An Experimental Study on the Frost Prevention using Micro Liquid Film of an Antifreeze Solution

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ABSTRACT: The effect of antifreeze solution liquid film on the frost prevention is experimentally investigated. It is desirable that the antifreeze solution spreads widely on the heat exchanger surface forming thin liquid film to prevent frost nucleation while having small thermal resistance across the film. A porous layer coating technique is adopted to improve the wettability of the antifreeze solution on a parallel plate heat exchanger. The antifreeze solution spreads widely on the heat exchanger surface with 100 μm thickness by the capillary force resulted from the porous structure. It is observed that the antifreeze solution liquid film prevents a parallel plate heat exchanger from frosting. The reductions of heat and mass transfer rate caused by the thin liquid film are only 1~2% compared with those for non-liquid film surface.

Nomenclature

A	: area [m^2]
d_n	: equivalent diameter of capillary tube [m]
d_p	: diameter of solid particle [m]
g	: gravitational acceleration [m/s^2]
h	: heat transfer coefficient [W/m^{2}K]
h_D	: mass transfer coefficient [kg/m^{2}s]
i_{fg}	: condensation latent heat [J/kg]
k	: thermal conductivity [W/mK]
l	: liquid column length [m, mm]
m	: mass flow rate [kg/s, g/min]
ΔP	: pressure difference [Pa]
q	: total heat transfer rate [W]
r	: radius of capillary tube [m]
Re_f	: film Reynolds number
T	: temperature [℃]
t	: time [s]
u	: velocity of liquid column [m/s, mm/s]
v	: vertical direction [m/s]
w	: humidity ratio
x	: cross-sectional direction [m]

Greek symbols

Γ	: mass flow rate per unit width [kg/ms]
δ	: liquid film thickness [μm]
θ	: contact angle [deg]
λ	: surface tension [N/m]
μ	: viscosity [kg/ms]
ρ	: density [kg/m^3]
ϕ	: porosity [%]

Subscripts

a	: air
L	: latent heat
l	: liquid film
s	: sensible heat
w	: wall

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1. Introduction

As refrigerating systems using a refrigerating cycle, such as a refrigerator and an air conditioner, are widely used in these days, demands for a high-efficiency refrigerating system are increasing. In an air-source refrigerating system, if a surface temperature of an evaporator drops below a freezing point of water (i.e. 0℃), water vapor around the evaporator loses its heat by the cold evaporator, and thus frost is formed on the surface of the evaporator. As frost forms on the surface of the heat exchanger, its efficiency decreases.

When the frosting continues for some time, the frost grows to be a frost layer, and the frost layer functions as an insulation layer between the cold surface of the evaporator and the air, thereby decreasing heat transfer efficiency. Due to the consecutive growth of the frost layer, the area of the air passage reduces, which causes an air pressure drop. Such a pressure loss affects operational characteristics of an air blower for supplying air across the evaporator, thereby reducing air flow rate at the evaporator. That is, heat transfer performance of the evaporator decreases because the air flow rate is reduced, and consequently, the entire refrigerating system is fatally damaged. Accordingly, a defrosting process for melting and removing the frost layer formed on the surface should be performed periodically.

Generally, the growth of the frost layer on the surface of an evaporator is affected by surrounding conditions, such as temperature of cooling surface, air flow rate, temperature and humidity of the air and so on. A growing process of the frost layer comprises three steps: crystallizing period, frost layer growing period and frost layer maturing period.[(1)] In detail, the frost layer growing process is a process in which phase transition of ambient water vapor molecules is consecutively made from a gaseous state to a solid state, and essentially includes super saturation process. That is, when water vapor in the air condenses, the condensing vapor passes the transition through a supersaturated liquid state and freezes, generating a frost crystal nucleus. Then, a frost layer begins to be generated centering on the frost crystal nucleus. Accordingly, if the supersaturated liquid is prevented from freezing into a frost crystal nucleus, the generation and growth of the frost on a surface of evaporator may be prevented.

