한국기계가공학회지, 제19권, 제1호, pp.114∼120(2020.01) ISSN 1598-6721(Print)
Journal of the Korean Society of Manufacturing Process Engineers, Vol. 19, No. 1, pp.114~120(2020.01) ISSN 2288-0771(Online)

https://doi.org/10.14775/ksmpe.2020.19.01.114

Numerical Analysis of Freezing Phenomena of Water around the Channel Tube of MF Evaporator

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MF증발기 채널관 주위의 결빙현상에 대한 해석적 연구

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(Received 22 October 2019; received in revised form 10 November 2019; accepted 24 November 2019)

ABSTRACT

In this study, the process of freezing around two consecutively arranged channel tubes used for evaporator heat exchange was numerically investigated. Numerical results confirmed that the vortex occurred between the front channel and the rear channel and also that the vortex occurred due to the rapid change of the channel at the rear of the rear channel. These vortices were found to play a role in reducing the ice layer to some extent by the growth of the ice layer at the front and rear of the channel tube. The freezing layer showed a tendency to gradually increase as it passed through the channel pipe. As the wall temperature in the channel pipe decreased, the thickness of the freezing layer increased. As the flow rate of water slowed, the thickness of the freezing layer became thicker. In particular, in the case of a slow flow rate of 0.03 m/s, the freezing layers of the front channel pipe and the rear channel pipe were connected to each other. The narrower the channel, the thinner the freezing layer was in both the front and rear channel tubes. It is found that these thin freezing layers are caused by the low thickness of the temperature boundary layer formed around the channel tube.

Key Words : Freezing(결빙), Channel Tube(채널관), Water(물), Numerical Analysis(수치해석), Heat Exchanger (열교환기)

1. Introduction

Evaporators and condensers made up of heat exchangers play an important role in absorbing and discharging heat in air-conditioning refrigeration systems. At the same time, they also significantly affect these systems' efficiency. In order to improve heat exchangers' efficiency, miniaturization, slimming, and aggregation have been recently proposed. For the first time, microchannel heat exchangers consisting of microchannels of tubes under 1 mm using Micro Electro Mechanical Systems (MEMS) have been suggested on the published paper by Tuckerman DB and Pease

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RFW[1]. These microchannel tube heat exchangers are suitable for high performance, miniaturization, and aggregation, and are proving to be superior in performance[2]. For instance, Park and Pega[3] have demonstrated that microchannel tube heat exchangers perform better than pin-tube heat exchangers in the same volume. Park[4] also evaluated the performance and pressure changes depending on the shape of the head connecting the tube in channel tube heat exchangers. If the evaporator heat exchanger is used more often in the accumulator—which cools down water and wastewater from various industrial processes—or if the refrigerant in the evaporator tube drops below freezing temperatures, the fluid flowing outside the evaporator is subject to freezing[5]. As Fig. 1 shows, the cooling treatment system for water and the waste-heat recovery system for treating sewage tend to cause freezing problems around the externally-exposed heat exchanger. Therefore, an ice-making system is installed for externally-exposed heat-exchanger to prevent freezing, particularly freezing of the condenser.

The external freezing of the heat exchanger is influenced by the type of fluid, temperature, and flow rate, as well as the tube’s wall temperature, diameter, length, and other characteristics[6]. Suh and others[7-9] examined the factors that affect freezing within the straight piping, while Jeong[10] analyzed the freezing process within the straight piping considering the effects of natural convection.

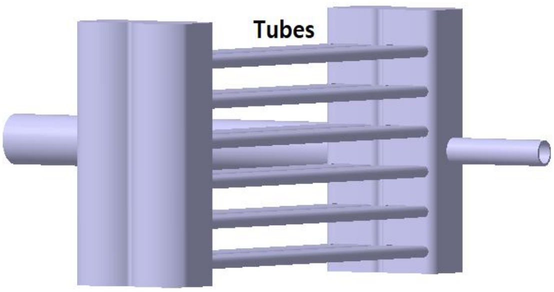

Fig. 1 Schematic diagram of the channel tubes installed into MF evaporator

In this study, we numerically and analytically examine the freezing process around the heat exchanger of externally-exposed Multi-Flow (MF) channel tubes, as Fig. 1 shows. The study’s aim is to verify the factors that affect freezing, the effects of changes in the exposed channel tube’s wall temperature, changes in flow rate, differences between channel tubes, and other effects on freezing.

