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An Experimental Study on the Behavior of Frost Formation in the Vertical Plate Heat Exchanger

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ABSTRACT

The influence of the frost formation in the vertical parallel-plate heat exchanger for different operating conditions(the temperature, the humidity and the velocity of the air, and the temperature of the cooling plate) is investigated. The performance of the heat exchanger is examined by introducing a parameter such as the energy transfer resistance. Correlations which relate energy transfer resistance, frost density, and frost thickness to Reynolds number, air temperature and humidity, and cooling plate temperature are developed. Static pressure drop and air flow rate are expressed in terms of free flow area of air.

1. INTRODUCTION

The characteristics of the heat and mass transfer process occurring between the surrounding air and cooling plate in the equipments such as an evaporator in the refrigerator are a major factor in the design analysis of the various refrigerating equipments. However, the complex mechanism of the frosting process gives rise to a difficulty in the design analysis. There is also little experimenal data available for the design analysis. Reid et al.[1] reported that the density of the frost layer increased with decreasing temperature of the cooling surface. However, the results of Trammel et al.[2] showed the opposite trend. O'neal et al.[3] showed that the frost layer with a high density formed at the leading edge of the heat exchanger. In the mean time, Abdel-Washed et al.[4] indicated that the frost density increased along with the flow direction of the air. O'neal[5], Kamei et al.[6], and Yamakawa[7] showed that frost growth was largely dependent of Reynolds number less than critical Reynolds number and was independent of Reynolds number greater than critical Reynolds number. The variation of the frost layer thickness along with the position in the heat exchganger still needs a satisfactory explanation. Hayashi et al.[8] and Niederer[9] indicated that a large amount of the frost formed at the leading edge of the heat exchanger. The purpose of this study is to examine the effects of air-stream temperature, humidity, velocity, and cooling plate temperature on a frost formation of a vertical parallel-plate heat exchanger.

2. EXPERIMENT

Fig.1 shows the schematic diagram of the experimental apparatus. The vertical plate placed in the test section was 0.4m wide and 0.3m height, and the initial depth of the air flow passage was 0.018m. The refrigerant passage inside the heat exchanger was constructed in the form of a maze to keep the surface temperature of the plate uniform. The front surface of the test section was constructed of acryl plate with 0.02m thickness to see the frosting phenomena. Four holes were perforated on the acryl plate to measure the frost thickness with a acrylic probe of the micrometer. Fig. 2 shows the frost thickness measurement locations on the acryl plate. Aluminum tapes with 50μm thickness and 0.01m wide were pasted on the same measurement locations in the surface of the heat exchanger. The mass and density of the frost formed on the surface of the cooling plate were measured at each measurement location by weighing the mass of the frost formed on the tape using a precision balance. The surface temperatures of the frost layer and cooling plate need to be measured to investigate the effect of the frost layer on the heat transfer and to measure the frost thermal conductivity. In this study, infrared radiation thermometer was used to measure the surface temperature of the frost layer at each location. The surface temperature of the heat exchanger was measured using T-type thermocouple at each measurement location as shown in Fig.2. The heat transfer into the frost layer from the air was also measured at each location. As shown in Fig.2, this was accomplished by measuring the temperature difference across the bakelite with 0.0014m thickness using T-type thermocouples(0.01mm thickness) mounted on both sides of the bakelite. The hot wire anemometer and the flow nozzle placed in the circulation section was used to measure the variations of the air flow rate through a test section due to frost growth. The variations of the static pressure drop of the air through heat exchanger were measured by measuring a static pressure differential between the inlet and exit of the test section using a precision manometer. The effective thermal conductivity of the frost layer is calculated using energy balance as follows :

$$k_{f,eff} = k_b \Delta T_b / \Delta T_f \cdot x_f / x_b \qquad (1)$$

where ΔT_f represents the difference between the mean temperature of the surface of the frost layer and the mean temperature of the cooling plate, and ΔT_b is the temperature difference across the bakelite. Based on the enthalpy of the air and the frost surface, the energy transfer coefficient is expressed as follows :

