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FROST FORMATION ON TWO-DIMENSIONAL FINS WITH NON-UNIFORM TEMPERATURE DISTRIBUTIONS

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ABSTRACT

In this study, experiments were conducted to analyze the characteristics of frost formation on a heat exchanger fin with a non-uniform temperature distribution. The local fin temperature, frost thickness and frost surface temperature were analyzed for various frosting parameters and fin thickness. As a result, the difference of frost properties is more significant in perpendicular to airflow due to the fin thermal conductivity than in parallel to airflow due to the leading edge effect. Moreover, based on the characteristics of heat exchanger fin, thermal conductivity of fin and fin thickness affect the characteristics of frosting with a reciprocity relation. Correlations of local frost thickness and frost surface temperature were proposed. When the correlations were compared with the measured local frost properties, the maximum error was 14% for frost thickness and the maximum difference in the frost surface temperature was 1.1°C.

INTRODUCTION

When water vapor contacts the fin surface of a heat exchanger operating at low temperature conditions, frost layer accumulates on the cold surface. Frost layer increases thermal resistance and blocks airflow channel as frosting time elapses, which results in the degradation of thermal performance of the heat exchanger. It is therefore essential to accurately analyze the frost behavior on heat exchanger fins.

Frost behaviors on cold surfaces have been numerically and/or experimentally investigated. Some researchers studied the frost behavior on a tube surface and suggested empirical correlations of frost properties [1-3], e.g., Schneider [1] presented the empirical correlation of frost thickness, Sengupta et al. [2] proposed the correlations of frost thickness and heat transfer at high temperature conditions, and Kim et al. [3] expressed dimensionless correlations of frost properties as functions of frosting parameters. Investigations of frosting behaviors on a cold plate were performed by many researchers [4-7]. Especially, Yonko and Sepsy [5] and Lee et al. [6] defined effective thermal conductivity of frost layer as a function of frost density only. Yang and Lee [7] proposed correlations of dimensionless frost properties by using various frosting parameters. Recently, some researchers considered fin heat conduction in investigating the frost behavior on plate fins [8-10]. Chen et al. [8] analyzed the frost formation on heat

NOMENCLATURE

A	[m^2]	Fin surface area
F	[-]	Frost properties
Fo_L	[$\alpha_a \cdot t_{op} / L_{fin}^2$]	Fourier number
H	[m]	Height of the test section
H_{fin}	[m]	Fin height
L	[m]	Length of test section
L_{fin}	[K]	Fin length
Re_L	[$u_a \cdot L_{fin} / \nu_a$]	Reynolds number
T	[K]	Temperature
t_{op}	[s]	Operation time
t_{fin}	[mm]	Fin thickness
k_{fin}	[W/m·K]	Fin conductivity
u	[m/s]	Air velocity
W	[m]	Width of test section
w	[g/Kg$_a$]	Absolute humidity ratio
x		Measurement point in air flow direction
y	[mm]	Frost thickness
z		Measurement point in air flow direction
Greek symbols		
α	[m^2/s]	Thermal diffusivity
ν	[m^2/s]	Dynamic viscosity
Superscript		
$*$		Dimensionless
Subscripts		
al		Aluminum
b		Fin base
cu		Copper
fs		Frost surface
ref		Reference

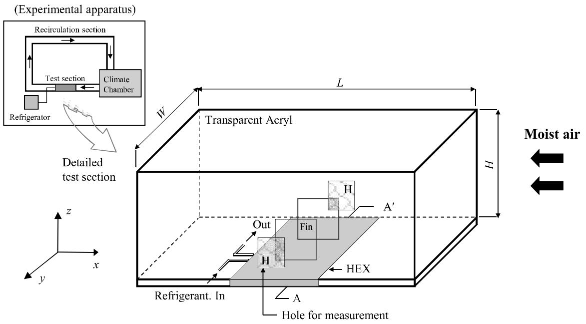
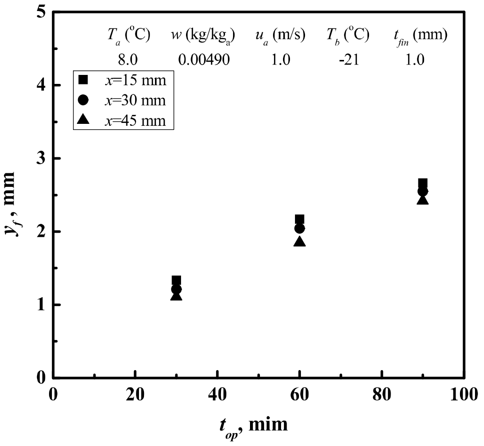
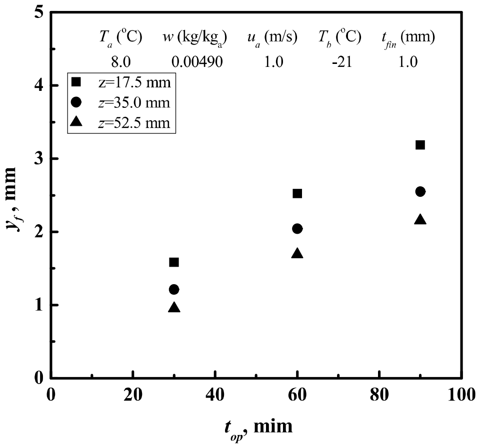


