Numerical Simulation on Cooling Process of Phase Change Cool Storage Device for Rail Vehicle Air Conditioning System

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Abstract. In order to face emergency situation of the rail vehicle air conditioning system, a cool storage device was designed. The device was made up of phase change paraffin and heat exchanger. For the purpose of optimum system design, the mathematic model of phase change and heat transfer in process of cool discharging was established, numerical simulation was finished. Discharging rate of cool and cooling capacity of the device was analyzed. According to the calculation results, the wind speed and air temperature had the greatest influence on the cooling effect, while the thermal conductivity had little effect on it.

1. Introduction
The rapid development of rail vehicles such as high-speed railway, motor train and subway has met people's growing transportation needs, but how to make full-closed carriages meet passenger's minimum requirements for comfort within a certain period of time when emergency situations occur is the biggest problem. A phase change cold storage device, which has the advantages of high energy storage density and approximate isothermal storage and cooling process, is invented in this paper to adjust the temperature of the full-closed carriages.

Ye Hong et al. [1] found the effective thermal conductivity of the phase change material on the tube side has a significant impact on the performance of the heat exchanger. An experimental study on the shell-and-tube phase change heat exchanger with paraffin as heat storage material is carried out by Anita Trp [2]. Zanxia Wu et al. [3] found that the high temperature phase change material meet the requirements of Submarine cold storage air conditioning. After detailed researched, solid-solid phase change paraffin is selected as the energy storage material for air conditioning of railway vehicles, which not only can be repeatedly melted and solidified without supercooling but also remains solid state.

2. Cooling Process Simulation Calculation of Cold Storage Device
Numerical simulation method is used to simulate complex phase-change process.

2.1. Geometric Model Simplification
For the structure of air duct and the condition of wind resistance, Circular tube bundles and flat tube bundles is placed in the air supply duct of train air conditioning system as two kinds of cold storage device’s structure.

The circular tube heat exchange unit is simplified into a 2D model of the section, as shown in Figure 1. Among them, L1 is the width direction spacing of each heat exchange tube in the heat exchanger, L2 is the height direction spacing of the heat exchange tube, and d is the outer diameter of
heat exchange tube.

Figure 1. Simplified schematic diagram of simulation model for heat transfer unit of circular tube

Similarly, only a small section of the cross section in flat tube heat exchanger unit is intercepted as the research object, as shown in Figure 2. Among them, L is the width direction spacing of each heat exchange flat tube, H is the height of the heat exchange flat tube, and D is the thickness of heat exchange flat tube.

Figure 2. Simplified schematic diagram of simulation model for flat tube heat transfer unit

2.2. Physical Model
The calculation object is circular tube and flat tube bundles (filled with phase change materials) in Figure 1, 2. The pipe is made of aluminium alloy; the phase change material is solid-solid phase change paraffin. And its phase change temperature is 20°C. Other physical properties are listed in the following table:

| Material name            | density /kg·m⁻³ | Thermal conductivity /W·(m·K)⁻¹ | Specific heat capacity /J·(kg·K)⁻¹ | Kinematic viscosity /m²·s⁻¹ |
|--------------------------|-----------------|---------------------------------|-----------------------------------|-----------------------------|
| Air                      | 1.28            | 0.0026                          | 1005                              | 1.59×10⁻⁵                   |
| phase change material    | 0.88            | 2.38                            | 3.22                              | solid                       |
| aluminium alloy          | 2700            | 170                             | 880                               | solid                       |

The following simplifications and assumptions are made for the heat transfer of the calculated object:
1) The main heat transfer direction of circular tube is radial; the main heat transfer direction of flat
1) The tube is perpendicular to the wall.
2) The air velocity and temperature distribution between the voids of each single tube in the heat exchanger unit are uniform.
3) The heat exchange process of each single tube in the heat exchanger unit is completely the same.
4) The wall thickness is 0.5 mm, so the heat transfer in the pipe wall is simplified to heat transfer resistance.

2.3. Mathematical Model

In summary, the simulation calculation of the unit type cold storage heat exchanger cooling process is simplified to the simulation calculation of the single tube cooling process.

1) Control equation:

$$\rho c \frac{\partial T}{\partial t} = \nabla \cdot (\lambda \nabla T) + S$$

In this formula, \(\rho\) is the phase change material density, \(T\) is the instantaneous temperature of phase change material, \(\lambda\) is the thermal conductivity of phase change material, \(S\) is the phase change latent heat of phase change material.

2) Initial conditions: The initial temperature of phase change material and pipe was 17°C, and the air supply temperature of duct was 35°C.