This research is based on the idea of that a frost on the surface of heat exchanger can be prevented if antifreeze solution is sprayed on its surface, on which an antifreeze solution liquid film suppresses frost crystal nucleus generation by absorbing supersaturated water. The water vapor and antifreeze solution is mixed, before the vapor becomes supersaturated liquid and then grows to frost crystal nucleus.

Antifreeze solution that is supplied on the surface of heat exchanger can restrain the degradation of evaporator by preventing frost, but liquid film of antifreeze solution should be as thin as possible because antifreeze solution itself gets into another thermal and flow resistance of the heat exchanger. Therefore, a small amount of the antifreeze solution is supplied on the surface of the evaporator to reduce heat transfer resistance as well as flow resistance between the heat exchanger surface and air.

In this study, a porous layer coating technique is adopted to improve wettability of antifreeze solution on the heat exchanger surface. Even if the quantity of antifreeze solution is minimized, antifreeze solution spreads widely on the surface of the evaporator to prevent local formation of a frost layer by unequal distribution of sprayed antifreeze solution.

The objectives of this study is to investigate the effect of antifreeze liquid film on a frostless heat exchanger, capable of preventing degradation of performance of a heat exchanger by suppressing frost crystal nucleus causing growth of frost and wettability enhancement of antifreeze solution on porous layer coating surface.

2. Analysis model

2.1 Porous layer coating

Porous layer coating technique is applied on the surface of heat exchanger to improve wettability of antifreeze solution. Schematic diagram of the surface where porous layer is coated is shown in Fig. 1. Antifreeze solution can cover the surface with thin liquid film and improve wettability remarkably because liquid that is supplied on the surface spreads through porous layer by capillarity. Antifreeze solution wettability on aluminum surface with porous layer coating is enhanced more remarkably than that on treated surface with hydrophilic polymer which is used often for evaporator as well as that on bare aluminum surface.

Porous layer can be formed by coating solid particles on the surface using thermal spray process or adhering solid particles to the surface using suitable reactive adhesive. In this research, heat exchanger surface is coated with a mixture of silica powder of 10~30 μm diameter and reactive adhesive and thickness of porous layer is about 50 μm.

2.2 Wettability prediction model

Liquid flow on surface with porous layer

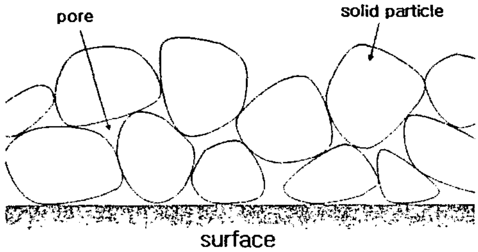


Fig. 1 Schematic of porous layer coating.

spreads out much by capillary force.[2-4] Phenomenon that antifreeze solution spreads in porous layer can be modeled by capillary tube flow. Poiseuille's equation implies this capillary tube flow,[3] so an increasing rate of liquid column length is expressed as following.

$$\frac{dl}{dt} = \frac{\Delta P r^2}{8\mu_l l} \tag{1}$$

where μ_l is viscosity of antifreeze solution, l is length of liquid column, and ΔP means pressure difference that generate flow in capillary tube. In the case of horizontal capillary tube, a capillary force which generates flow is as following.

$$\Delta P = \frac{2\lambda}{\lambda} \cos\theta \tag{2}$$

where λ is surface tension, and θ is interface contact angle.

By rearranging Eqs. (1) and (2), Eq. (3) is induced as following.

$$\frac{dl}{dt} = \frac{\left(\frac{2\lambda}{r}\cos\theta\right) r^2}{8\mu_l l} \tag{3}$$

Integrating Eq. (3), capillary tube flow model gives the length of liquid column which extends to horizontal direction as following.

$$l = \sqrt{\left(\frac{\lambda\cos\theta}{2\mu_l}\right) rt} \tag{4}$$

If solid particles which form porous layer are spherical and have a diameter of d_p, the flow passage of porous layer supposes to consist of capillary tube of diameter d_n, which is described by porosity of porous layer and diameter of capillary tube.[4]

$$d_n = 2r = \frac{2}{3}\frac{\phi}{(1-\phi)} d_p \tag{5}$$

From Eqs. (4) and (5), the spread width and its increasing rate of antifreeze solution by capillarity can be predicted by Eqs. (6) and (7), respectively.