Figure 1 Experimental apparatus and test section



(a) In the x-direction at z=35 mm



(b) In the z-direction at x=30 mm

Figure 2 Transient frost thickness on 2-D fin

exchanger fins considering the fin heat conduction but omitting the change of the airflow at airside caused by the frost growth, and compared the results with experimental data of Chen et al. [9]. Kim et al. [10] presented a mathematical model for predicting the frost behaviors on heat exchanger fins considering the fin heat conduction, and proposed a correlation of equivalent temperature for heat transfer. The consideration of a non-uniform temperature distribution on the fin has started up recently, and therefore few empirical correlations of frost properties on the fin with non-uniform temperature distribution have been reported.

The objective of this study is to propose empirical correlations of frost properties, i.e., frost thickness and frost surface temperature, on a heat exchanger fin with a non-uniform temperature distribution. We analyze the local fin temperature and frost behavior in the directions parallel and perpendicular to the airflow above the heat exchanger fins. The empirical correlations are expressed as functions of Reynolds number, Fourier number, humidity ratio, dimensionless temperature, dimensionless fin thickness, dimensionless fin thermal conductivity and measuring positions.

EXPERIMENTAL

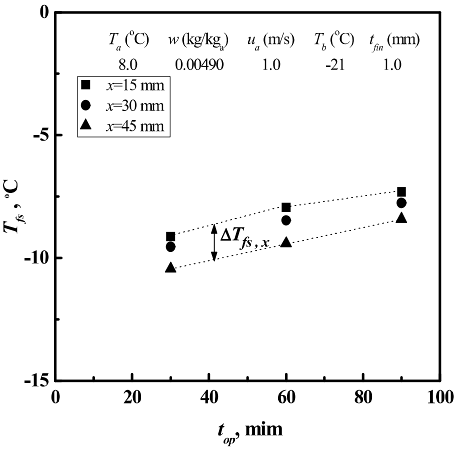
Figure 1 shows the experimental apparatus including a climate chamber to regulate air temperature and humidity, a test section to perform frosting experiments with heat exchanger fins, a refrigeration section to control flow rate and temperature of the refrigerant, and a recirculation section. The size (L X W X H) of the test section was (300 X 150 X 150 mm). Holes were drilled on side walls of the test section for the measurement of frost thickness and frost surface temperature. These holes were kept closed during the frosting experiments and opened only when measurements were conducted. The fins were made of aluminium (k_{fin}=220 W/mK) and size of the fin(L_{fin} X H_{fin}) was 60 X 70 mm. The thickness of the fin (t_{fin}) were 0.6, 0.7, 0.8, 0.9 and 1.0 mm. A solution of ethylene glycol and distilled water mixed with a mass ratio of 5:5 was used as the refrigerant. A maze-type refrigerant path was manufactured to maintain a constant temperature at the fin base. The locations of the measurements of fin temperature, frost thickness and frost surface temperature were 9 points with quartering the fin. The fin surface temperature was measured with type-T thermocouples attached at each point. Thickness and surface temperature of the frost were measured using a micrometer and an infrared imaging camera every 30 minutes.

The uncertainties of the fin surface temperature, frost thickness, and frost surface temperature were 0.49℃, 0.03 mm, and 0.31℃, respectively [11].