3) Boundary conditions: The convective heat transfer boundary conditions on side wall of pipe are as follows:

$$\lambda \frac{\partial T}{\partial n} = h(T - T_a)$$

In this formula, \(\lambda\) is the thermal conductivity of phase change material, \(T\) is the instantaneous temperature of phase change material, \(T_a\) is the ambient temperature (air supply temperature of duct), \(h\) is the convective heat transfer coefficient of tube wall [4].

4) Source term processing:

How to deal with the source term is the core problem and difficulty of phase change heat transfer. The equivalent heat capacity method is used to deal with it in this simulation calculation, that is, the real-time latent heat of phase change in the phase change temperature range is superimposed on the original specific heat capacity of the phase change material according to the phase change curve obtained from DSC test, which enables the equivalent heat capacity method to reflect actual change of phase change’s latent heat in the phase change temperature range in real time. As shown in the following figure:

![Figure 3](image)

**Figure 3.** Specific heat capacity of cold storage material in phase-change temperature region (19°C - 24°C)
3. Calculation Results and Analysis

3.1. Influence of Wind Speed Change on Cooling Time

The influence of air velocity outside the tube on heat transfer of circular tube and flat tube is ultimately reflected in the influence of air flow on convective heat transfer, and the size of air velocity directly determines the size of convective heat transfer coefficient. The relationship between convective heat transfer coefficient and wind speed obtained by theoretical calculation of the air longitudinally passing through the tube bundle is shown in the following table [5]:

| Pipe size /mm | Outer diameter of tube:10 | Flat tube: 100 × 5 | Flat tube: 100 × 10 | Flat tube: 100 × 15 |
|---------------|---------------------------|---------------------|---------------------|---------------------|
| 5m/s          | 20                        | 19                  | 19                  | 19                  |
| 7m/s          | 26                        | 25                  | 25                  | 25                  |
| 9m/s          | 31                        | 31                  | 31                  | 31                  |

For example, when the flat tube thickness is 5 mm, the initial temperature is 17°C, the ambient temperature is 35°C, and the thermal conductivity of the cold storage material is 2.38 W/m K, the heat flux density and the cumulative cooling capacity per unit tube length change with time at different wind speeds as shown in Figures 4 and 5:

![Figure 4. Variation curves of heat flux density on tube wall under different wind velocities](image-url)
Figure 5. Variation curve of cooling capacity per unit tube length under different wind velocities

Under the same working conditions, the heat transfer unit of circular tube with diameter of 10 mm is also simulated, simulation results is listed:

Table 3. Cooling time of 5 mm pipe thick flat pipe and 10 mm pipe diameter circular pipe at different wind speeds

| Wind speed/m·s⁻¹ | 100% Cooling time/s | Decreased cooling time/% | Cooling capacity per unit length of pipe/J·m⁻¹ | Wind speed/m·s⁻¹ | 100% Cooling time/s | Decreased cooling time/% | Cooling capacity per unit length of pipe/J·m⁻¹ |
|------------------|---------------------|--------------------------|-----------------------------------------------|------------------|---------------------|--------------------------|-----------------------------------------------|
| 5                | 1395                |                          |                                               | 5                | 1504                |                          |                                               |
| 7                | 1062                | 23.87                    | 82520                                         | 7                | 1163                | 22.67                    | 13138                                         |
| 9                | 858                 | 19.21                    |                                               | 9                | 979                 | 15.82                    |                                               |

3.2. Influence of Ambient Temperature Change on Cooling Time

For example, when the flat tube thickness is 5 mm, the initial temperature is 17°C, the wind speed is 9 m/s and the thermal conductivity of the cold storage material is 2.38 W/m K, the heat flux density and the cumulative cooling capacity per unit tube length under different ambient temperatures are shown in Figures 6 and 7 respectively:

Figure 6. Variation curves of heat flux density on tube wall at different environmental temperatures
Figure 7. Variation curve of cooling capacity per unit tube length at different environmental temperatures

Under the same working conditions, the heat transfer unit of circular tube with diameter of 10 mm is also simulated, simulation results is listed:

Table 4. Cooling time of 5 mm pipe thick flat pipe and 10mm pipe diameter circular pipe at different ambient temperatures

| Ambient Temperatures /°C | 100% Cooling Time/s | Decreased Cooling Time/% | Cooling Capacity per Unit Length of Pipe /J·m⁻¹ | Ambient Temperatures /°C | 100% Cooling Time/s | Decreased Cooling Time/% | Cooling Capacity per Unit Length of Pipe /J·m⁻¹ |
|--------------------------|----------------------|--------------------------|-----------------------------------------------|--------------------------|----------------------|--------------------------|-----------------------------------------------|
| 28                       | 1848                 | 0                        | 75096                                        | 28                       | 2098                 | 0                        | 11939                                        |
| 35                       | 858                  | 53.57                    | 82520                                        | 35                       | 979                  | 53.34                    | 13138                                        |
| 42                       | 562                  | 34.50                    | 89899                                        | 42                       | 645                  | 34.12                    | 14363                                        |