$$l=\sqrt{\left(\frac{\lambda\cos\theta}{2\mu_l}\right)\left[\frac{\phi}{3(1-\phi)}\right]d_p t} \tag{6}$$

$$\frac{dl}{dt}=\left(\frac{\lambda\cos\theta}{4\mu_l l}\right)\left[\frac{\phi}{3(1-\phi)}\right]d_p \tag{7}$$

2.3 Heat tranfer model for liquid film

When the heat exchanger surface in contact with moist air is at the temperature below the dew-point for the air or freezing point, condensation or frosting of water vapor will occur on the heat exchanger surface. Both temperature and humidity of air decrease during condensation or frosting process, therefore sensible and latent heat transfer occur simultaneously.

Heat transfer process on an aluminum plate heat exchanger of this study is shown in Fig 2, where antifreeze solution exists in a form of thin liquid film between air and plate heat exchanger. Antifreeze solution flows down plate heat exchanger by gravity and absorbs condensed water from air to prevent frost formation. If ignoring shear force by air flow and buoyancy effect, antifreeze solution has following vertical velocity distribution.

$$v=\frac{g}{\mu_l}\rho_l\delta^2\left[\frac{x}{\delta}-\frac{1}{2}\left(\frac{x}{\delta}\right)^2\right] \tag{8}$$

Integrating this velocity multiplied by density across the liquid film yields the following mass flow rate of antifreeze solution per unit width of surface. Accordingly, the liquid film thickness is expressed as functions of viscosity, density and mass flow rate per unit surface width of antifreeze solution.

$$\Gamma=\int_0^{\delta}\rho_l v dx=\frac{g\rho_l^2}{3\mu_l}\delta^3 \tag{9}$$

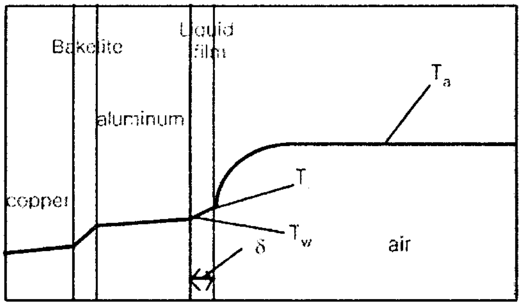


Fig. 2 A diagram for heat transfer process on the heat exchanger.

$$\delta=\sqrt[3]{\frac{3\mu_l\Gamma}{g\rho_l^2}} \tag{10}$$

From the Nusselt analysis,[5] assuming that heat transfer across liquid film is due to conduction only, whereupon heat transfer rate across liquid film is given by

$$dq=\frac{k_l}{\delta}(T_l-T_w)dA \tag{11}$$

Heat transfer rate from moist air to liquid film at a temperature below the air dew-point is expressed as following using double potential model.

$$dq=dq_s+dq_L \tag{12}$$

$$dq_s=h(T_a-T_l)dA \tag{13}$$

$$dq_L=h_D(w_a-w_l)i_{fg}dA \tag{14}$$

where h is sensible heat transfer coefficient, and h_D is mass transfer coefficient. Equation (13) describes sensible heat transfer rate driven by temperature difference of air and liquid film. Equation (14) gives latent heat transfer rate by an amount of water condensate from moist air to antifreeze solution film.

Temperature and humidity at the interface between liquid film and air are evaluated by assuming that moist air is saturated at the interface. When antifreeze solution covers the heat exchanger surface below freezing point, heat transfer performance is analyzed using Eqs. (12) to (14), and mass transfer coefficients are calculated from experimental data.

3. Experiments

The experimental setup is constructed as shown in Fig. 3 to observe antifreeze solution wettability and its effect on heat transfer performance, when antifreeze solution is supplied on the heat exchanger surface.

