# LOW TEMPERATURE PHASE CHANGE MATERIAL FOR COLD STORAGE AND ITS APPLICATION TO REFRIGERATED TRANSPORTATION

by

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*This paper applies the phase-change cold storage technology to refrigerated transportation to reduce the energy consumption. Experiment data showed that the electronic expansion valve can be randomly adjusted to simulate the temperature within negative 25 °C to negative 5 °C, and a system for defrosting at low temperature and auxiliary refrigeration based on phase-change thermal energy storage of diethylene glycol were developed to guarantee the reliability of the cold chain system.*

Key words: *refrigerated transportation, degree of superheat, defrosting, temperature control, phase change*

## Introduction

With the fast development of China national economy and improvement of standards of living, the cold chain of food has been formed and freight volumes of refrigerated (frozen) food have increased. Vehicle-mounted refrigerators offer many advantages in favorable refrigerating effect, simple operation, safety and low energy consumption. An electronic expansion valve becomes an important means for truly optimizing such refrigeration systems [1]. Scholars have investigated the refrigeration system of refrigerator cars and their temperature-control performances. For example, Kayansayan *et al.* [2] explored numerically the effectiveness of flow field and temperature distribution in containers. Lazzarin and Noro [3] compared the performances and investigated energy-saving potentials of thermal and electronic expansion valves applied in an air conditioner factory. De Micheaux *et al.* [4] studied the infiltration heat load during the opening of a refrigerated truck body. Flick *et al.* [5] applied the stochastic model to the evolution of food products along the cold chain. Hasan and Siren [6] studied the performance of plain circular and oval tube evaporatively cooled heat exchangers, Chow *et al.* [7] analysed air-conditioners at low-rise residences.

In recent years, scholars have explored how to improve the heat transfer efficiency of evaporators, refrigeration performances of vehicle-mounted refrigerators, flow field distribution within refrigerators. However, it was rarely studied whether the temperature control by electronic expansion valve can effectively solve the problem of insufficient refrigeration ca-

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pacity of the system at a large temperature difference and reduce frost layer accumulated at drainage hole of freezers in vehicle-mounted refrigerators. In this paper, according to the control characteristics of electronic expansion valve in refrigeration system, the refrigeration system of the vehicle-mounted refrigerator was designed to reduce the energy consumption of perishable food during refrigerated transportation.

## Temperature control design of thermal and electronic expansion valves

The R404a refrigerant was chosen for the vehicle-mounted refrigerator to explore the refrigeration efficiency. The room temperature was 36.2 °C and the humidity was 75%. A self-designed test bench was composed of refrigeration units, a refrigerator body, a control system for constant temperature and humidity and a miniature data acquisition. The refrigeration system of the vehicle-mounted refrigerator is shown in fig. 1.

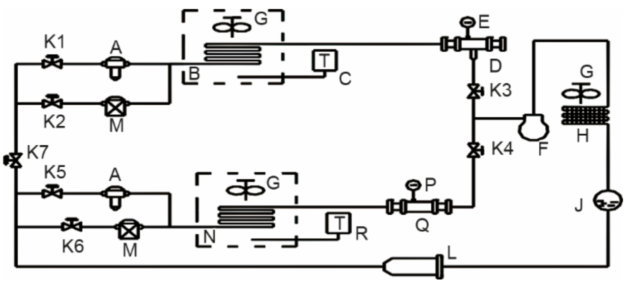


**Figure 1. The refrigeration system of the vehicle-mounted refrigerator;** *A – thermal expansion valve, B – evaporator in the cooler, C and R – temperature controller, D and Q – control valve for steam pressure, E and P – pressure gauge, F – compressor, G – fan, H – condenser, J – liquid receiver, L – device for drying and filtering, M – electronic expansion valve, N – evaporator in the freezer, K1-K7 – control valves*

The temperature-control mode of the thermal expansion valve works when K2 and K6 (manual valves) are closed while the control valves K1 and K5 are opened. The temperature-control mode of the electronic expansion valve works when the manual valves K1 and K5 are closed while control valves K2 and K6 are opened.

