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An Analytical Study on the Heat Transfer Characteristics of MF Evaporation Tubes Attached with a Fin

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핀이 부착된 MF증발관의 열전달 특성에 대한 해석적 연구

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ABSTRACT

In this study, the heat transfer process around the finned channel tubes is numerically examined. Serially arranged tubes of an evaporator were used for heat exchange. The numerical analysis results confirmed that the vortex generated at the rear of the channel pipe was caused by the fin. Furthermore, it was also confirmed that the temperature difference was large between the inlet and outlet ends of the fin. The temperature of the location where the fin was attached to the channel pipe was found to be close to the surface temperature of the channel wall. However, the temperature rose rapidly closer to the ambient air temperature of 350 K towards the fin end, located at a distance of 0.035 m; it was found to have a significant influence on the heat transfer around the fin-attached channel tube. The wider the vertical flow path, the lower the total heat transfer coefficient. However, the overall heat transfer coefficient increased as the horizontal flow path narrowed. The increment is attributed to an increase in the heat transfer amount due to increased heat transfer surface.

Keywords : Fin(핀), Channel Tube(채널관), Air(공기), Numerical Analysis(수치해석), Heat Exchanger(열교환기)

1. Introduction

Heat exchangers, such as energy plants, in the machinery industry are an essential element of the overall industry, and for this reason, studies related to various types of heat exchangers have been conducted for a long time to improve heat exchange performance between working fluids. Various heat exchangers have been developed according to different industrial uses. Evaporators and condensers used as heat exchangers in the air conditioning and refrigerant systems significantly affect the efficiency of the system. Furthermore , they have an important role in absorbing or discharging heat from and into the air. When heat exchange between gas and liquid is required, heat exchangers, such as fin-tube or flat tube-fin heat exchangers, are commonly used as

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they have an extended heat transfer area on the gas side. Fin-tube heat exchangers are widely used as evaporators or condensers for household and industrial air handling units due to their simple structure and manufacturability.

To increase the efficiency of heat exchangers, recent trends include miniaturization, lightweighting, and integration of heat exchangers. Tuckerman and Pease et al. first proposed a microchannel-type heat exchanger composed of fine channels of 1 mm or less in a tube using microprocessing (MEMS)[1]. These microchannel tube heat exchangers are suitable for high performance, miniaturization, and integration, and their excellent performance is being verified[2,3]. Park and Pega[4] showed that the microchannel tube heat exchanger has better heat exchange performance than the fin-tube heat exchanger in the same volume. Park et al.[5] evaluated the performance and pressure changes according to the shape of the head connecting the tube into the channel-tube heat exchanger. In these heat exchangers, the refrigerant flows through the tube, air flows between the fins outside the tube, and most of the heat resistance is on the air side. High-performance fins, such as wavy fins, slit fins, louvered fins, and fins with vortex generators, have been developed to reduce the thermal resistance of the air side, revealing that the mechanism for promoting heat exchange change varies with the flow to the periphery changes according to the shape of the fin[6]. In particular, the louvered fin is known to be the most efficient fin shape in terms of heat transfer, and thus, it is mainly used in air-cooled heat exchangers in automobiles and aircraft[7]. To investigate the fin-tube heat exchanger in this study, literature related to the heat exchanger has been reviewed. Various studies conducted so far have attached flat-type fins to the tube to improve heat exchange performance. Zukauskas and Ulinskas[8] presented various correlations between the flow resistance and heat transfer coefficient in handling the heat transfer around the tube in a crossflow, and Moh et al.[9] performed a numerical analysis on the heat exchanger model of a three-row array. Giordano et al.[10] showed that the horseshoe vortex existing in the area where the circular cylinder and annular fin meet had a great influence on heat transfer.

To improve the efficiency of the fin-tube type heat exchangers, this study mainly used evaporators in the air conditioning and refrigerant system and assumed that the three-dimensional flow change around the fin-tubes will be closely related to the heat transfer of the heat exchanger. In this regard, as shown in Fig. 1, this study numerically analyzes the heat transfer characteristics when there is air flow around the heat exchanger of a multi-flow (MF)-type channel tube with fins exposed to the outside. This study examines the effects of flow rate change, gap difference between channel tubes, and gap between fins on the heat transfer coefficient to determine the factors affecting heat transfer.