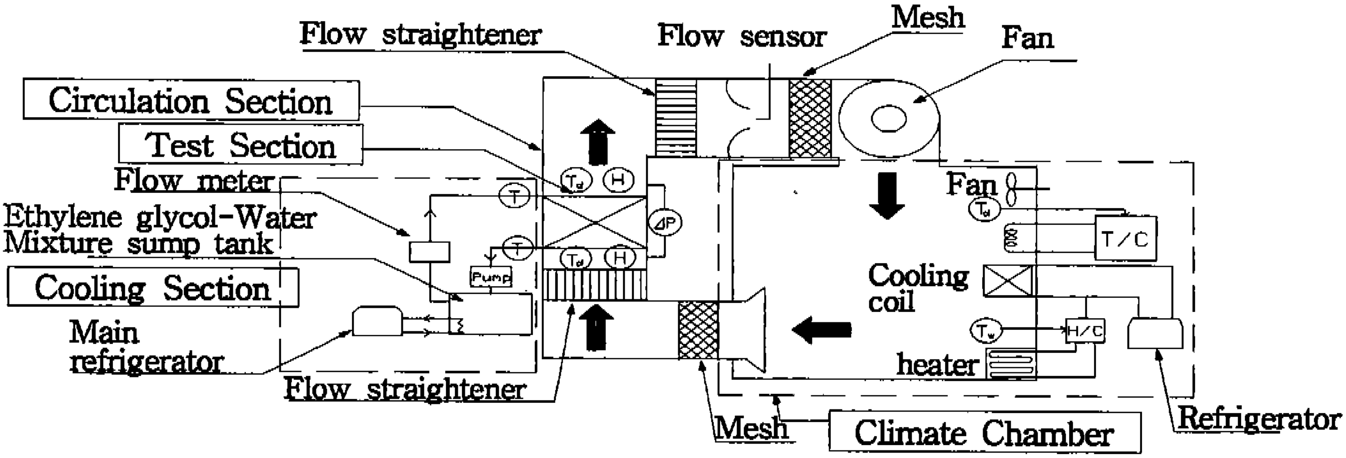
$$h_e = \dot{Q}/[A \cdot (i_a - i_{f,s})/C_{p,a}] \qquad (2)$$

where $C_{p,a}$ is isobaric specific heat of air and $\dot{Q}$ is heat rate to frost layer from humid air. The energy transfer resistance between the air and cooling plate is defined as

$$R_e = [(i_a - i_p)/C_{p,a}]/\dot{Q} \qquad (3)$$

where i_a, $i_{f,s}$, and i_p in eqs. (2) and (3) indicate enthalpy of an air, frost surface, and cooling plate. respectively, and are given by

$$i_a = C_{p,a} \cdot T_a + h_{sv} \cdot w_a \ , \quad i_p = C_{p,a} \cdot T_p + h_{sv} \cdot w_s(T_p) \ , \quad i_{f,s} = C_{p,a} T_{f,s} + h_{sv} w_s(T_{f,s}) \qquad (4)$$



H/C : humidity controller T/C : temp. controller ⬅ : Air flow (H): humidity sensor

(Td) : thermocouple(dry temp.) (Tw) : thermocouple(wet temp.) (ΔP) : differential manometer

Fig. 1 Schematic diagram of the experimental apparatus

Here, $w_s(T_{f,s})$ represents a saturation humidity at the frost surface temperature $T_{f,s}$, while $w_s(T_p)$ indicates a saturation humidity at the cooling plate temperature T_p.

3. RESULTS AND DISCUSSIONS

The effect of the frosting phenomena on the performance of the vertical parallel-plate heat exchanger is examined under the experimental conditions shown in Table.1. The frequency of input current of a fan which circulates the air is kept the same as the one in a real evaporator.

Fig.3 depicts the frost growth as a function of position and time. It is shown that the frost thickness is thick at the entrance of the heat exchanger and the frost thickness difference between the entrance and the exit increases with time. The reason for this is that mass transfer occurs more actively near the entrance of the heat exchanger because there is a large amount of the vapor in the air near the entrance compared to the exit of the heat exchanger. Frost thickness grows rapidly at the initial stage and the frost growth rate is reduced with time. Another possible explanation is that the frost grows very rapidly because mass transfer is enhanced due to the coarseness and high density of the frost at the initial stage. The frost growth rate diminishes due to the rapid reduction in mass transfer because the frost acts like a resistance to the heat and mass transfer with time. Fig.4 shows the effect of entrance air temperature and velocity on the frost growth. The case with low air velocity condition shows different phenomena in the frost growth compared with the other cases. The reason for this is that the initial frost state is kept for a relatively long period because the amount of vapor transferred into the frost layer from the moist air is very small. With increasing air temperature, the amount of the mass trasnsfer between the air and frost layer increases, however the frost thickness is reduced because the density becomes high with the increase of the temperature gradient inside the frost layer. Fig.5 represents the variations of the frost density with entrance air temperature, humidity, and velocity, and cooling plate temperature. It is found that the frost density becomes high with increasing entrance air temperature.