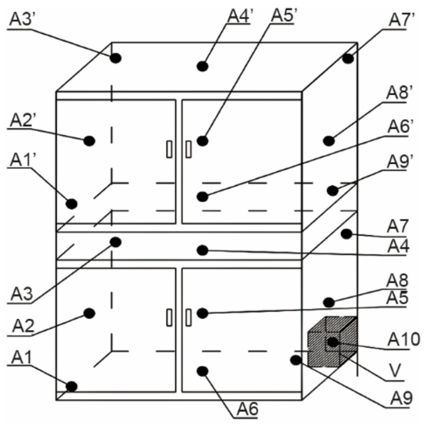


**Figure 2. Distribution of measuring points for temperature in the vehicle-mounted refrigerator;** *A1-A10 – measuring points for temperature and V – monitoring device for de-icing based on phase-change*

Before distributing the simulated measure points for temperature, it is necessary to balance the internal and external temperatures of the refrigerator to make them as close as possible. In our study, T-thermocouples were applied to measure temperature. There were 19 measure points and the distance of various measuring points to the internal wall of the refrigerator body was no less than 50 mm. The distribution of measuring points is shown in fig. 2.

Closing control valves K1, K2, and K5 while opening the control valve K6, the changes in temperature within the freezer with time under the load of 6-8% are shown in fig. 3.

The internal initial temperature of the refrigerator body was adjusted to 36.2 °C. As shown in fig. 3, within 90 minutes after starting the system, the temperature in the freezer rapidly reduced and the internal average temperature of the refrigerator body was about –5 °C. The outlet temperature of the evaporator was 1.0-2.5 °C lower than the average temperature and their temperature difference gradually increased upon prolonged operation of the refrigeration system. Subsequently, with the stable operation of the system, the temperature gradually decreased. When the system had been running for 214 minutes, the internal average temperature of the freezer was about –18 °C, reaching the temperature standard required of the freezer.

According to the simulated measure result, when conducting the simulation measure and regulating the units, it can be found that frost layers were repeatedly accumulated on the back of the freezer and at the vicinity of the right-lower corner (around the drainage hole for condensed water) of the freezer to form non-uniform ice layers. As shown in the simulation results, freezing started to occur on the back and at the right-lower corner of the freezer after the system had been run for 20 minutes. After 40 minutes, the thickness of frost layer increased to 2.20 mm, and it became 5.40 mm after system ran for 75 minutes.

## The system for defrosting (de-icing) and auxiliary refrigeration based on phase-change

The frost layer affects greatly the flow field [8-11], as a result, the cooling capacity is diminished, and the freezer defrosting [12, 13] is much needed, here the phase-change materials [14-16] are used for this purpose. The monitoring system for defrosting (de-icing) based on phase-change of diethylene glycol within the freezer of the vehicle-mounted refrigerator is illustrated in fig. 4, and its flowchart is shown in fig. 5.

The principle of the defrosting (de-icing) system based on phase-change at low temperature is as: after sending regulation instruction by the control system Z, the solution tank II was started, thus valves K11, K12, K15, and K16 were opened. Under the effect of the circulating pump Y3, the diethylene glycol (with concentration of 33% at temperature of –15 °C) flowed into the plate heat exchanger IV to transfer heat with the diethylene glycol (with concentration of 2.2% at temperature of –3 °C). Afterwards, the diethylene glycol (–17 °C) flowed back to solution tank II to begin a new cycle.

Under the effect of the circulating pump Y4, the diethylene glycol (with concentration of 2.2% at temperature of –3 °C) successively transferred heat with the refrigerant within the evaporator N in the freezer and the diethylene glycol (with concentration of 33% at temperature of –15 °C) at the left-hand side of the plate