Test setup consists of a plate heat exchanger, an antifreeze solution spraying device, a chiller which is for generating low temperature brine to be supplied to the plate heat exchanger as a refrigerant and also regulating the temperature of antifreeze solution, and an air conditioner to supply air of constant temperature and humidity.

Air duct that encloses aluminum plate surface is composed of transparent acrylic plastic, so that observation of plate heat exchanger surface is possible. The width of air flow passage at plate heat exchanger is 10 mm.

An antifreeze solution supplying device is installed to maintain thin liquid film on the heat exchanger surface as shown in Fig. 3. In this study, three nozzles are positioned at the top of plate surface, and a small amount of antifreeze solution falls in drops and spreads completely on the heat exchanger surface. Because the amount of supplied antifreeze solution is very small, mass flow rate is measured using a balance and a stopwatch.

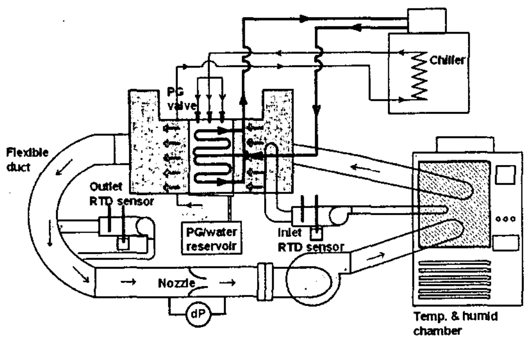


Fig. 3 Schematic of performance test setup.

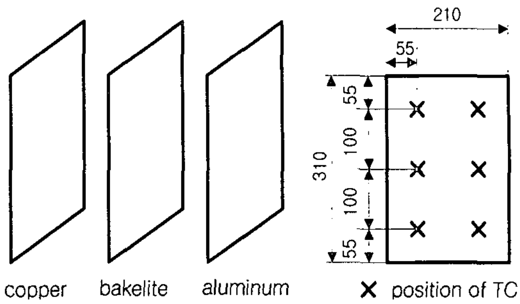


Fig. 4 Schematic of plate heat exchanger.

A plate heat exchanger consists of three layers as shown in Fig. 4. The front layer is aluminum plate where heat and mass transfer with moist air occur, intermediate layer is Bakelite plate of 1 mm thickness to measure the heat flux, and the end layer is copper plate which have multiple flow paths for brine flow inside the layer to reduce and control the temperature of aluminum plate surface. Aluminum plate is used as heat exchanger surface in contact with moist air to mimic aluminum fin of fin-tube heat exchanger. The size of aluminum plate is $200 \times 300 \times 5\,mm^3$. Contact resistances among each layer are minimized by applying thermal grease on contact surfaces of each layer. T-type thermocouples are attached on both sides of Bakelite plate and back side of aluminum plate at the positions in Fig. 4.

Wettability of antifreeze solution at ambient temperature is measured on the surface of porous layer coated plate, and compared to that of bare aluminum plate by visualization experiment using CCD camera.

Table 1 Test conditions

Plate temperature [℃]	−10
Air temperature [℃]	20
Relative humidity [%]	50, 60, 70
Air flow rate [cmh]	31, 42, 51
Supplied brine flow rate [g/min]	3, 6, 9

All the test conditions for frost prevention and heat transfer performance are listed in Table 1. Relative humidity of supplied air is varied from 50% to 70%, and air temperature and surface temperature of aluminum plate are kept by 20℃ and −10℃, respectively. Air flow rate ranges from 31 to 51 CMH, which corresponds to 3500 ~6000 of air side Reynolds number. Propylene/water mixture is selected as an antifreeze solution. The concentration of the antifreeze solution is maintained by 50% during the tests.

Test data of temperature, pressure and mass flow rate are collected by personal computer. RTD sensors, a nozzle type air flow meter and a pressure transducer are used to measure air side temperature, humidity, flow rate and pressure loss as shown in Fig. 3. RTD sensors and Coriolis force mass flow meters are installed to measure the temperature and mass flow rate of antifreeze solution and brine.