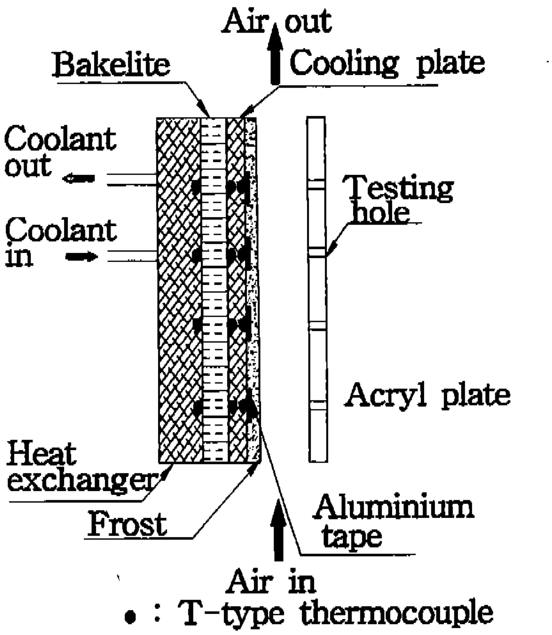


Fig. 2 Side view of heat exchanger in the test section

Table 1 Experimental conditions

	Initial inlet air velocity	Inlet air humidity	Inlet air temperature	Cooling plate temperature
Baseline condition	3.9 (m/sec)	70.0 (%)	8 (℃)	-15 (℃)
High velocity condition	6.2 (m/sec)	70.0 (%)	8 (℃)	-15 (℃)
Low velocity condition	1.1 (m/sec)	70.0 (%)	8 (℃)	-15 (℃)
High air humid. condition	3.9 (m/sec)	80.0 (%)	8 (℃)	-15 (℃)
Low air humid. condition	3.9 (m/sec)	60.0 (%)	8 (℃)	-15 (℃)
High air temp. condition	3.9 (m/sec)	57.2 (%)	11 (℃)	-15 (℃)
Low air temp. condition	3.9 (m/sec)	86.1 (%)	5 (℃)	-15 (℃)
High plate temp. condition	3.9 (m/sec)	70.0 (%)	8 (℃)	-11 (℃)
Low plate temp. condition	3.9 (m/sec)	70.0 (%)	8 (℃)	-26 (℃)

This results from the increase of the amount of the vapor transferred into the frost layer with increasing temperature and vapor pressure gradients in the frost layer by the increase of the energy flux transferred into the frost surface. In the case of high air humidity and low cooling plate temperature, the mass flux of the vapor transferred into the frost surface from the air is increased while the frost density becomes low due to a large increase of the frost thickness. Frost density increases with increasing entrance air velocity. This fact can be attributed to the increase of temperature gradient in the frost layer which is caused by a large amount of energy transfer due to high air velocity. Density increases monotonically in all cases except the one with low air velocity. The phenomena occurred at the low velocity condition seems to be similar to the one observed by Hayashi[8]. The results of this study for the frost thickness and density can be summarized as the following equations ;

$$x_f = 1.511\left(\frac{T_a-12.3}{T_a-13.2}\right)\left(\frac{w_a-3.574\cdot10^{-3}}{w_a-2.901\cdot10^{-3}}\right)\left(\frac{T_p+9.1}{T_p-8.0}\right)\left(\frac{Re}{Re_0}\right)^{0.304} t^{f_1(w_a,Re)} \tag{5}$$

$$\rho_f = 10.297\left(\frac{T_a-14.4}{T_a-13.3}\right)\left(\frac{w_a-6.413\cdot10^{-3}}{w_a-6.059\cdot10^{-3}}\right)\left(\frac{T_p+38.8}{T_p+45.4}\right)\left(\frac{Re}{Re_0}\right)^{0.24} t^{f_2(w_a,Re)} \tag{6}$$

where

$$f_1(w_a, Re) = 0.18\,(3.17 - w/w_0)\,(Re/Re_0)^{0.078}$$

$$f_2(w_a, Re) = 0.21\,(3.14 - w/w_0)\,(Re/Re_0 - 0.26)^{0.02}$$

Fig.6 depicts the variations of the amount of the energy transfer as a function of the air temperature, humidity and velocity. All heat fluxes initially shows a rapid decrease and then gradually converges to a constant value. The reason is that the energy transfer resistance between the air and cooloing plate increases rapidly due to the fast frost growth at the initial stage of the frost formation and then the energy transfer resistance converges to a constant value due to the reduction of the frost growth. The total energy flux has a large value with increasing air velocity. However, for the case of low air velocity one can see the variations for a relatively long period since the decreasing rate of the energy flux is relatively small. As indicated earlier, this is due to the fact that the thermal resistance effect of the frost layer is relatively small because the frost growth rate is small for a low air velocity condition. With increasing air temperature, the energy flux has a large value for two reasons. First, a driving force for the energy transfer increases. The other reason is that energy