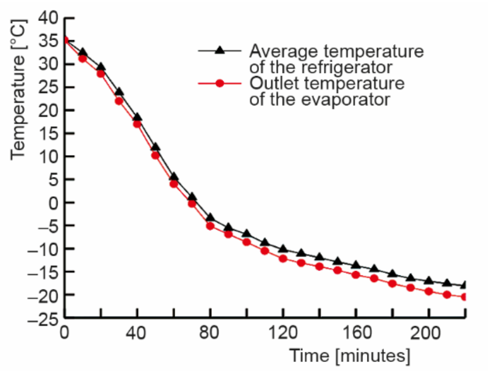


**Figure 3. Changes of temperature in the freezer with time under a load of 6-8%**

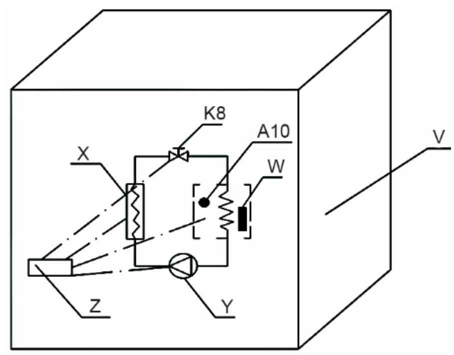


**Figure 4. The monitoring system for defrosting (de-icing) through heat storage by the phase-change material within freezer of vehicle-mounted refrigerator;** *V – monitoring devices for de-icing through heat storage by the phase-change material, W – auxiliary heating system, X – device for phase-change heat transfer, Y – circulating pump, Z – control system, K8 – solenoid valve, and A10 – measuring points for temperature*

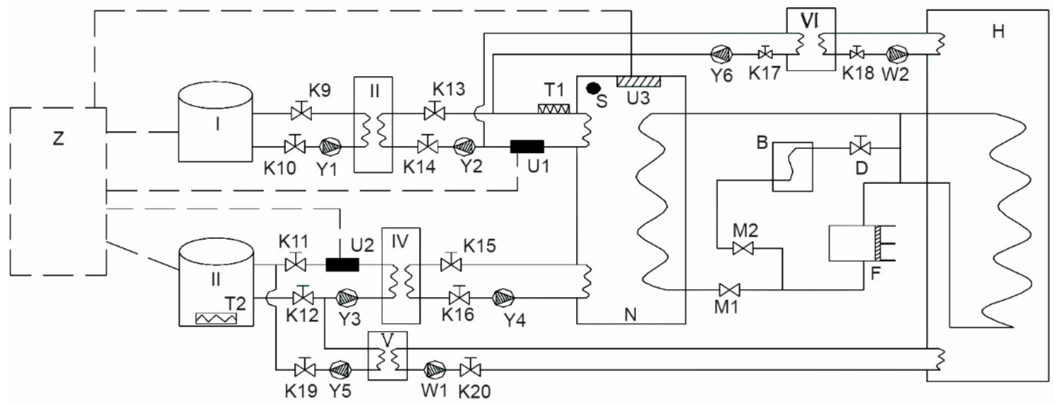


**Figure 5. The flowchart of the system for defrosting (de-icing) and auxiliary refrigeration based on phase-change within freezer of vehicle-mounted refrigerator;** *F – compressor, B – evaporator in cooler, N – evaporator in freezer, H – condenser, D – control valve for steam pressure, M1, M2 – electronic expansion valves, S – drainage hole, I, II – solution tanks, III-VI – plate heat exchangers,* $Na_2SO_4{\cdot}10H_2O$ *– energy accumulator, U1-U3 – temperature sensor, Z – control system, Y1-Y6 – circulating pumps, W1 and W2 – electronic pump, T1, T2 – auxiliary electric heating wire, K9-K20 – control valve*

heat exchanger IV. The temperature of the diethylene glycol after undergoing heat transfer was about –1 °C. The working fluid at the right-hand side of the plate heat exchanger IV released the phase-change heat, which was used for defrosting (de-icing) the surface of the coiler at the drainage hole of the freezer. Afterwards, a new cycle started. The $Na_2SO_4{\cdot}10H_2O$ energy accumulator U2 was utilised to monitor the changes in temperature of the diethylene glycol (with concentration of 33%) by absorbing heat from the working fluid–diethylene glycol (with concentration of 33%): when the temperature had decreased slightly, the accumulator U2 sent signals and then the control system Z emitted regulation instruction to conduct auxiliary heating by timeously starting auxiliary electric heating wire T2. In the case that the temperature of the solution decreased significantly, the accumulator U2 sent signals and then control system Z instructed the circulating pump Y5 and the electronic pump W1 to be started, and valves K19 and 20 to be opened. By doing so, the carrier – working fluid transferred heat in the plate heat exchanger IV with circulating cooling water at the side of the condenser for recycling condensing heat to prevent diethylene glycol (with concentration of 33%) from being frozen in the operating process at the side of solution tank II.

