Purdue University
Purdue e-Pubs

International Refrigeration and Air Conditioning Conference

School of Mechanical Engineering

2004

Modeling of Frost Behavior on a Cold Plate

Dong Keun Yang
Hanyang University

Dong Hoon Lee
Hanyang University

Jung Soo Kim
Hanyang University

Kwan Soo Lee
Hanyang University

Follow this and additional works at: http://docs.lib.purdue.edu/iracc

Yang, Dong Keun; Lee, Dong Hoon; Kim, Jung Soo; and Lee, Kwan Soo, "Modeling of Frost Behavior on a Cold Plate" (2004). *International Refrigeration and Air Conditioning Conference.* Paper 717.
http://docs.lib.purdue.edu/iracc/717

This document has been made available through Purdue e-Pubs, a service of the Purdue University Libraries. Please contact epubs@purdue.edu for additional information.
Complete proceedings may be acquired in print and on CD-ROM directly from the Ray W. Herrick Laboratories at https://engineering.purdue.edu/Herrick/Events/orderlit.html

MODELING OF FROST BEHAVIOR ON A COLD PLATE

Dong-Keun YANG[1], Dong-Hoon LEE[1], Jung-Soo KIM[1], Kwan-Soo LEE[2]

[1]Department of Mechanical Engineering, Graduate School, Hanyang University, 17 Haengdang-dong, Sungdong-gu, Seoul, 133-791, KOREA

[2]School of Mechanical Engineering, Hanyang University, 17 Haengdang-dong, Sungdong-gu, Seoul, 133-791, KOREA
(Phone : +82-2-2290-0426, Fax : +82-2-2295-9021, E-mail : ksleehy@hanyang.ac.kr)

ABSTRACT

This paper presents a mathematical model to predict the frost properties and heat and mass transfer within the frost layer formed on a cold plate. The laminar flow equations for the moist air and the empirical correlations of local frost properties are employed in order to predict the frost layer growth. The correlations of the local frost density and the effective thermal conductivity of the frost layer, derived from the various experimental data, are expressed as a function of the various frosting parameters: Reynolds number, frost surface temperature, absolute humidity and temperature of moist air, cooling plate temperature, and frost density. The numerical results are compared with experimental data to validate the present model, and they agree well with the experimental data within a maximum error of 10%. The heat and mass transfer coefficients obtained from the numerical analyses are also presented. Results show that the model for frost growth using the correlation of the heat transfer coefficient without considering the air flow has a limitation in its application.

1. INTRODUCTION

The heat exchangers used in the air-conditioning and the refrigerating systems (i.e., the domestic and industrial refrigerators, heat pumps, freezers and air conditioners) operate under the frosting conditions. The thermal performance of a heat exchanger in the early frosting stage is slightly improved due to the increase in the surface area for the heat transfer. However, the performance is degraded with the frosting time, as the frost layer acts as the thermal resistance between the moist air and the frost layer surface. It also blocks the air flow and aggravates the thermal performance of a heat exchanger. The characteristics of the heat and mass transfer with the frost growth should be predicted prior to designing the heat exchanger since the frost formation is a dominant factor in determining the performance of the refrigeration system.

Previous researchers in the area of the frost formation investigated the characteristics of the heat and mass transfer with the frost layer growth on the surface of simple geometry such as the cold plate and the cold cylinder. Jones and Parker (1975), Sami and Duong (1989), Lee *et al*. (1997) and Yun *et al*. (2002) used the correlations of the heat and mass transfer coefficients between the moist air and the frost layer surface, and analyzed the diffusion equation of the water-vapor to predict the growth of the frost layer formed on the cold plate. The numerical results were compared with the experimental data of the selected frost properties in order to validate it. However, the variation of the air flow with the frost growth was not considered in the researches, since these studies employed the correlations for the heat and mass transfer coefficients. In the case when the local heat transfer coefficient is not well-defined in the analysis domain (i.e., when the boundary layers between adjacent fins are mutually interfered by the frost layer growth, or when the geometry, on which the frost is formd, is complex.), the accuracy of the numerical result is not guaranteed. Also, since the initial frost density in the previous researches (Jones and Parker, 1975, Sami and Duong, 1989, Lee *et al*., 1997) is assumed, the numerical results may give different results depending on the frosting conditions. Parish and Sepsy (1972), and Raju and Sherif (1993) dealt with the boundary layer equation of the air flow in order to predict the frosting behavior on the cold cylinder surface, and used the correlations of the frost density and the effective thermal conductivity of the frost layer. The empirical correlations in the previous researches (Jones and Parker, 1975, Sami and Duong, 1989, Lee *et al*., 1997, Yun *et al*., 2002, Parish and Sepsy, 1972, Raju and Sherif, 1993) are derived from limited frosting conditions and expressed as a functions of only specific frosting parameter. Hence, these previous models can be applicable to the limited range of the frosting conditions. The previous researchers (Ismail *et al*., 1997, Ismail and Salinas, 1999, LeGall *et al*., 1997, Chen *et al*., 1999, Lüer and Beer, 2000) analyzed the frost layer growth by using the porosity, defined as the ratio of the frost density to the ice density. However, their numerical results showed a large deviation from the experimental data because the uncertain coefficients affecting the numerical results were chosen arbitrary. The previous researchers, so far, assumed the water-vapor on the frost layer surface is saturated. However, Na and Webb (2004a, 2004b) have recently suggested the model with the supersaturated air condition at the frost surface for predicting the frost growth and the heat and mass transfer. Na and Webb's work does not reflect the variation of the air flow with the frost layer growth as the work involved only with the correlations of heat and mass transfer coefficients. It is not easy to use the model from Na and Webb (2004a, 2004b) since it consists of complex correlations depending on the specific frosting condition.