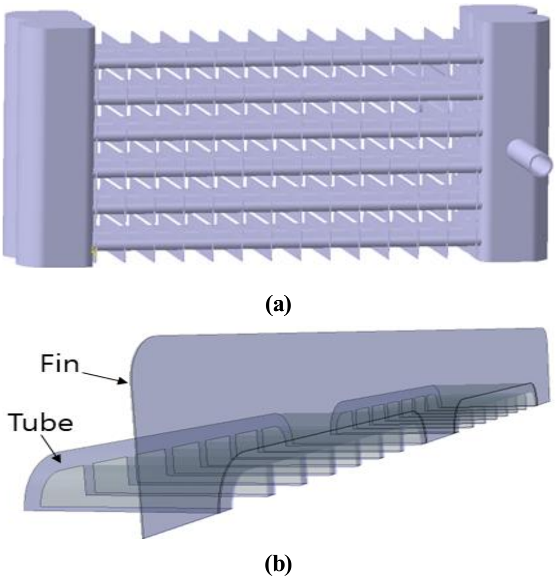
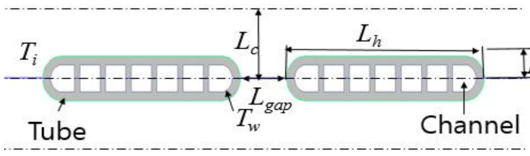


Fig. 1 Schematic diagram of the channel tubes installed into MF evaporator : (a) MF evaporator, (b) finned channel tube

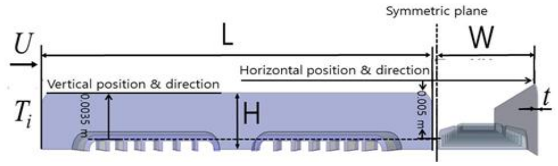
2. Numerical Analysis

2.1 Problem Setting

The evaporator of the refrigerator targeted in this study, as shown in Fig. 1, is typically composed of MF tubes. As a low-temperature refrigerant flows into the tube, and liquid evaporates through an evaporation process at a certain temperature. To absorb more heat from the outside, the evaporator consisting of a heat exchanger must have good thermal performance. In the evaporator, as shown in Fig. 1(a), two MF channel tubes with seven channels inside are arranged at the front and rear in the flow direction of the external fluid, and six MF channel tubes are arranged in a vertical direction perpendicular to the flow direction. The MF channel tubes are spaced at a L_{gap} distance in the flow direction of the external fluid and set at two intervals in the direction perpendicular to the external direction of fluid flow. To maximize the heat transfer effect from the external air flow by considering the symmetry of the evaporator and the heat transfer phenomenon, in this study, a fin was attached to the MF channel tube as shown in Fig. 1(b). The external fluid was air, which is uniformly introduced into the evaporator at a speed of V_i and a temperature of T_i. The refrigerant flows into the MF channel tube, and the evaporation of the refrigerant occurs at T_w, assuming that the temperature is maintained to be constant. The air density flowing around the MF channel tube was assumed to be constant regardless of the temperature. This study conducted a numerical analysis in a 3D steady state by considering the 3D flow around the fin. The horizontal position is a measure at the bottom-left of Fig. 2(b) and was measured at a distance of 3 mm from the MF channel tube, and the vertical position was measured at a distance of 10 mm from the center of the fin. The heat transfer in the solid constituting the MF channel tube wall was considered by applying the conduction heat transfer equation, and more information on the governing and related equations regarding the air flowing around the MF channel tuber are provided in the References[11,12].



(a)



(b)

Fig. 2 Schematic diagram of the heat transfer of air around a channel tubes: (a) Tubes, (b) Fin & measuring position and direction

2.2 Analysis Conditions and Methods

The water flowing around the MF channel tube flows at a uniform rate at a temperature of 350 K. Because the material of the channel tube and fin is aluminum (Al) and the refrigerant flows through seven channels, the temperature of the inner wall of the channel is constant. Table 1 shows the basic conditions for the size of the MF channel tube, temperature of the channel wall, and air velocity.