The principle of the auxiliary refrigeration system based on phase-change at low temperatures works as: The control system Z sent its instruction to start solution tank I (that is valves K9, K10, K13, and K14 were opened). Under the effect of circulating pump Y1, the diethylene glycol (with concentration of 2.2% at temperature of –1 °C) flowed back to the solution tank I (about –3 °C) after undergoing heat transfer with the diethylene glycol (with concentration of 33% at temperature of –15 °C) within the plate heat exchanger III. Thereafter, a new cycle was conducted. During practical operation of the system, the flocculent ice (frozen to release phase-change heat) generated within solution tank I can be filtered and removed by employing a centrifugal filter. Moreover, the concentration of solution within the solution tank I was monitored and solution in reserve was added appropriately to maintain the stability of the concentration of the solution (with concentration of 2.2%).

Under the effect of circulating pump Y2, the diethylene glycol (with concentration of 33% at temperature of –15 °C) successively transferred heat with refrigerant within evaporator N in the freezer and the diethylene glycol (with concentration of 2.2% at temperature of –1 °C) at the left-hand side of plate heat exchanger III. The temperature of diethylene glycol undergoing heat transfer was about –17 °C. Thereafter a new cycle started. $Na_2SO_4 \cdot 10H_2O$ energy accumulator U1 can monitor the change of temperature of diethylene glycol(with concentration of 33%) by absorbing heat from the diethylene glycol(with concentration of 33%): when the temperature decreased slightly, U1 sent signals and then control system Z issued regulating instruction to conduct auxiliary heating by timeously starting auxiliary electric heating wire T1, on condition that the temperature had significantly decreased, U1 sent signals and then control system Z issued regulating instruction to start circulating pump Y6 and electronic pump W2 and open valves K17 and 18. In this way, the carrier–working fluid transferred heat in plate heat exchanger VI with circulating cooling water at the side of the condenser for recycling condensing heat to prevent diethylene glycol (with concentration of 33%) from being frozen in the operating process at the side of the evaporator.

The devices including solution tanks (I and II) for phase-change heat storage (release) at low temperatures within the freezer of the vehicle-mounted refrigerator are displayed in fig. 6.

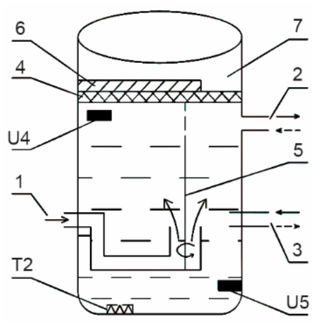


**Figure 6. Devices mounted on solution tanks (I and II);** *1 – injection port of heavy and light liquids, 2 – inlet and outlet of heavy liquid (diethylene glycol), 3 – outlet and inlet of heavy liquid (diethylene glycol), 4 – liquid–liquid separator, 5 – rotating blades for separating heavy and light liquids, 6 – top-mounted pre-coat filter, 7 – port for taking ice, T2 – auxiliary electric heating wire, and U4 and U5 – temperature sensors*

As shown in fig. 6, insoluble heavy and light mixed liquids were injected to the hybrid cavity within the tank from the injection port 1 (or the inlet for adding clean water into the tank after flocculent ice was taken out from the port 7 for taking ice at top of the solution tank). Afterwards, the mixed cavity was divided into two vertical cavities through the rotating blades 5 (with function of self-priming pump) for separating heavy and light liquids so that they remained mutual equilibrium in the flowing process. Temperature sensors U4 and U5 were applied to timeously monitor changes in surface temperature of solution at the top, and bottom, of the tank. When the temperature of solution in the hybrid cavity within the tank decreased slightly, the control system sent regulating instructions to carry out auxiliary heating by timeously starting the auxiliary electric heating wire T2.