The most of the previous researchers have so far not considered the variations of the air flow during the frost formation process, or they employed the uncertain diffusion equations and unreliable empirical correlations. Also, the initial frost properties used by previous researchers are obtained either by adjusting the values from the numerical results or from the experimental observation at specific frosting conditions. Therefore, in this study, the laminar equations for the air flow are analyzed in order to secure the accuracy of the numerical results and avoid numerical arbitrariness, and the correlations of the frost density and the effective thermal conductivity of the frost layer are employed to predict the frost growth on the cold plate. For the establishment of this model, the correlations of the local density and the effective thermal conductivity of the frost layer are derived as functions of the various frosting parameters.

2. CORRELATIONS OF FROST PROPERTIES

So far, the frost layer formed on the cold plate is experimentally examined by the previous researchers. Hayashi *et al*. (1977), and Hosoda and Uzuhashi (1967) stated that the frost density is affected by the frost surface temperature. Östin and Anderson (1991), and Yonko and Sepsy (1967) ascertained that the effective thermal conductivity of the frost layer strongly depends on the frost density. Most of the previous researchers (Hayashi *et al*., 1977, Hosoda and Uzuhashi, 1967, Östin and Anderson, 1991, Yonko and Sepsy, 1967) derived the correlations of the frost properties by considering specific frosting parameters at the limited operating conditions. However, the correlations of the frost properties can be expressed as functions of various frosting factors. Therefore, the experimental data (Yang and Lee, 2004) obtained from various operating conditions are rearranged in this study, and the correlations of the local frost density and the effective thermal conductivity are derived as the functions of frosting parameters by using the rearranged data. The local frost density is correlated by considering the frost surface temperature and the frosting factors (Reynolds number, absolute humidity and temperature of moist air, and cooling plate temperature) as follows:

$$\rho_f = 0.9567\,\mathrm{Re}_L^{-0.0237}\, w^{-1.2621}\left[\exp\left(\frac{T_{fs}-T_{tp}}{T_a-T_p}\right)\right]^{3.9347} \tag{1}$$

The local effective thermal conductivity of the frost layer is expressed as a function of the frost density and the relevant frosting parameters, and its correlation is given as:

$$k_{f,\,eff} = 0.5252\,\mathrm{Re}_L^{-0.0224}\left(\frac{\rho_f}{\rho_{ice}}\right)^{0.2653} w^{0.0372}\left[\exp\left(\frac{T_a-T_{tp}}{T_a-T_p}\right)\right]^{-0.1616} \tag{2}$$

In Figs. 1 and 2, the local frost density and effective thermal conductivity calculated from the correlations are compared with the experimental data (Yang and Lee, 2004). The proposed correlations agree well with the experimental data within a maximum error of 10%. The application range of the correlations presented in this study is as follows: the air temperature of 5 to 15℃, air velocity of 1.0 to 2.5 m/s, absolute humidity of 0.00322 to 0.00847 kg/kg$_a$, and cooling plate temperature of -35 to -15℃.

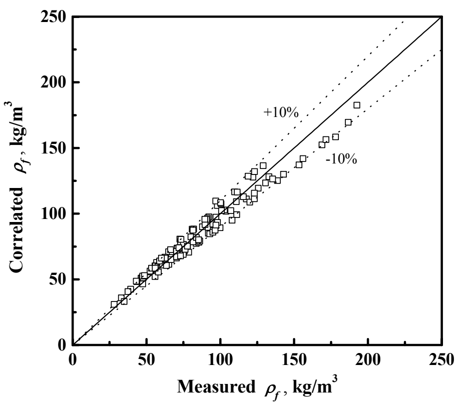

Figure 1 : Comparison of the measured and correlated data of the frost layer density