To numerically analyze the heat transfer process of the air around the MF channel tube, the governing equations, such as the continuous, momentum, and energy equations, were discretized by using the finite volume method. The final solution to the algebraic equation was obtained by using Star-CCM+, a commercial CFD solver. The segregated model was applied to the convection term of air, and the $k-\epsilon$ standard model was applied to turbulence to calculate the velocity and temperature fields. The results of the calculation

Table 1 Configuration reference conditions for a channel tube with air cooling

Specification	Physical Values
Multi-Flow Tube Size ($L_h \times L_v$)	14.9 mm×2.7 mm
Channel Size	1.5 mm×1.7 mm
Vertical Distance of Tubes ($2L_c$)	9.5 mm
Tube Gap (L_{gap})	3.4 mm
Height of Fin (H)	4.35 mm
Length of Fin (L)	38.6 mm
Thickness of Fin ($2t$)	0.08mm
Width of Flow Channel ($2W$)	6 mm
Inlet Velocity (V_i)	0.05m/s
Wall Temperature of Channel (T_w)	300 K
Inlet Temperature of Air (T_i)	350 K

were evaluated by utilizing the formula for the overall heat transfer coefficient and expressed as Equation (1), which can be derived as the result of Star-CCM+ .

$$U_i = \frac{1}{\frac{1}{h_i} + \frac{A_i \ln(r_o/r_i)}{2\pi k L} + \frac{A_i}{A_o}\frac{1}{h_o}} \qquad (1)$$

The used grid was based on a quadrilateral grid, and a body-fitted coordinate was applied for the precise calculation of the viscous force and the freezing layer on the wall; about 500,000 grids were employed.

The verification of the model used in the numerical analysis of this study is described in detail in the References[11,12]. The experimental and analysis results from the numerical models applied in this study were relatively consistent.

3. Analysis Results and Discussion

3.1 Heat Transfer Characteristics Around the Finned Channel Tube

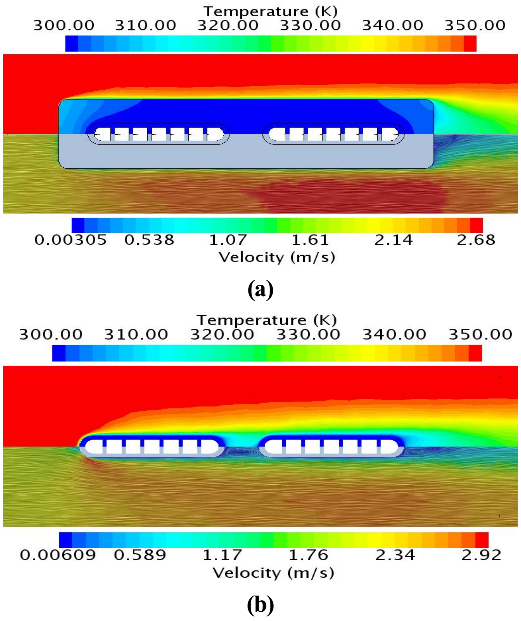


Fig. 3 Distributions of air flow velocity and temperature around the finned channel tubes: (a) Fin, (b) Tubes

Because air flows around the channel tube with fins that maintain a low internal wall temperature, the temperature decreases due to heat loss. Based on the most representative conditions shown in Table 1, these cooling phenomena are described as below.

Fig. 3 shows the temperature change caused by heat transfer on the upper side around the channel tube and the air velocity distribution around the channel tube on the lower side. First, according to Fig. 3(a), which shows the location where the fin was attached onto the channel tube, the temperature inside the Al channel tube was similar to the temperature of the inner wall of the channel tube because of conduction heat transfer. However, the temperature inside the fin attached to the outer wall of the channel tube approaches the air temperature as it goes toward the end of the fin because of conduction heat transfer resulting from the temperature of the surrounding air. In particular, the temperature significantly changes at the inlet and outlet ends of the fin because the contact surface of the air per unit volume of the fin is relatively wider than that of the central part, thereby promoting heat transfer. The air flow indicates that a wake vortex occurs at the back of the fin due to the fin. However, according to Fig. 3(b), which shows the symmetrical surface area of the channel tube 5 mm away from the fin attached to the channel tube, the temperature boundary layer originating from the front channel tube becomes thicker as it goes toward the rear channel tube. The end of the last tube is formed about three times thicker at about 5.63 mm in comparison to the end of the first tube at the front MF channel tube and the last tube of the rear MF channel tube. Simultaneously, a vortex is formed between the channel tubes and at the rear of the rear channel tube, unlike the flow of the portion where the fin is attached to the air flow field, and the change in temperature accordingly occurs.