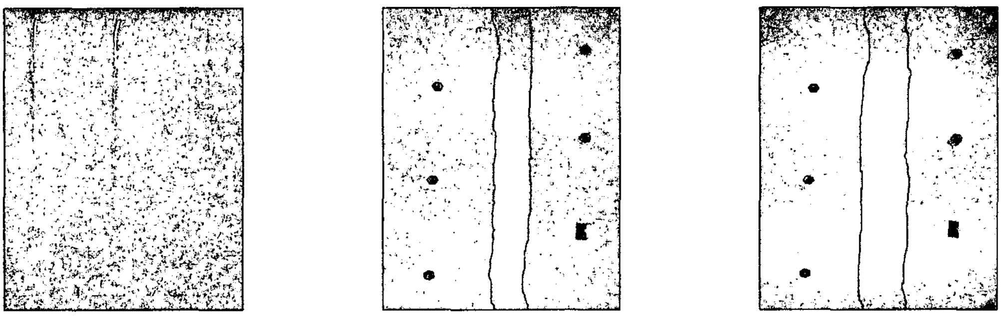
4. Results

4.1 Wettability enhancement

Wettability of antifreeze solution is tested on the surface of porous layer coated plate as well as bare aluminum plate. Figure 5 shows typical results of wetting shapes on two types of vertical plate surfaces obtained by the photographic observation. A small amount of antifreeze solution is supplied at the top of plate surfaces at room temperature. It is clear that the motion of stream on a vertical surface is driven by gravity, and that the shear stress at the liquid-solid interface is much greater than at the liquid-air interface. It is also apparent that surface tension should play a major role in determining a motion. When a liquid flows down a flat surface, several different flow regimes can be observed, depending on the flow rate and the physical properties of the liquid-solid surface system. When the flow is 0.3 g/min at vertical surface of bare aluminum plate, a single laminar rivulet which has 6 mm width is formed as shown in Fig. 5 (a). On the porous coating surface in Fig. 5 (b) and (c), wetting width of flow stream increases greatly by 20~40 mm due to capillarity.

Using Eqs. (6) and (7), the spread width and its increasing rate of antifreeze solution on porous coating surface are calculated and shown in Fig. 6. It is assumed that the particle diameter and porosity of coating layer are 30 μm and 25%, and contact angle, viscosity, and surface tension of antifreeze solution are 20°, 0.064 kg/ms and 0.036 N/m. Spreading rate decreases rapidly in 2 or 3 minutes, after that point decreasing rate becomes slow.

Accordingly, except steep increase of spread width in the beginning, antifreeze solution spreads in proportion to time. These simulation results



(a) Bare surface (m_l=0.3 g/min) (b) Porous layer coating surface (m_l=0.3 g/min) (c) Porous layer coating surface (m_l=1.7 g/min)

Fig. 5 Wetting shape on the dry surface.

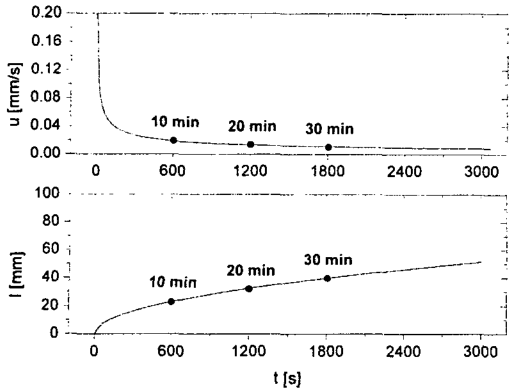


Fig. 6 Wettability length and velocity of antifreeze solution with the lapse of time.

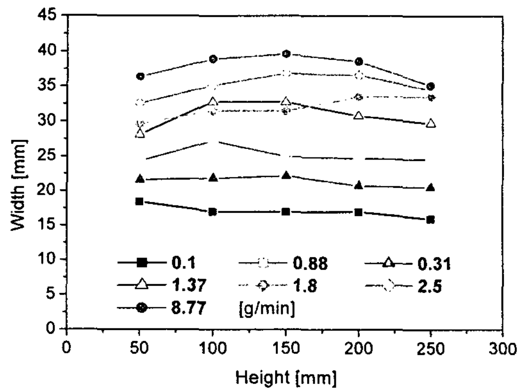


Fig. 8 Wettability with respect to mass flow rate of brine.