3.3. Effect of Thermal Conductivity on Cooling Time
A simulation is calculated under the conditions of initial temperature 17°C, ambient temperature 35°C, wind speed 9 m/s but different thermal conductivity to investigate the influence of thermal conductivity of cold storage material on its cooling time. The simulation results of heat transfer units of 5 mm thick flat tube and 10 mm diameter circular tube are listed in the following table:

Table 5. Cooling time of 5 mm pipe thick flat pipe and 10mm pipe diameter circular pipe at different thermal conductivity

| Thermal Conductivity /W·(m·K)⁻¹ | 100% Cooling Time/s | Decreased Cooling Time/% | Cooling Capacity per Unit Length of Pipe /J·m⁻¹ | Thermal Conductivity /W·(m·K)⁻¹ | 100% Cooling Time/s | Decreased Cooling Time/% | Cooling Capacity per Unit Length of Pipe /J·m⁻¹ |
|---------------------------------|----------------------|--------------------------|-----------------------------------------------|---------------------------------|----------------------|--------------------------|-----------------------------------------------|
| 1.4                             | 865                  | 0                        | 82520                                        | 1.4                             | 996                  | 0                        | 13138                                        |
| 2.38                            | 858                  | 0.72                     | 13138                                        | 4                               | 971                  | 0.82                     | 13138                                        |
| 4                               | 854                  | 0.47                     | 13138                                        |                                 |                      |                          |                                               |
3.4. Influence of Tube Thickness (Tube Diameter) on Cooling Time
A simulation is calculated under the working conditions that 17°C initial temperature, 35°C ambient temperature, 2.38 W/m·K thermal conductivity coefficient of the cold storage material, 9 m/s wind speed, but different tube thickness (tube diameter) to investigate the effect of tube thickness (tube diameter) on the cooling time of the cold storage device, and simulation results is listed:

Table 6. Cooling time of 5mm pipe thick flat tube and 10mm tube diameter circular tube at different tube thickness (tube diameter)

| tube thickness /mm | Flat tube | | | circle tube | | |
| --- | --- | --- | --- | --- | --- | --- |
| 100% cooling time/s | Decreased cooling time /% | Cooling capacity per unit length of pipe /J·m⁻¹ | tube diameter /mm | 100% cooling time/s | Decreased cooling time /% | Cooling capacity per unit length of pipe /J·m⁻¹ |
| 5 | 858 | 56.18 | 82520 | 5 | 508 | 44.09 | 3147 |
| 10 | 1958 | 36.53 | 185381 | 7 | 732 | 25.23 | 6561 |
| 15 | 3085 | 286314 | 10 | 979 | 13138 |

4. Conclusions and Recommendations
The following conclusions can be drawn:
1) The most important factors affecting the cooling time are wind speed (convective heat transfer coefficient) and ambient temperature, the slightly weaker factor is tube thickness (tube diameter). In addition, the change of ambient temperature has a great influence on the cumulative cooling capacity.
2) Thermal conductivity has little effect on cooling time.
3) The following principles should be followed when selecting materials and designing the structure: phase change latent heat should be taken into account while thermal conductivity should not be taken into adequate account; flat tubes are recommended for comprehensive consideration.
   The structure, size and air supply temperature of heat exchanger should be reasonably selected.

5. References
[1] Hong Ye, Xiao Hao, Danpeng Cheng, et al 2008 Numerical investigation on heat storage and heat exchange of the shell-and-tube phase change heat exchanger Journal of Solar Energy 29 (12) 1499-1503.
[2] Trp A 2005 An experimental and numerical investigation of heat transfer during technical grade paraffin melting and solidification in a shell-and-tube latent thermal energy storage unit Solar Energy 79 (6) 648-660.
[3] Zanxia Wu, Gang Wu, Qianghong Zeng, et al 2008 Numerical simulation of cold storage materials used in submarine air conditioning Fluid machinery 36 (5) 75-78.
[4] Shuying Wu, Nan Wang, Dongsheng Zhu, et al 2012 Study on thermal conductivity of nanocopper/paraffin composite phase change heat storage materials New chemical materials 40 (5) 104-106.
[5] Rosnaud. Handbook of Basic Heat Transfer Science [M]. Science Press, 1992.
[6] Yudong Liu, 2005 Preparation and thermophysical properties of nanocomposite low temperature phase change cold storage materials (Chongqing: Chongqing University).
[7] Aigang Pan, Jundiao Wang, Xianjie Zhang 2014 Phase change heat transfer numerical analysis based on equivalent heat capacity method and enthalpy method Computer simulation 31 (2) 315-319.