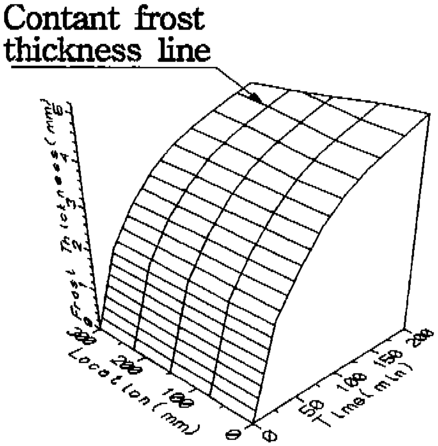


Fig. 3 The growth of the frost

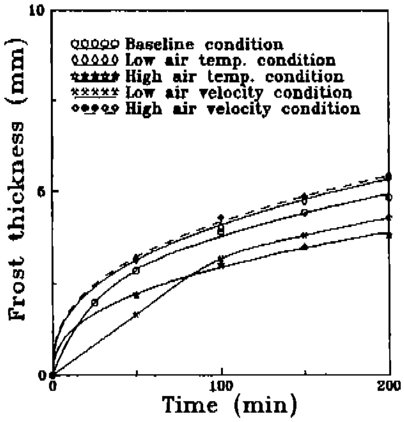


Fig. 4 The variation of the frost thickness

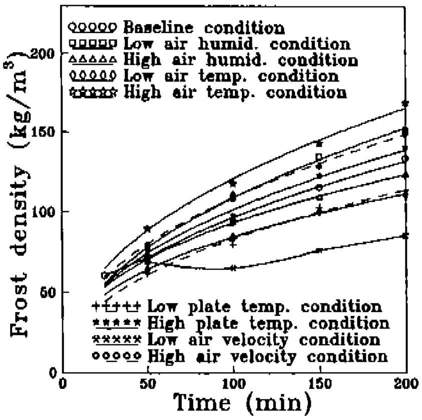


Fig. 5 The variation of the frost density

transfer resistance of the frost layer resulting from high frost density and thin frost thickness is small. The case with high air relative humidity(80%) initially shows a large value of the energy flux compared with the one with baseline condition(70%). However, the high air humidity condition eventually has a smaller value of the energy flux than baseline condition because the reduction of the energy flux continues for a relatively long period and the reduction magnitude is large in the case of high relative humidity. This is due to the fact that a driving force of the energy transfer between moist air and cooling plate increases in the case of high relative humidity, while energy transfer resistance between moist air and cooling plate increases owing to the thick frost formation with a low density. It is also shown that energy flux has a large value because of a large driving force of the energy transfer with decreasing temperature of the cooling plate. The equation for energy transfer resistance is defined by

$$R_e = 1/(h_e \cdot A) + x_f/(k_{f,eff} \cdot A) \tag{7}$$

where the first term represents convective energy resistance and the second term indicates conductive energy resistance and $k_{f,eff}$ is a effective thermal conductivity including both heat conduction inside the frost layer and energy transfer by the vapor diffusion. Fig.7 shows the variations of the frist and second terms in eq.(7) with time. At the initial stage of the frost formation, convective energy resistance is dominant because of a very thin frost thickness. However, the convective energy resistance inside the frost layer increases rapidly with time due to the fast frost growth with low density. The conductive energy resistance is about 67 percent of the total energy transfer resistance in two hundred minutes. The convective energy resistance continues to decrease. This means that the energy transfer coefficient continues to increase. This trend conflicts with the reported result[7]. One can see that the fact that the energy transfer coefficient continues to increase results from decrease of the hydraulic diameter and the increase of the velocity by a reduction in the air flow passage resulting from a frost growth. Fig.8 shows the variation of the energy transfer resistance between the air and cooling plate as a function of enterance air temperature, humidity, velocity, and cooling plate temperature. With increasing enterance air humidity, the frost grows rapidly and the energy resistance has a large value due to a low frost density. The energy transfer resistance has a small value with increasing enterance air temperature. This is due to the fact that the frost thickness is thin and frost density is high. It is also shown that energy transfer resistance has a large value because the frost with a low density and thick thickness