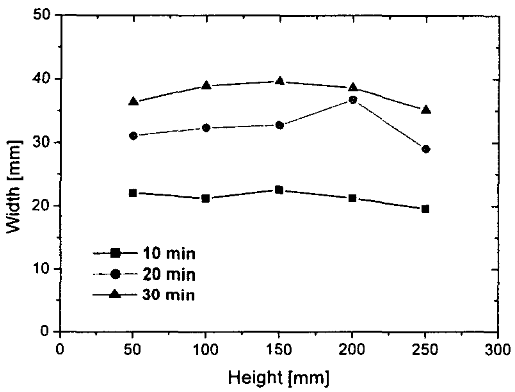


Fig. 7 Wettability variation with the lapse of time (m_l=2.5 g/min).

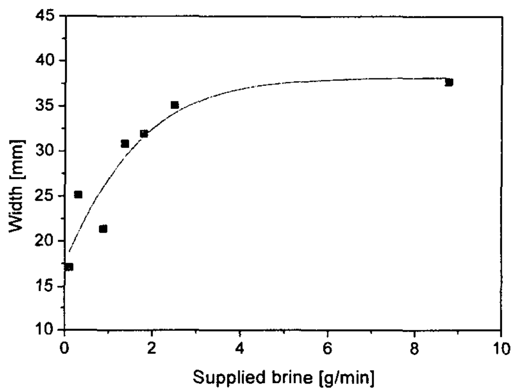


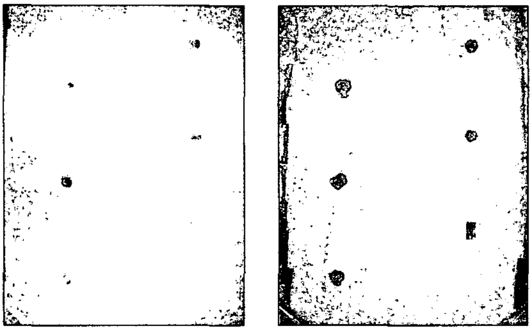
Fig. 9 Averaged wettability with respect to mass flow rate of brine.

agree with the wettability test result in Fig. 7. Spread width with respect to vertical height of aluminum plate shows no large variation and increases as time goes by. Therefore, wettability performance of this study is represented by the test result after 30 minutes from antifreeze solution supply.

Figure 8 expresses spread width with respect to height of vertical plate at several mass flow rate of antifreeze solution. As mass flow rate of antifreeze solution increases, the wetted area also increases. In Fig. 9 average spread width is displayed as a function of mass flow rate of antifreeze solution. Accordingly, as the quantity of supplied antifreeze solution increases, wetted width grow larger, however, augmentation of spread width rapidly slowes down more than 3 g/min.

4.2 Frost prevention

In Fig. 10 (a), typical photography of frost layer that forms on the surface of aluminum plate where antifreeze solution is not supplied is shown, and with the lapse of frosting time, the frost thickness increases rapidly. By adopting porous layer coating technique in this study, Fig. 10 (b) shows frost formation can be successfully prevented by antifreeze solution liquid film. That is, the antifreeze solution liquid film



(a) Frosting surface (b) Frost-less surface

Fig. 10 Photography of aluminum plate under frost condition.

spreads widely on the aluminum plate surface with porous coating, which prevents the formation of frost layer on the heat exchanger surface. The antifreeze solution is supplied at the same temperature with heat exchanger surface to reduce the effect by temperature difference.

When antifreeze solution spreads on heat exchanger surface, heat and mass transfer coefficients of air side are displayed in Fig. 11 with respect to air flow rate. As you see trend line that is marked in solid line, heat and mass transfer coefficients increase with increasing air flow rate.

Uncertainty in experimental results, are estimated using the method proposed by Kline and McClintock,[6] and the results are shown in Table 2.