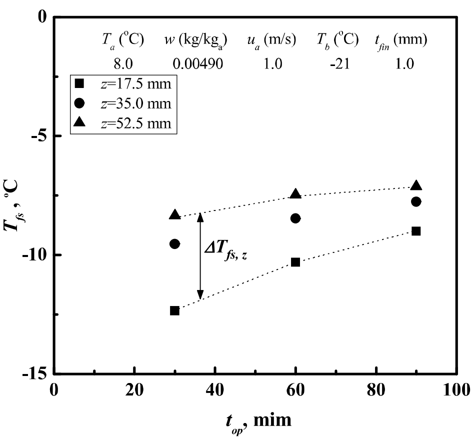
RESULT AND DISCUSSION

Frosting experiments were conducted to analyze local fin temperature and frost behavior characteristics on a two-dimensional fin surface, in the airflow direction and the direction perpendicular to airflow. We set 25 cases according to the Design of Experiment. The experimental conditions were as follows:

$$278.15 \le T_a \le 284.15 \text{ K},\ 246.15 \le T_b \le 258.15 \text{ K},\ 1.0 \le u_a \le 2.0 \text{ m/s},$$
$$3.33 \le w \le 6.34 \text{ g/kg}_a,\ 0 \le t_{op} \le 5400 \text{ s and } 0.6 \le t_{fin} \le 1.0 \text{ mm}.$$



(a) In the x-direction at z=35 mm



(b) In the z-direction at x=30 mm

Figure 3 Transient surface temperature of frost formed on 2-D fin

Frost characteristics

The temperature on two-dimensional (2-D) fin was high at the early stage of frosting due to the thin frost layer, through which the heat transfer between the fin and moist air under forced convection was relatively high. As the operation time elapsed, the fin temperature gradually decreased due to the increase in thermal resistance by frost growth. Especially, the fin temperature gradient in the airflow direction was relatively small, while that in the direction perpendicular to airflow was significant because of the effect of fin heat conduction.

Figure 2 shows the transient frost thickness on a 2-D fin. In the airflow direction, the frost thickness near the leading edge (x=15 mm) was slightly greater than that close to the trailing edge (x=45 mm) due to the leading edge effect. Accordingly, the change of the gradient of frost thickness was insignificant, as operation time elapsed. To the contrary, in the direction perpendicular to airflow, the frost growth was with time was significant compared to that in the airflow remarkable at the fin base, and the gradient of frost thickness direction. This implies that the frost growth on 2-D fins is significantly influenced by the fin surface temperature.

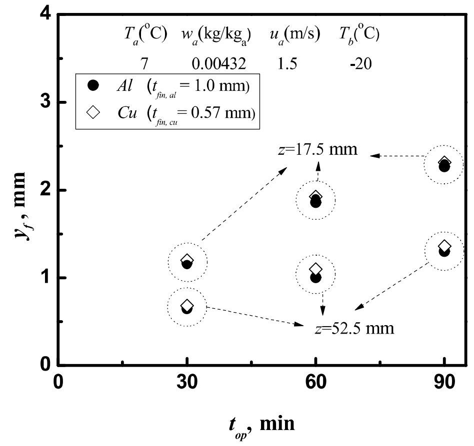


Figure 4 Comparison of the frost thickness between aluminum ($t_{fin,al}$=1.0 mm) and copper ($t_{fin,cu}$=0.57 mm) fins at x= 30 mm

Figure 3 shows the surface temperature of frost formed on a 2-D fin, as frost grew with time. The frost surface temperature in airflow direction was lower at the trailing edge of the fin, compared to that at the leading edge of fin. In addition, the change of the gradient of frost surface temperature in the airflow direction($\triangle T_{fs,x}$) was insignificant. In the direction perpendicular to airflow, the frost surface temperature was lower at the fin base due to the effect of low fin temperature. Especially, the gradient of frost surface temperature in the direction perpendicular to the airflow($\triangle T_{fs,z}$) gradually decreased, as frost layer accumulated with time. This is because the effect of fin heat conduction on the frost surface temperature was significant due to the thin frost layer at the early stage of frosting, and decreased with increasing frost thickness with time.

