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Effects of initial parameters on the internal-melt ice-on-tube while icing[†]

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Abstract

Numerical simulation method is widely used in studying ice-storage process in an ice-storage system. In this paper, the three-dimensional dynamical mathematical model of the ice-storage process in a single tube is established and the process is solved by the enthalpy method. Effects on the performance of heat-exchange, caused by variation of velocity of the refrigerant, inner diameter of the tube, initial temperature of the external water and inlet temperature of the refrigerant, are simulated and analyzed.

Keywords: Internal-melt ice-on-tube; Ice storage; Enthalpy method; Heat exchange capability

1. Introduction

With the gradual aggravation of the world energy crisis, ice-storage air-conditioning systems have been applied more and more widely because of the relatively simple structure and significantly social and economical benefits. In the variety of ice-storage systems, internal-melt ice-on-tube system is extolled for its highly reliability and capability of storing and melting ice rapidly. Therefore, investigation on the characteristics of ice melting in this system has great value for application and development of ice-storage technology. Due to the importance of this subject, there have been a large number of related theoretical [1-3] and experimental [4, 5] researches in western countries. However, in China, since related studies began lately from 1990s, domestic theoretical [6, 7] and experimental [8, 9] investigations are still in the starting stage. In this paper, dynamical simulation of the ice-storage process in internal-melt ice-on-tube system has been made using the enthalpy method, and effects on the performance of heat-exchange caused by variation of initial parameters have been simulated and analyzed.

2. Physical model

Ignoring the impacts of natural convective heat transfer, the icing process in a single tube with glycol as refrigeration is setting up, and following assumptions are made to simplify the problem:

(1) The water in the ice bank tank is ideal fluid and in a homogeneous state, the initial temperature is constant, $t_w > 0\,^{\circ}\mathrm{C}$;

(2) In the process of heat transfer, the physical parameters of glycol, ice and water are constant;

(3) Axial heat conduction (along the flow direction) can be neglected;

(4) In a single tube, the distribution of temperature and velocity of glycol in the same section is homogeneous and constant;

(5) The wall of tube is quite thin and the heat conductivity is great, hence heat resistance of the wall can be neglected;

(6) Natural convective heat transfer of the external water is neglected;

(7) Thermal insulation of the ice bank tank is in a high level, and heat loss to the surroundings can be neglected.

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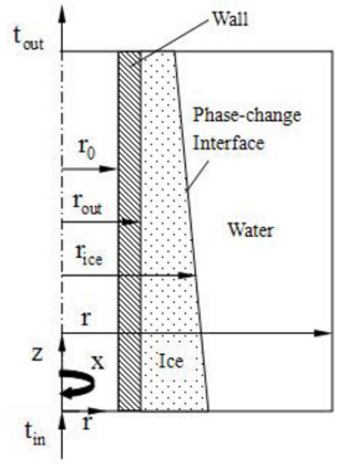

Fig. 1. Sketch of the physical model.

3. Mathematical model solution method

Cylindrical coordinate system is adopted to establish the mathematical model, and governing Equations [10] are shown as following:

Convective heat transfer equation (in the tube):

$$\frac{\partial t_b}{\partial \tau} = -v_b \frac{\partial t_b}{\partial x} + \frac{2k_t}{r_0(\rho c_p)_b} \frac{\partial t_t}{\partial r}\Big|_{r_0} \tag{1}$$

Heat conduction equation (in the ice layer):

$$(\rho c_p)_s \frac{\partial t_s}{\partial \tau} = k_s\left(\frac{\partial^2 t_s}{\partial r^2} + \frac{1}{r}\frac{\partial t_s}{\partial r} + \frac{\partial^2 t_s}{\partial z^2} + \frac{1}{r^2}\frac{\partial^2 t_s}{\partial \theta^2}\right) \tag{2}$$

Heat conduction equation (in the water layer):

$$(\rho c_p)_l \frac{\partial t_l}{\partial \tau} = k_l\left(\frac{\partial^2 t_l}{\partial r^2} + \frac{1}{r}\frac{\partial t_l}{\partial r} + \frac{\partial^2 t_l}{\partial z^2} + \frac{1}{r^2}\frac{\partial^2 t_s}{\partial \theta^2}\right) \tag{3}$$

Energy Equation (in the phase-change interface):

$$\left[1 + \left(\frac{\partial r(\tau)}{\partial z}\right)\right]\left(k_s \frac{\partial t_s}{\partial r} - k_l \frac{\partial t_l}{\partial r}\right) = \lambda \rho_s \frac{\partial r(\tau)}{\partial \tau} \tag{4}$$