The following assumptions are made for numerical study of the monitoring model for defrosting (de-icing). The zone in the freezer is likely to be frosted and frozen and air in the freezer is treated as incompressible ideal air, the influence of frozen food, supporting material, *etc*. within the freezer on the flow field is ignored, the model is simplified into a 3-D problem, and the temperature of the closed zone is uniform. The grid division of the vehicle-mounted refrigerator model is shown in fig. 7.

As shown in fig. 7, the mesh of the model was divided by hexahedron. The minimum element control of the mesh in the air area in the closed interval was 1.5 mm, and the minimum element control of the heating tube and the heat transfer fluid area in the tube was 0.5 mm.

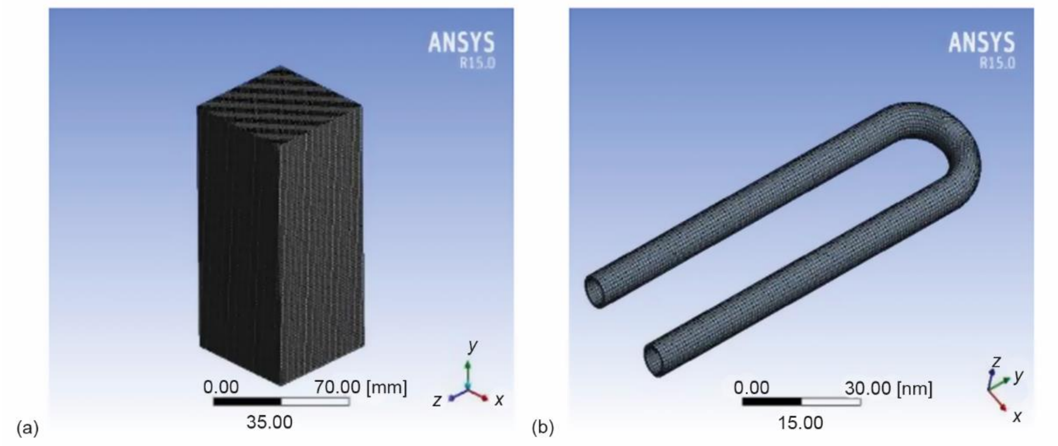


**Figure 7. The grid division of the vehicle-mounted refrigerator model; (a) overall grid division and (b) heating tube meshing**

## Results and analysis

By conducting theoretical analysis, 3-D unsteady-state numerical simulation was carried out. The cloud atlas (at the location where the center of the heat exchange tube was normal to, and 20 mm from the section) of changes in temperature in the closed region at different times is shown in fig. 8. Cloud atlas (40 seconds) of temperature distribution at parallel to the heating tube ($D$ = 20 mm, $D$ = 30 mm, and $D$ = 40 mm) at different positions is shown in fig. 9.

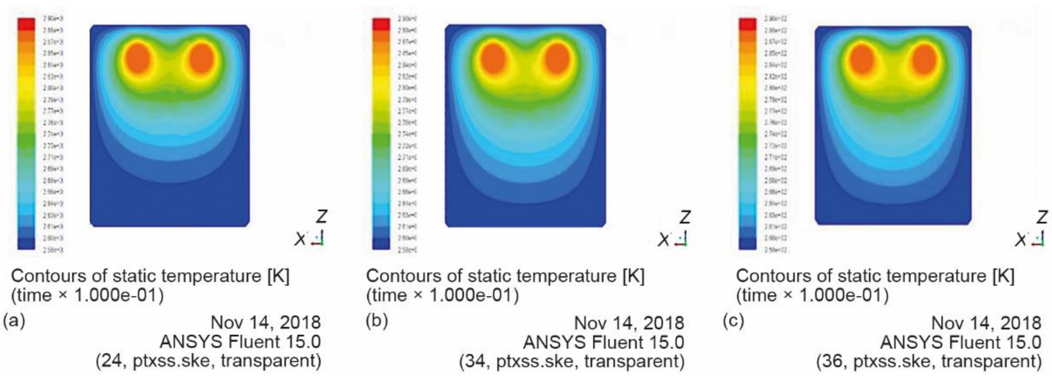


**Figure 8. Cloud atlas (H = 60 mm) of temperature distribution at cross-sections at different times; (a) 10 seconds, (b) 20 seconds, and (c) 60 seconds**