Table 2 Uncertainty of air flow rate, heat transfer and heat and mass transfer coefficients

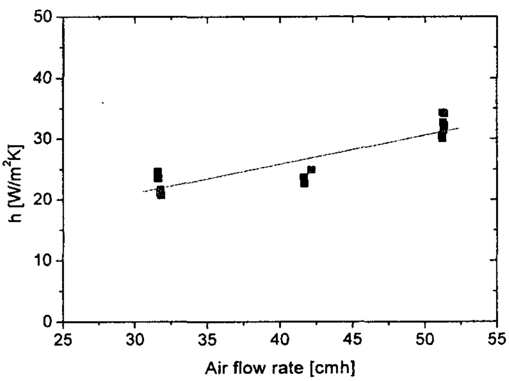
	q_s	h	q_L	h_D
41 cmh	11.17%	11.34%	21.39%	21.48%
51 cmh	11.02%	11.21%	19.87%	19.96%

Using Eq. (10), liquid film thickness is presented in Fig. 12 as a function of film Reynolds number. The liquid film is very thin and its thickness ranges from 100 to 180 μm, and film Reynolds number is defined as following.

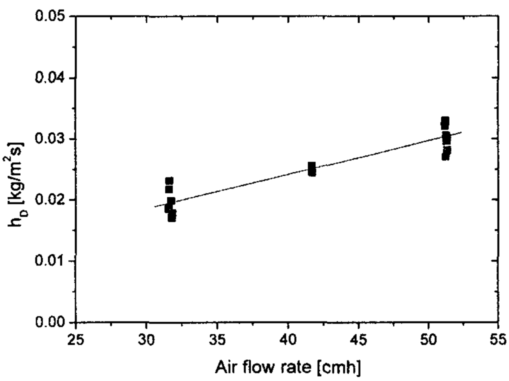
$$\mathrm{Re}_f = \frac{4\Gamma}{\mu_l} \tag{15}$$

Figure 13 displays air side heat and mass transfer coefficients with liquid film thickness under two different air flow rate conditions. Heat and mass transfer coefficient is affected definitely by air flow rate as shown in Fig. 11. However, Fig. 13 shows only small variation of heat and mass transfer coefficients according to liquid film thickness within experimental uncertainty.

The heat transfer performance reductions by liquid film are presented in Fig. 14 as a func-



(a) Heat transfer coefficient



(b) Mass transfer coefficient

Fig. 11 Heat and mass transfer coefficient of air side with variable air flow rate.

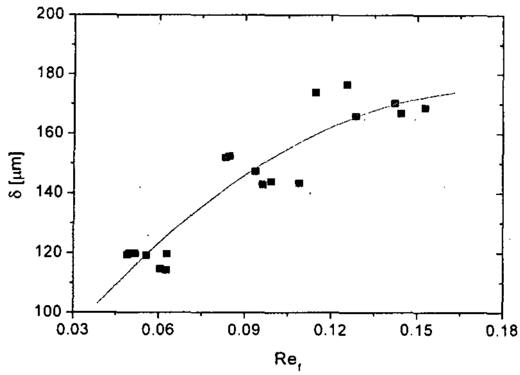


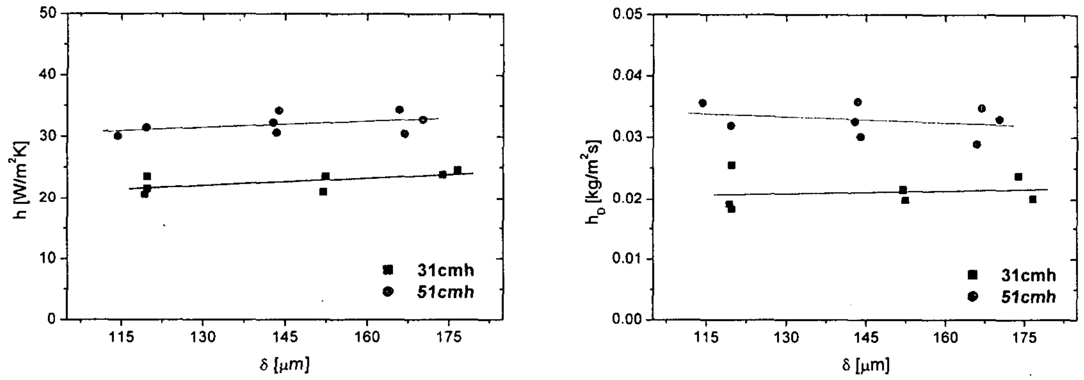
Fig. 12 Liquid film thickness on frost-less surface with film Reynolds number.