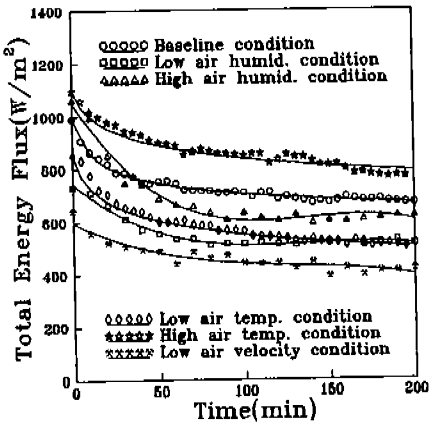


Fig. 6 The variation of the total heat flux

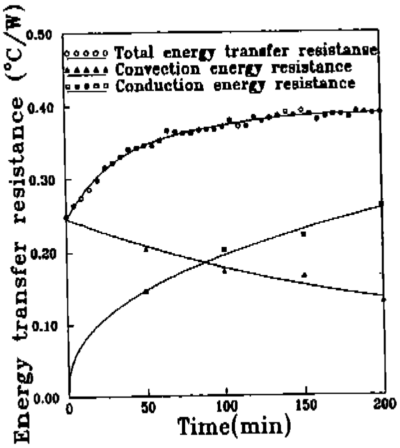


Fig. 7 The variation of the energy transfer resistance

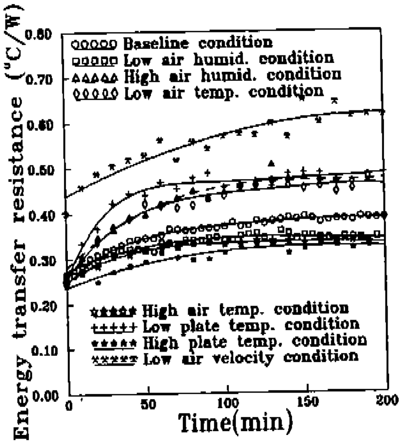


Fig. 8 The variation of the energy transfer resistance

is formed with the decrease of the cooling plate temperature. Energy transfer resistance has a small value because increasing entrance air velocity causes a small value of convective energy resistance. Energy transfer resistance in all cases converges to a constant value in a short period of time except the low air velocity condition. One can see that energy transfer resistance varies a little after one hundred minutes and eventually converges to a constant value. Converged energy transfer resistance can be expressed as follows ;

$$R_{e,steady} = 0.1192\left(\frac{T_a+47.7}{T_a+6.6}\right)\left(\frac{w_a-7.183\cdot 10^{-3}}{w_a-6.308\cdot 10^{-3}}\right)\left(\frac{T_p+1.2}{T_p-9.7}\right)\left(\frac{Re_0}{Re}\right)^{0.325} \quad (8)$$

The air mass flow rate through a heat exchanger continues to decrease with time, while the pressure drop occurred through a heat exchanger continues to increase. This results from the fact that frost growth blocks air flow. The variations of air mass flow rate and pressure drop with air flow area are expressed as ;

$$(\dot{m}_a/\dot{m}_{a,0}) = -0.376 + 2.848(a(t)/a_0) - 1.473(a(t)/a_0)^2 \quad (9)$$

$$(\Delta P/\Delta P_0) = 51.4 - 100.4(a(t)/a_0) + 50.0(a(t)/a_0)^2 \quad (10)$$

where $\dot{m}_{a,0}$, a_0, and ΔP_0 represent air mass flow rate, free flow area of air, and pressure drop, respectively when there is no frost formation.

4. CONCLUSIONS

1. Vapor mass and heat flux transferred into the cooling plate from the air initially decrease rapidly and then the decreasing rate diminishes with time.
2. With increasing entrance air temperature, the frost thickness becomes thin and the frost with a high density is formed.
3. With increasing entrance air humidity and decreasing the cooling plate temperature, the frost thickness increases, however, the frost density becomes low.
4. Frost thickness and density increase with increasing entrance air velocity.
5. Energy transfer resistance between the air and cooling plate increases with increasing air humidity and decreases with the increases of air temperature, cooling plate temperature and air velocity.
6. Energy transfer resistance between the air and cooling plate increases rapidly at the initial stage, however, the increasing magnitude is not significant with time.
7. The energy transfer resistance between the air and cooling plate is mainly governed by convective resistance at initial stage of the frost formation and then conductive resistance by a frost layer becomes dominant
8. Frost thickness and density, and energy transfer resistance are expressed as a function of air temperature, humidity, velocity and cooling plate temperature. Air mass flow rate and pressure drop are also expressed in terms of air flow area.

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