As shown in figs. 8 and 9, when the system had run for 10 seconds, the temperature of the section in the closed region at $H$ = 60 mm had changed. At 20 seconds, the heated zone was gradually extended and it gradually stabilised. The frosting of the coiler in the freezer decreased the heat transfer performance, causing a reduction in efficiency of the refrigeration system. The result showed that if a monitoring system for de-icing based on phase-change was set in a zone where frosting easily occurred in the freezer of the vehicle-mounted refrigerator, the temperature 60 mm from the zone could increase significantly within a short time.

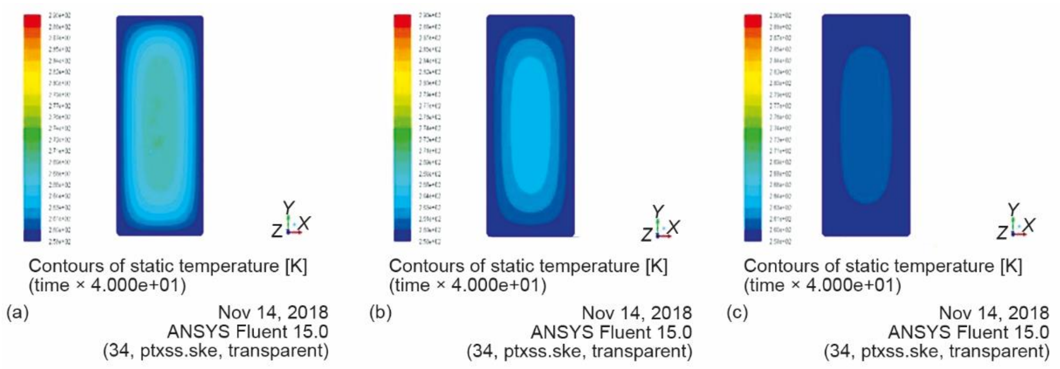


**Figure 9. Cloud atlas (40 s) of temperature distribution at parallel to the heating tube at different positions; (a) 20 mm, (b) 30 mm, and (c) 40 mm**

Frosting of freezer coils reduces the heat transfer capacity, resulting in less efficient refrigeration systems. At the same time and at different sections, the closer the distance from the heating tube, the higher the temperature, that is, the temperature at $D = 20$ mm > $D = 30$ mm > $D = 40$ mm. The results showed that the phase change de-icing monitoring system is set up in the frosting area of the on-board freezer, and the temperature in the area of 60 mm can be greatly improved in a short time, which can quickly and effectively defrost and prevent the frosting (ice) phenomenon on the coil surface at the drainage hole. In this way, it rapidly and effectively realised defrosting and prevented frosting (freezing) on the surface of the coiler at the drainage hole. The results revealed that the established model for monitoring and analyzing defrosting (de-icing) based on phase-change was reasonable. Through the simulation results, the defrosting scheme was verified to be feasible. This research applied phase-change cold storage technology to refrigerated transportation equipment (such as vehicle-mounted refrigerators, refrigerated carriages, *etc.*), aiming to reduce the energy consumption of perishable food during refrigerated transportation.

## Conclusions

This research applies the phase-change cold storage technology to refrigerated transportation equipment, and the result showed that in a vehicle-mounted refrigerator system, compared with the thermal expansion valve, the electronic expansion valve could be randomly adjusted to simulate the temperature within –25 °C to –5 °C. Under working conditions, when the load in the freezer was varied by 6%-8%, the average temperature within the freezer reduced to –5 °C to –18 °C. A systemic scheme was proposed for compensating for insufficient refrigeration capacity under a large temperature difference, realising refrigeration of the auxiliary system, timely monitoring and precise defrosting (de-icing). After the system was optimised and improved, the electronic expansion valve can effectively control the opening of the valve to guarantee stability of the refrigeration system.

The future research frontier is to study the wetting property of frosted surface, a super-hydrophobic surface [17, 18] can produce an extremely high moisture repellence to remove ice efficiently.

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