Figure 4 shows the comparison of frost thickness between 1-mm-thick aluminum fin and 0.57-mm-thick copper fin(k_{fin}=390W/mK) with time, in the direction perpendicular to the airflow at x=30 mm, under the identical frosting condition. The difference in frost thickness between two fins was very small. This is because any two fins of the equal length and height would have the same fin temperature distribution, if the values of fin thickness times fin conductivity, i.e., $t_{fin} x k_{fin}$, are identical [12]. Based on this phenomenon, the empirical correlations considering the product of fin conductivity and fin thickness as a parameter would be derived.

Empirical correlations

Empirical correlations of frosting thickness and frost surface temperature were expressed as functions of dimensionless parameters, such as frosting parameters (air temperature, air velocity, absolute humidity, fin base temperature and operation time), measurement parameters (frost thickness and surface temperature), geometric parameters (fin height, fin length and fin thickness), air properties (thermal diffusivity, dynamic viscosity), fin conductivity, and measurement locations (x and z), i.e.,

$$F = f(T^*, w, \mathrm{Re}_L, \mathrm{Fo}_L, t_{fin}{}^*, k_{fin}{}^*, x^*, z^*) \tag{1}$$

where

$$T^* = \frac{T_a}{T_a - T_b},\ \mathrm{Re}_L = \frac{u_a L_{fin}}{\nu}, \mathrm{Fo}_L = \frac{\alpha t_{op}}{L_{fin}}, t_{fin}^* = \frac{t_{fin}}{t_{fin,ref}},$$
$$k_{fin}^* = \frac{k_{fin}}{k_{fin,ref}}, x^* = \frac{x}{L_{fin}}, z^* = \frac{z}{H_{fin}} \tag{2}$$

Here, $t_{fin,ref}$ = 1.0 mm and $k_{fin,ref}$ = 220 W/mK.

Empirical correlations of the dimensionless local frost properties, due to the inhomogeneous frost formation on a heat exchanger fin, were derived by the least square method as follows:

$$y_{f,loc}^* = \frac{y_f}{L_{fin}} = 10778\left(T^*\right)^{-1.57153}\left(w\right)^{0.52359}\left(\mathrm{Re}_L\right)^{-0.09516}$$
$$\times\left(\mathrm{Fo}_L\right)^{0.63373}\left(t_{fin}^* \times k_{fin}^*\right)^{0.53587}\left(e^{x^*}\right)^{-0.27792}\left(e^{z^*}\right)^{-1.16033} \tag{3}$$

$$T_{fs,loc}^* = \frac{T_{fs} - T_b}{T_a - T_b} = 2.0226\left(T^*\right)^{-0.66243}\left(w\right)^{0.35837}\left(\mathrm{Re}_L\right)^{0.12164}$$
$$\times\left(\mathrm{Fo}_L\right)^{0.14292}\left(t_{fin}^* \times k_{fin}^*\right)^{-0.18627}\left(e^{x^*}\right)^{-0.23017}\left(e^{z^*}\right)^{0.57220} \tag{4}$$

The applicable conditions of the correlations are $278.15 \le T_a \le 284.15$ K, $246.15 \le T_b \le 258.15$ K, $1.0 \le u_a \le 2.0$ m/s, $3.33 \le w \le 6.34$ g/kg$_a$, $0 \le t_{op} \le 5400$ s, $0.132 \le t_{fin} \times k_{fin} \le 0.222$ W/K, $0 \le x \le 0.06$ m and $0 \le z \le 0.07$ m.

The correlations of Eq. (3) and Eq. (4) predicted well the frost thickness with a maximum error of 14% and the frost surface temperature with a maximum difference of 1.1℃, respectively.

CONCLUSION

Frosting experiments were conducted and correlations of frost properties, i.e., frost thickness and frost surface temperature, for a heat exchanger fin with a non-uniform temperature distribution. We analyzed the local temperature and frosting characteristics of a 2-D fin in the airflow direction and the direction perpendicular to the airflow, for various operating conditions of air temperature, air velocity, absolute humidity and fin base temperature. As a result, the frost behavior on heat exchanger fins was closely related with the fin conductivity. Correlations of the local frost properties on heat exchanger fins were derived as functions of Reynolds number, Fourier number, humidity ratio, dimensionless temperature, dimensionless fin thickness, dimensionless fin thermal conductivity and measuring positions, and these correlations predicted the measured data well, with a maximum error of 14% for frost thickness and with a maximum difference of 1.1℃ for frost surface temperature.

ACKNOWLEGEMENT

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