3.2 Influence of Internal Wall Temperature on the Channel Tube

Due to the low temperature of the inner wall of the channel tube, a temperature boundary layer is formed near the outer wall of the channel tube. The temperature of the air flowing through the flow channel varies according to the temperature of the inner wall of the channel tube. To understand the effects of this change on the heat transfer in the channel tube, the T_w values were varied to 275K, 300K, and 330K, which were selected as they are within the temperature range of the actual test performance evaluation standards. Fig. 4 shows the temperature changes along the horizontal line, as in the horizontal direction shown in Fig. 2(b), in the longitudinal direction of the channel tube from the plane of symmetry to the fin at a position of 5 mm in the vertical direction from the front channel tube`s surface; the dashed line, solid line, and dotted line refer to 275 K, 300 K, and 330 K, respectively. In all cases, the temperature on the inner wall surface of the channel tube decreases sharply as it goes toward the fin. This result suggests that heat transfer is rapidly occurring in the fin. Furthermore, the lower the wall temperature of the channel tube, the lower the overall temperature. Fig. 5 shows the temperature change of the fin according to the wall temperature of the

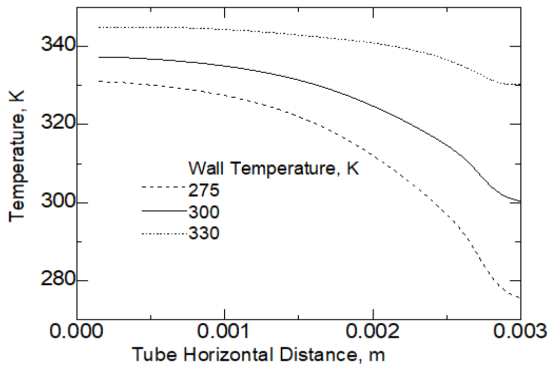


Fig. 4 Temperature distributions along the line 5mm above from the horizontal center line of the front tube surface for several cases of temperatures at the inner wall of tube

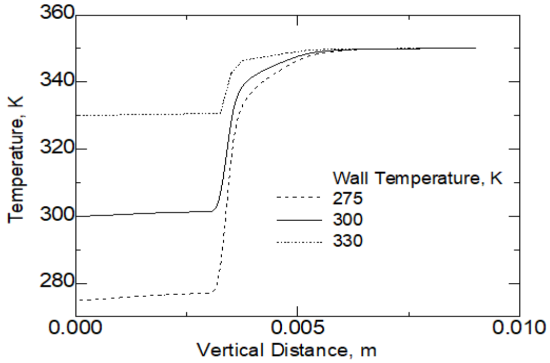


Fig. 5 Temperature distributions along the vertical line of fin at the center of the front tube surface for several cases of temperatures at the inner wall of tube

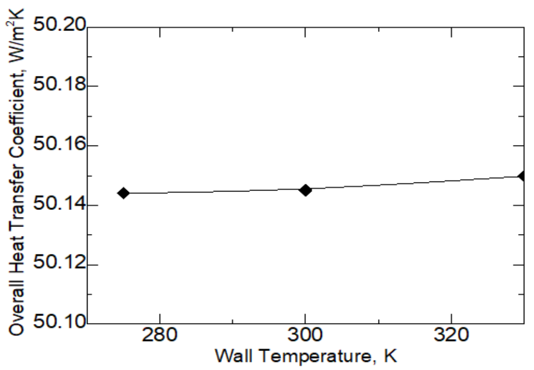


Fig. 6 Variation of the overall heat transfer coefficient for the finned tubes with the inner wall temperature of tube

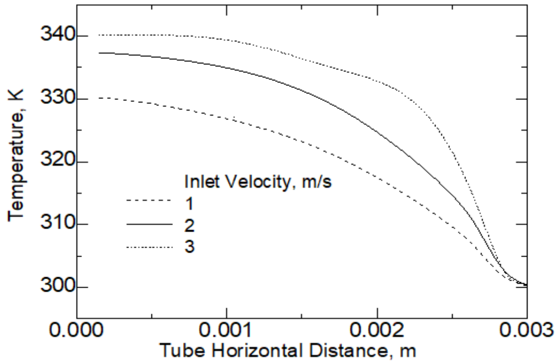


Fig. 7 Temperature distributions along the line 5mm above from the horizontal center line of the front tube surface for several cases of temperatures at the inner wall of tube