2. Analysis

2.1 Problem setting

Refrigerator evaporators are generally composed of MFs, as Fig. 1 shows, and they are vaporized from liquid form through a process of evaporation at a constant temperature with low temperature refrigerant flowing into the tube. If the temperature of the refrigerant in the evaporator is lower than the freezing temperature of the fluid around the evaporator, then freezing occurs around the evaporator. As Fig. 1 shows, the evaporator has seven channels of MF channel tubes. Two are ffarranged forward and backward in the direction of external fluid flow, while the other five are arranged perpendicularly to the direction of flow. Considering the evaporator’s symmetry and freezing, as Fig. 2 shows, the MF channel tubes were set L_{gap} at intervals in the direction of the flow of external fluid and L_c at intervals perpendicular to the direction of the flow of external fluid. The external fluid in this case is water, and it is

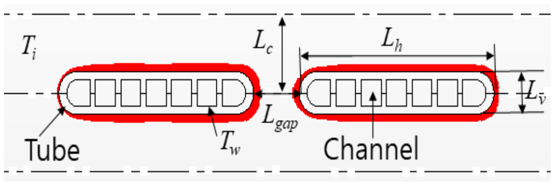

Fig. 2 Schematic diagram of the freezing phenomena of water around a channel tubes

brought into the evaporator at a V_i speed of uniform rate from left to right with a temperature of T_i Refrigerant flows into the MF channel tube with a temperature that is kept constant at T_w lower than the water's freezing point, considering the evaporation process. It is assumed that the density of water flowing around the MF channel tube is constant regardless of temperature.

In this study, the freezing process around MF channel tubes is numerically analyzed in two-dimensional steady-state conditions using an Eulerian multiphase model based on fixed grids and continuum formulation. Heat transfer within the solid material, which makes up the wall of the MF channel tube, was considered by applying a conduction heat transfer equation. The governing and related equations for the flow of water around the MF channel tube are mentioned in detail in the references[11,12].

2.2 Analysis methods and conditions

Water flowing into the area around the MF channel tube was set to flow at a uniform rate at a temperature of 15° C. The MF channel tube was constructed out of aluminum (Al), and the temperature of the channel's inner wall was constant as refrigerant flowed through the seven channels inside the MF channel tube. Table 1 shows the size of the MF channel tube, the temperature of the channel wall, and the basic conditions for the water flow rate.

Table 1 Configuration reference conditions for a channel tube with water freezing

Specification	Physical Values
Multi-Flow Tube Size ($L_h \times L_v$)	14.9mm×2.7mm
Channel Size	1.5mm×1.7mm
Distance of Tubes ($2L_c$)	9.5mm
Tube Gap (L_{gap})	3.4mm
Inlet Velocity (V_i)	0.05m/s
Wall Temperature of Channel (T_w)	263k
Inlet Temperature of Water (T_i)	288.15k

Using a finite volume technique to analyze the freezing process of water around an MF channel tube, a governing equation—including an equation of continuity, a momentum equation, and an equation of energy—was summed up through an algebraic equation. Then, the solution was obtained using the commercial CFD Solver, Star-CCM+. In particular, the movement of the boundary surface based on freezing was treated with a volume fraction considering the mercy zone based on a fixed grid. Meanwhile, changes in water and ice density due to temperature were ignored. For convection terms, the segregated model was applied. For turbulence flow, the speed and temperature fields were calculated by applying the $k-\epsilon$ standard model. Grating based on quadrilateral grating was used in the calculations, with body-fitted coordinates applied for the precise calculation of the viscous forces and the freezing layer on the wall. Approximately, 500 thousand grids were used. The verification of the numerical model used in the study's numerical analysis is described in detail in the references[11,12] and identified to be relatively consistent with the experimental results and the study's analytical results.

3. Analytical results and discussion

3.1 Freezing characteristics around channel tubes

The flow of refrigerant below the freezing point inside the channel tube in the MF stream causes the water flowing around the channel tube to freeze on the tube's surface. In this study, this freezing phenomenon is considered based on the representation in Table 1.