Eqs. (2), (3), (4) could be transformed into a unified expression involving two variables using the enthalpy method, the result is:

$$\rho \frac{\partial h}{\partial \tau} = k\left(\frac{\partial^2 t}{\partial r^2} + \frac{1}{r}\frac{\partial t}{\partial r} + \frac{\partial^2 t}{\partial z^2} + \frac{1}{r^2}\frac{\partial^2 t_s}{\partial \theta^2}\right) \tag{5}$$

where,

Table 1. Basic parameters of calculation.

specific heat of refrigerant	3.85kJ/ (kg·°C)
density of refrigerant	1030kg/m^3
heat conductivity of refrigerant	0.5W/ (m·°C)
dynamic viscosity of refrigerant	1.77mPa·s
velocity of refrigerant	0.5m/s
inlet temperature of refrigerant	-10 °C
inner diameter of tube	17mm
external diameter of tube	20mm
inner diameter of ice bank tank	0.4m
length of ice bank tank	1m
heat conductivity of ice	2.215W/ (m·°C)
density of ice	916kg/m^3
specific heat of ice	2090J/ (kg·°C)
heat conductivity of water	0.551W/ (m·°C)
density of water	1000kg/m^3
specific heat of water	4187J/ (kg·°C)
Phase-change temperature	0 °C
latent heat of phase change	335kJ/kg
initial temperature of water	20 °C

$$\rho = \begin{cases} \rho_s \\ \rho_l \end{cases} \qquad k = \begin{cases} k_s & h_s < h_s^* \\ k_l & h_l > h_l^* \end{cases} \tag{6}$$

$$t = \begin{cases} t_{ph} + (h - h_s^*)/c_s & h < h_s^* \\ t_{ph} & h_s^* \le h \le h_l^* \\ t_{ph} + (h - h_l^*)/c_l & h > h_l^* \end{cases} \tag{7}$$

where x is polar coordinate, degree; r is radial coordinate, m; z is axial coordinate, m; t_b is the temperature of fluid in the tube, °C; t_t is the temperature of the wall, °C; t_s is the temperature of the ice layer, °C; t_l is the temperature of the water, °C; k_b, k_s, and k_l are separately heat conductivity of glycol, ice and water, W/ (m·°C); ρ_b, ρ_s and ρ_l are separately density of glycol, ice and water, J/ (kg·°C); τ is time, s; λ is latent heat of phase change, J/kg; t_{ph} is the phase-change temperature, °C; h_s^* and h_l^* are separately enthalpy of ice and water in the condition that $t = t_{ph}$, J/kg.

4. Effects of different initial parameters

The ice bank tank is designed as a cylinder, and the basic parameters of calculation are shown in Table 1.

Simulation results and analysis are discussed as following:

Fig. 2 shows that, heat-exchange quantity increases with the increasing time of ice storage, and heat transfer rate tends to increase at first then decrease along with the increasing time of ice storage. In the first 7 hours of ice storage, along the radial direction the status of water in the tank is mixture of ice and water. Heat resistance between the tube and the phase-change interface gradually increases along with the increasing time of ice storage, yet the amount of ice significantly increases around the phase-change interface along with the time increasing, which exerts more positive effects on ice storage than the negative effects caused by the increasing of heat resistance between the tube and the phase-change interface. Therefore, before the interface reaches the wall of ice bank tank, heat-exchange rate increases along with the time increasing. After 7 hours of ice storage, water at the entrance of ice-on-tube fully freezes and the freezing part moves along the axial direction. After the interface reaches the wall, ice storage quantity is confined by the wall of ice bank tank and heat-exchange rate decreases gradually.

Fig. 3 shows effects of variation of velocity of refrigerant on heat-exchange quantity. In the same ice storage time, heat-exchange quantity increases along with increasing of velocity of refrigerant. The result is reasoned for that, outlet refrigerant temperature decreases with the increasing of refrigerant velocity, and temperature difference between tube wall and ice increases along the axial direction with time increasing, then more cooling-capacity would be provided in the same period of ice storage, and heat-exchange quantity would increase.

Fig. 4 shows effects of variation of inner diameter of the tube on heat-exchange quantity. In the same ice storage time, heat-exchange quantity increases along with increasing of inner diameter of the tube. The result is reasoned for that the larger the inner diameter of the tube, the more refrigerant flows through the tube in the same ice storage time, the more cooling-capacity would be provided, and then heat-exchange quantity would increase as the temperature difference inside the system increasing.

Fig. 5 shows effects of variation of initial tem-

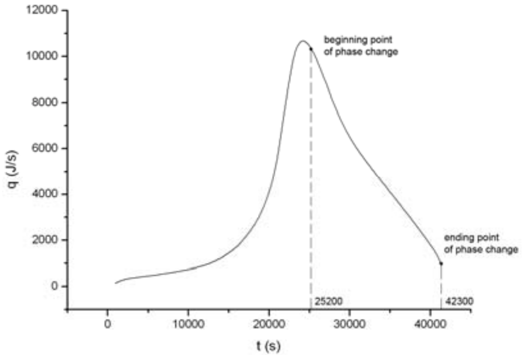

Fig. 2. Heat transfer rate changing with time.