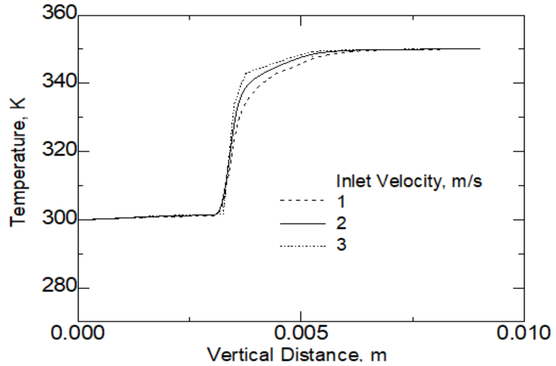


Fig. 8 Temperature distributions along the vertical line of fin at the center of the front tube surface for several cases of temperatures at the inner wall of tube

channel tube in the vertical direction, shown in Fig. 2(b). According to the Fig. 5, the temperature of the fin attached to the channel tube is first similar to the wall surface temperature of the channel tube, and the temperature rapidly rises from 0.0035 m to 0.0065 m at the end of the fin. As such, the fin has a characteristic of approaching the ambient air temperature of 350 K. The same temperature change is observed in the measurement distance of 0.003 m in the horizontal direction and in the designated distance in the vertical direction, which suggests that the slope of temperature change according to the distance is the same. As the channel tube wall temperature lowers, the slope of the temperature rise graph becomes higher, and in comparison to the slope of 275 K, the slope was determined to be about 62% at 300 K and about 15% at 330 K. The overall heat transfer coefficient is compared and reported in Fig. 6. Because the change in the overall heat transfer coefficient according to the wall temperature is less than 0.01, little change has occurred.

3.3 Effects of Flow Rate

To determine the change in the temperature layer formed on the wall of the channel tube according to the flow velocity of the air flowing around the channel tube, the temperature changes were selected from the range of test performance evaluation standards by varying the flow velocity V_i of air to 1 m/s, 2 m/s, and 3 m/s, which is shown in Fig. 7; dashed line, solid line, and dotted line refer to 1 m/s, 2 m/s, and 3 m/s, respectively. Overall, the lower the air flow rate, the lower the temperature. This phenomenon is understood to occur as the flow rate decreases, and thus, the time for sufficient

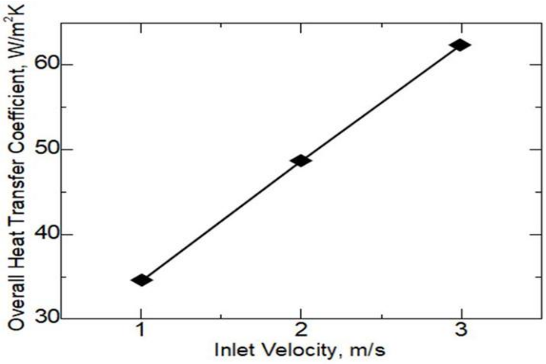


Fig. 9 Variation of the overall heat transfer coefficient for the finned tubes with the inner wall temperature of tube

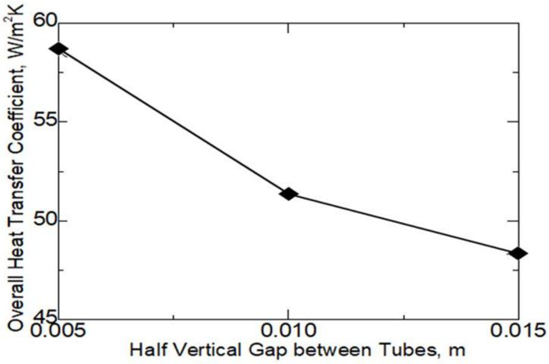


Fig. 10 Variation of the overall heat transfer coefficient for the finned tubes with the half vertical gap between tubes

cooling of the air is prolonged. According to Fig. 8, which shows the temperature change vertically along the fin, there is nearly no overall temperature change according to the flow rate, whereas the air temperature decreases as the flow rate decreases near the end of the fin. According to Fig. 9 which indicates the change of the overall heat transfer coefficient, the coefficient was determined to be 34.97 W/m^{2}K, 48.76 W/m^{2}K, and 62.13 W/m^{2}K when the flow rate was 1 m/s, 2 m/s, and 3 m/s respectively, which shows that the coefficient increased as the flow velocity increased. The difference in the coefficient was 27.16 W/m^{2}K when the flow velocity was 1 m/s and 3 m/s. This result suggests that the air velocity has a significant influence on the heat transfer of the fin-attached channel tube.

