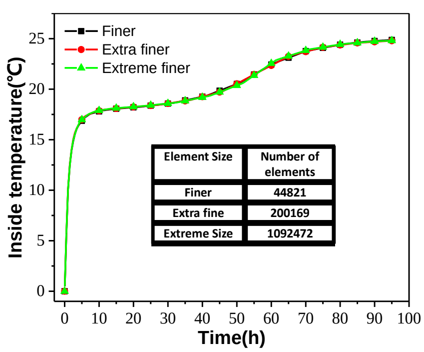


Fig 2 Inside temperature of the box with different grid sizes.

When grid size reduced, the difference of the inside temperare was limited to 5%. Hence, a finer grid size with the number of elements at 44821 was slected for the simulation. The simualtion model was validated by the experiment under the same conditions. Fig. 3 shows the comparsion of the simualtion and experimental results. One can see that, the temperature trend shows good aggreement. The cooling duration time error with inside temperature under 8 °C is limited to 0.3%.

2.5 Results and discussions

2.5.1 Arrangement of the PCM inside the box

Fig. 4 demonstrates the stabilized inside temperature and the cooling duration time of the box with various arrangements of PCM. One can see that when 20% of the PCM is placed at the top and 80% of the PCM is distributed uniformly on the four side walls, the inside temperature can be kept at the lowest temperature range and the box has the longest cooling time.

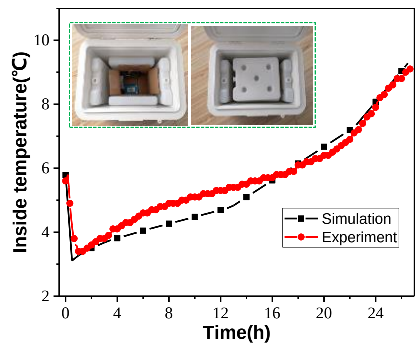


Fig 3 Comparison of simulation and experimental results

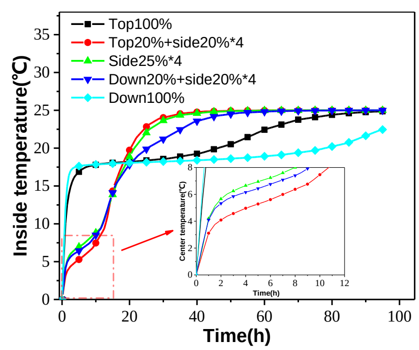


Fig 4 Temperature distribution of PCM materials at different locations.

2.5.2 PCMs with different melting points

The PCMs with different melting points can affect the cooling duration time of the box. As can be seen from Table 4, with the PCM having a melting point of 3 ° C used in the box, the cooling duration time is longest, which can reach up to 11.8h.

Table 4: Comparison of cooling duration time with PCM at different melting points

Melting point(℃)	Duration time below 8 ° C（h）
2	11.2
3	11.8
4	11.2
5	10.8
8	6

2.5.3 Comparison of different insulation materials

Fig. 5 compares the inside temperature of the box with different insulation materials. One can see that, VIP material can greatly extend the cooling duration time of the box by 6 times compared with that of the PU.

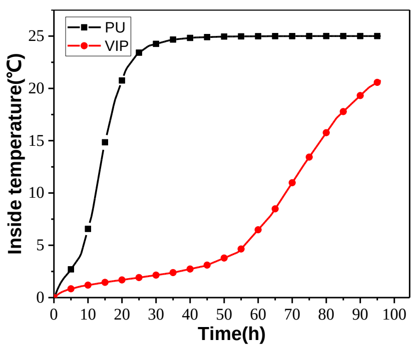


Fig. 5 Difference in box center temperature when using different box materials

2.6 Conclusions

This article focuses on designing a portable cold box using PCM based thermal energy storage. The effects of the locations of the PCMs, the melting points of the PCMs and the insulation materials on the cooling duration time of the box were investigated. It was found with 20% of the PCM on the top and 80% of the PCM distributing uniformly on the four side internal walls, the stabilized inside temperature is lowest and the cooling duration time is longest.

It was found that when the PCM had a melting point of 3℃, the stabilized inside temperature of box performed the lowest. Besides, VIP could greatly extend the cooling duration time by 6 times.

The innovative achievements in this study can be used as the design guideline of the portable box for the cold chain.

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