Fig. 3 shows the velocity distribution of fluids

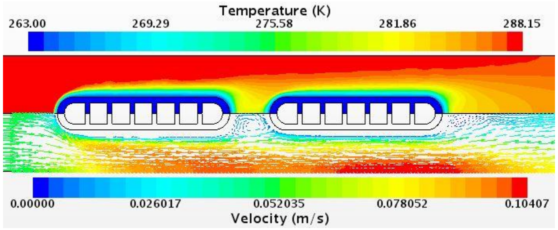

Fig. 3 Distributions of water flow velocity and temperature during ice forming around the channel tubes

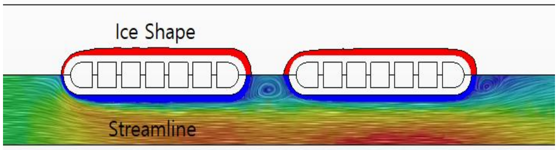

Fig. 4 Shape of ice thickness(upper) and streamline(lower) around the channel tubes

due to temperature changes in the channel tube, which are caused by conduction heat transfer at the top and freezing around the channel tube at the bottom. Noting the temperature change first, it is clear that the temperature inside the aluminum-based channel tube is almost the same as the temperature of the wall inside the channel tube. This is due to the transfer of conductive heat; however, the temperature rises increasingly as it makes contact with water within the ice formed around the channel tube. There is a rapid change in temperature at the entrance of the channel tube on the left; moreover, it is possible to confirm that the ice layer at the entrance is forming at the thinnest rate. The figure represents that the temperature of the water around the rear channel tube is running lower, on average, than the temperature around the front channel tube. This causes the freezing layer around the rear channel tube to form relatively thicker than the layer around the front channel tube.

Fig. 4 illustrates the shape of the freezing layer at the top and the flow field at the bottom, identifying the flow changes around the channel tube due to the freezing layer formed on the channel tube's wall. As water passes through the front and rear channel tubes, the flow rate accelerates as it narrows due to the formation of the ice sheet and the channel tube's width. It is possible to verify that a vortex forms and becomes locked up between the front and rear channel tubes, with rapid expansion of the flow path width through the front channel tubes and rapid contraction of the flow path through the rear channel tubes. A sharp change in the flow also causes a similar vortex in the channel tube's rear. These vortexes have been shown to play a role in somewhat reducing the freezing layer in the rear of the channel tubes at both the front and the rear. Meanwhile, the frozen layer tends to become thicker as it passes through the channel tube. The study confirmed that this trend is caused by the thinning of the temperature boundary in front of the channel tube, with the freezing process progressing as the layer becomes thicker in the rear.

3.2 Effects of the surface temperature of the channel tube's inner wall

Since cold refrigerant is flowing inside the channel tube, the resulting low temperature leads to the formation of an ice layer on the channel tube's outer wall. The inner wall's temperature changes depending on the temperature of the refrigerant flowing into the channel tube. To verify the effect of this phenomenon on the ice sheet's thickness, the ice layer's thickness change when T_w is set as 258K, 263K, and 268K was conducted; this is shown in Fig. 5. In the figure, the one-point line represents 258K, the solid line represents 263K, and the dotted line represents 268K. As the temperature of the channel tube's wall decreases, the thickness of the freezing layer increases. In particular, there are significant changes in the thickness of the frozen

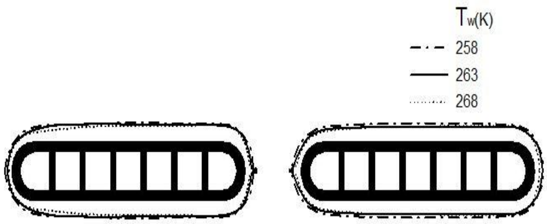

Fig. 5 Variation of ice shape formed on the wall of channel tubes with the outside wall temperature

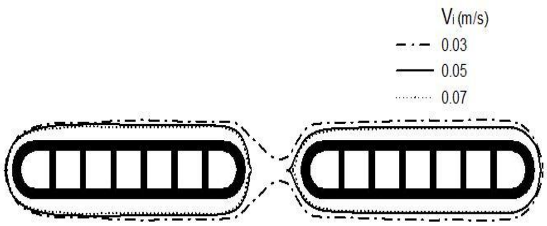

Fig. 6 Variation of ice shape formed on the wall of channel tubes with the inlet velocity of water

layer around the channel tube at the back. This can be explained that is because the water's temperature is relatively is lower around the rear channel tube than around the front channel tube, creating an ice layer sensitive to the temperature of the wall inside the channel tube when the water is freezing.