3.4 Effect of Flow Path Width

Fig. 10 shows the change in the overall heat transfer coefficient of the channel tube when varying the symmetric width L_c of the flow path width of the air flowing around the fin-attached channel tube, i.e., the flow path spacing 2 L_c(refer to Fig. 2) in the direction perpendicular to the direction in which air flows. The change in the overheat transfer

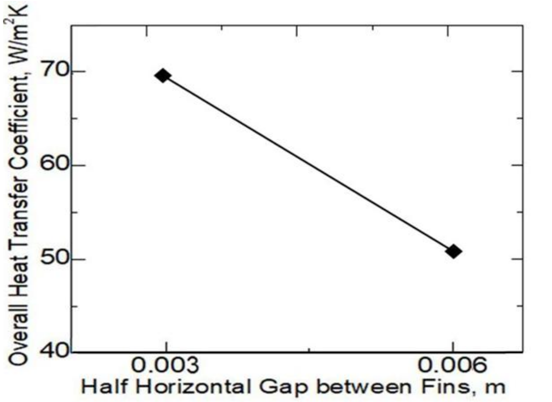


Fig. 11 Variation of the overall heat transfer coefficient for the finned tubes with the half horizontal gap between fins

coefficient was displayed by randomly varying the flow path width L_c to 0.005 m, 0.010 m, and 0.015 m. The overheat transfer coefficients were determined to be 58.73 W/m^{2}K, 51.24 W/m^{2}K, and 48.01 W/m^{2}K when the flow path widths were 0.005 m, 0.010 m, and 0.015 m, respectively. These results confirm that the overall heat transfer coefficient lowers as the flow path width becomes higher, and the coefficient has a value of m^{2}K. It can be seen that the wider the channel width, the lower the total heat transfer coefficient, and the difference in the coefficient was 10.72 W/m^{2}K when the flow path widths were 0.005 m and 0.015 m.

Fig. 11 shows the changes in the overall heat transfer coefficient by randomly varying the distance between the fin-attached channel tubes, which was a distance of $2W$ between the fins, to W. The values of the coefficient were 68.73 W/m^{2}Km and 51.24 W/m^{2}K when the distances between the fins were 0.003 m, and 0.006 m. According to Fig. 11, as the flow path width narrows, the overall heat transfer coefficient increases, showing the significant difference between the two as 17.49 W/m^{2}K. These results confirm that heat transfer increases because the narrower the channel width, the narrower the fin attachment distance; therefore, the heat transfer surface rises.

4. Conclusion

This study numerically analyzed the heat transfer process around the channel tube with two fins arranged in a row, which were used for heat exchange in the evaporator.

1) According to the results of numerical analysis, a vortex was generated and trapped at the rear end of the channel tube due to the fin, and the temperature was significantly changed at the inlet and outlet ends of the fin.
2) The temperature in the fin attached to the channel tube was nearly the same as the temperature on the wall of the channel tube. The temperature rose from 0.035 m, where the end of the fin is located, showing a characteristic of approaching the ambient air temperature of 350 K. However, the change in the overheat transfer coefficient according to temperatures of 275 K, 300 K, and 330 K in the MF channel tube was insignificant at 0.01.
3) When the air velocities were 1 m/s, 2 m/s, and 3 m/s, the overall heat transfer coefficients were determined 34.97 W/m^{2}K, 48.76 W/m^{2}K, and 62.13 W/m^{2}K, respectively, which significantly affected the heat transfer of the fin-attached channel tube.
4) When the vertical flow path widths were 0.005 m, 0.010 m, and 0.015 m, the overall heat transfer coefficients were 58.73 W/m^{2}K, 51.24 W/m^{2}K, and 48.01 W/m^{2}K, respectively. According to the observed tendency, the wider the flow path width, the lower the overall heat transfer coefficient.

When the horizontal flow path widths were 0.003 m and 0.006 m, the overall heat transfer coefficients were 68.73 W/m^{2}K and 51.24 W/m^{2}K. As the flow path width narrows, the overall heat transfer coefficient increases. This phenomenon is explained by the fact that the heat transfer increases due to the rise of the heat transfer surface by the attachment of the fin-per-unit-flow path width.

5. Acknowledgement

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