tion of film Reynolds number. Although heat and mass transfer performance decrease, as film Reynolds number increases, performance deterioration is very small by 1~2%. Therefore, the variation of liquid film thickness by increase of the quantity of antifreeze solution hardly does not influence heat and mass transfer performance of heat exchanger.

Conclusively, because liquid film thickness is very small by micro scale, thermal resistance of the liquid film is small enough to ignore.

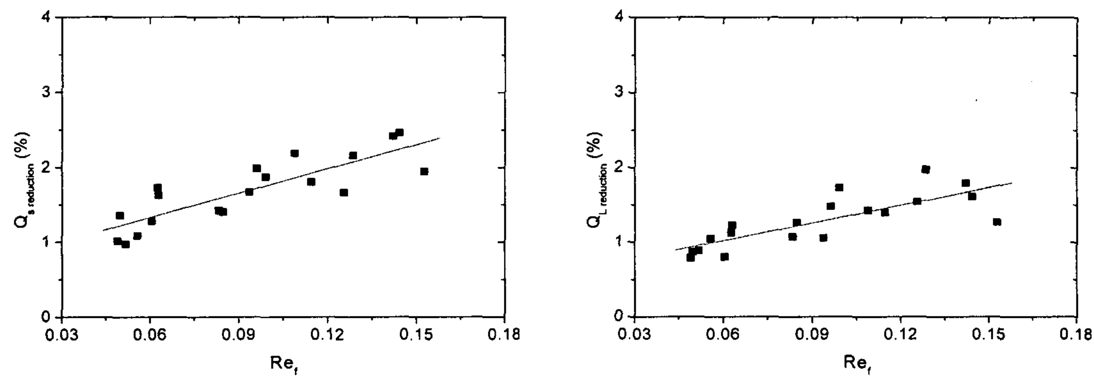
5. Conclusions

In this study, by investigating frost prevention performance by antifreeze solution spraying on plate heat exchanger, several conclusions are drawn as following.



(a) Heat transfer coefficient (b) Mass transfer coefficient

Fig. 13 Heat and mass transfer coefficient of air side with liquid film thickness.



(a) Heat transfer rate (b) Mass transfer rate

Fig. 14 Performance deterioration of heat exchanger by liquid film.

(1) When porous layer coating technique is applied on the surface of aluminum plate, wettability of antifreeze solution is remarkably improved by capillarity.

(2) The frost formation on the surface of aluminum plate is prevented by thin liquid film of antifreeze solution under frosting air condition.

(3) It is possible to keep thin liquid film of 100 μm on heat exchanger surface, and heat transfer degradation of the liquid film is very small by 1~2%.

References

1. Hayashi, Y., Aoki, A., Adachi, S. and Hori, K., 1977, Study of frost properties correlating with frost formation types, Journal of Heat Transfer, Vol. 99, pp. 239-245.
2. Lee, J. W., Lee, D. Y. and Kang, B. H., 2003, An experimental study on the effects of porous layer treatment on evaporation heat transfer from an inclined surface, Proceedings of the SAREK, pp. 153-158.
3. Erik, K., 1996, Wetting and wicking, Textile Res. J., Vol. 66, pp. 660-668.
4. Kim, H. J. and Lee, J. H., 1992, Analysis of evaporative heat transfer in a porous layer by capillary model, Transaction of KSME (B), Vol. 16, pp. 391-399.
5. Collier, J. G. and Thome, J. R., 1994, Convective Boiling and Condensation, Clarendon Press, p. 445
6. Holman, J. P., Experimental Methods for Engineers, 6th ed., McGram-Hill Int. Edition, pp. 49-50.