3.3 Effects of flow rate

Changes in the thickness of the freezing layer formed on the channel tube's wall according to the flow rate of the water flowing around the channel tube are represented in Fig. 6. In the figure, the flow rate of water V_i is set as 0.03 m/s, 0.05 m/s, and 0.07 m/s. The one-point line represents 0.03 m/s, the solid line 0.05 m/s, and the dotted line 0.07 m/s, respectively. Overall, the slower the water's flow rate, the thicker the freezing layer. It can be seen that this phenomenon is more apparent in the rear channel tube than in the front channel tube. Regarding the formation of ice sheets between channel tubes, in the case of a slow flow rate of 0.03 m/s, the freezing layer of the front and rear channel tubes are tended to be connected. This phenomenon occurs when the flow rate slows down and when there is an extension in the time in which freezing can take place due to the development of sufficient water ice. Conversely, as the flow rate increases, we can see that the ice sheet between channel tubes disappears. Ultimately, it is evident that the water's flow rate has a significant effect on the formation of ice layers between channel tubes.

3.4 Effects of flow width

Varying the width of the water's flow path around the channel tube (i.e., the symmetrical width L_c of $2L_c$ (see Fig. 2)) in the direction of the entering water, changes in the freezing layer formed on the channel tube's outer wall are presented in Fig. 7. Setting the water's flow path width L_c to the varying values of 0.00275 m, 0.00475 m, and 0.00675 m revealed a change in the freezing layer.

As the flow width narrows (see Fig. 2), the thickness of the freezing layer in both the front and back channel tubes can be checked. As the width of the flow path narrows, the thickness of the temperature boundary layer that forms around the channel tube becomes thinner. In turn, this makes it more difficult for the freezing layer to form; thus, the layer is somewhat thinner.

Fig. 8 shows the thickness of the ice sheet at the horizontal center of each channel tube at both the front and rear. Meanwhile, the conditions of Fig. 7 indicate a change in the freezing layer when there is a variation in the water's flow path L_c. As the figure demonstrates, the narrower the flow width, the thinner the layer of ice in both the front and rear channel tubes. This confirms that this phenomenon is more apparent in the rear rather than the front channel tube.

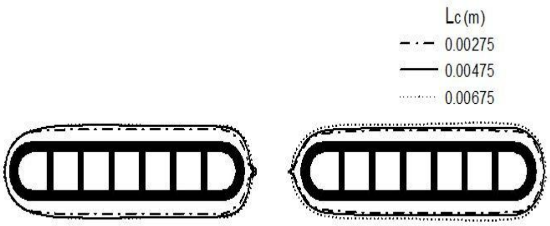

Fig. 7 Variation of ice shape formed on the wall of channel tubes with the flow channel width around the channel tubes

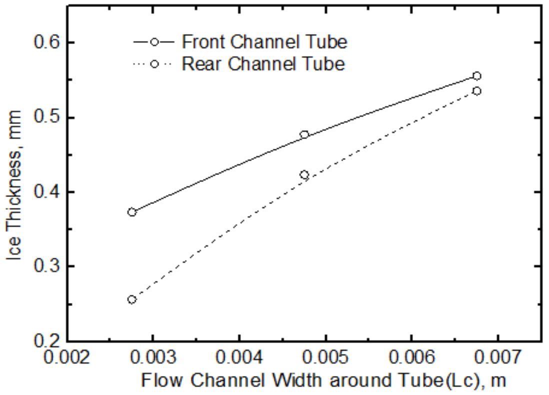

Fig. 8 Variation of ice thickness formed on the center wall of channed tubes with the flow channel width around the channel tubes

4. Conclusion

This study numerically analyzed the freezing process around two continuously placed channel tubes used for heat exchangers in evaporators. The findings of this numerical analysis confirmed that a vortex was formed and locked up between the front and rear channel tubes. Due to rapid changes in the flow path, a vortex also appeared in the rear channel tubes. These vortexes have been shown to play a role in somewhat reducing the freezing layer in the rear of the channel tubes at both the front and rear. The freezing layer tended to become thicker as it passed through the channel tube, and its thickness increased as the temperature of the wall in the channel tube decreased. The slower the water's flow rate, the thicker the freezing layer became. Particularly, for the slow flow rate of 0.03 m/s, the freezing layer of the channel tubes both at the front and rear exhibited a phenomenon of interconnection. Moreover, as the flow width narrowed, the thickness of the freezing layer became thinner in both the front and rear channel tubes. We found that as the width of the flow narrows, the thickness of the temperature boundary layer forming around the channel tubes become thinner, and consequently the generation of the freezing layer becomes somewhat thinner.

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