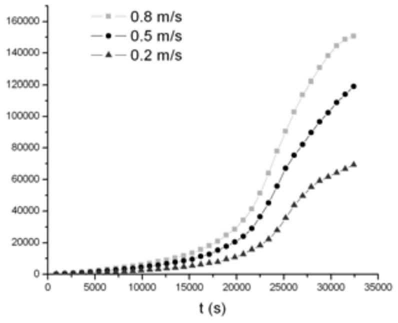

Fig. 3. Effects of variation of velocity of refrigerant on heat-exchange quantity.

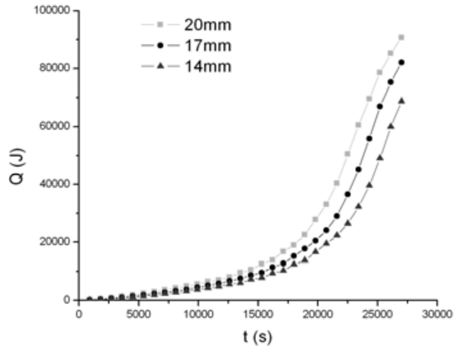

Fig. 4. Effects of variation of inner diameter of the tube on heat-exchange quantity.

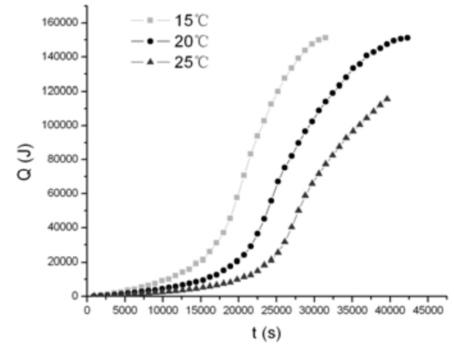

Fig. 5. Effects of variation of initial temperature of water on heat-exchange quantity.

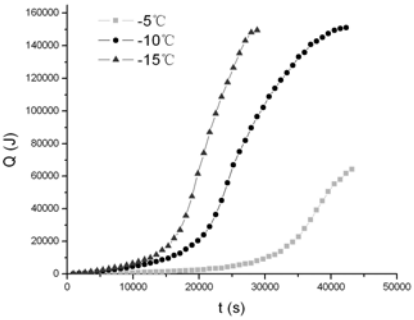

Fig. 6. Effects of variation of inlet temperature of refrigerant on heat-exchange quantity.

perature of water on heat-exchange quantity. In the same ice storage time, heat-exchange quantity decreases along with increasing of initial temperature of water. The result is reasoned for that the higher the initial temperature of water, the more sensible heat there is, and then more heat quantity would be demanded before the temperature of water reaches phase-change point, so that heat-exchange quantity would increase with decreasing of initial temperature of water in the same period of ice storage.

Fig. 6 shows effects of variation of inlet temperature of refrigerant on heat-exchange quantity. In the same ice storage time, heat-exchange quantity increases along with decreasing of inlet temperature of refrigerant. The result is reasoned for that if the inlet temperature of refrigerant is lower then the temperature of each point in the tube along the axial direction is lower at the same time, temperature difference inside the system would increase, therefore heat-exchange quantity would increase.

5. Conclusions

(1) Heat exchange rate gradually increases before the ice-storage radius reaches its maximum value, and heat exchange rate gradually decreases after the maximum value of ice-storage radius is reached.

(2) Phase change will take place in advance if the velocity of refrigerant accelerates or the inner diameter of ice-storage tube increases. Because of the influence of latent heat in phase change, the heat-exchange capability increases remarkably in the same time. In 7 hours of ice storage, the heat-exchange capability will increase to 1.75 times larger as the velocity of refrigerant increases every 0.3m/s, and it will increase to 1.4 times larger as the inner diameter of the tube increases per 3mm.

(3) Phase change will take place in advance if initial temperature of the external water decreases or inlet temperature of the refrigerant decreases. Because of the influence of latent heat in phase change, the heat-exchange capability increases remarkably in the same time. In 7 hours of ice storage, the heat-exchange capability will increase to 2.7 times larger as the initial temperature of the external water decreases every 5^{o}C, and it will increase to 15 times larger as the inlet temperature of the refrigerant decreases every 5^{o}C.

(4) At the condition that the inlet refrigerant temperature of -10 ^{o}C, refrigerant velocity of 0.5m/s, and initial water temperature of 20 ^{o}C, 99.5 percent of water would become ice at the ending time after 11.75 hours of ice storage.

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