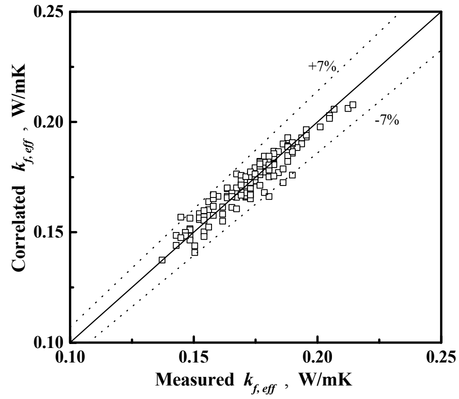

Figure 2 : Comparison of the correlated and measured data of effective thermal conductivity of frost layer

3. MATHEMATICALMODELING AND NUMERICAL METHOD

This paper presents a mathematical model to predict the characteristics of the heat and mass transfer into the frost layer by analyzing the frost layer growth. Figure 3 shows the computational domain for analyzing the frosting behavior, and the frosting process is assumed to be at quasi-steady state.

3.1 Mathematical Modeling

The laminar flow equations are employed to analyze the moist air, and the governing equations in tensor form are as follows:

$$\frac{\partial}{\partial x_i}\left(\rho u_i \phi\right) = \frac{\partial}{\partial x_i}\left(\sigma_\phi \frac{\partial \phi}{\partial x_i}\right) + S_\phi \tag{3}$$

where ϕ and S_ϕ for the continuity, *u*-momentum, *v*-momentum, energy and mass concentration are presented in Table 1, respectively.

Boundary conditions are determined by considering the physical phenomena depending on the variation of the air flow during the frost formation. The inlet conditions are determined by operating conditions, and the outlet conditions are imposed by the zero gradient in the normal direction. The constant temperature is maintained for the cooling plate, and the water-vapor on the surface of the cooling plate and frost layer are assumed to be saturated. Also, no-slip conditions are imposed at the cold plate and the frost layer surface. The boundary conditions applied in this study are shown in Table 2.

Energy balance must be satisfied on the frost surface, and its relation between the moist air and frost layer is given by (Lee *et al.*, 2003):

$$k_{f,\,eff}\left(\frac{\partial T}{\partial y}\right)_{y=y_f} = k_a\left(\frac{\partial T}{\partial y}\right)_{y=y_f} + \rho h_{sv} D \left.\frac{\partial m_w}{\partial y}\right|_{y=y_f} \tag{4}$$

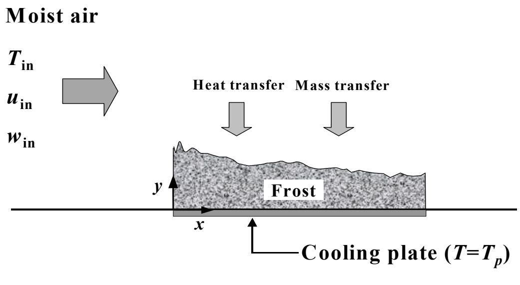

Figure 3 : Schematic diagram of the frost layer growth on a cold plate

Table 1 : ϕ, σ_ϕ, and S_ϕ used in equation (3)

Equations	ϕ	σ_ϕ	S_ϕ
Continuity	1	-	0
u-momentum	u	μ	$-\partial p / \partial x$
v-momentum	v	μ	$-\partial p / \partial y$
Energy	T	k_a / c_p	0
Mass concentration	m_w	ρD	0

Table 2 : Boundary conditions

Inlet	$u = u_{in}$, v=0, $T = T_{in}$, $m_w = m_{w,\,in}$
Outlet	$\frac{\partial u}{\partial n} = 0,\ \frac{\partial v}{\partial n} = 0,\ \frac{\partial T}{\partial n} = 0,\ \frac{\partial m_w}{\partial n} = 0$
Duct surface	$u = 0,\ v = 0,\ \frac{\partial T}{\partial n} = 0,\ \frac{\partial m_w}{\partial n} = 0$
Cold plate surface	$T = T_p,\ m_w = m_{w,\,sat}(T_p),\ \frac{\partial m_w}{\partial n} = 0$
Frost layer surface	$u = 0,\ v = 0,\ T = T_{fs},\ m_w = m_{w,\,sat}(T_{fs})$

where the correlation of the effective thermal conductivity, equation (2), proposed in this study, is used.
The water-vapor absorbed from the moist air to the frost surface is diffused inside the frost layer, and this increases the density and thickness of the frost layer, respectively. The mass fluxes transferred into the frost layer are calculated as follows:

$$m_f'' = \rho D \left. \frac{\partial m_w}{\partial y} \right|_{y_f} = m_y'' + m_\rho'' = m_y'' + \frac{y_f}{\Delta t}\left(\rho_f^{t+\Delta t} - \rho_f^t \right) \tag{5}$$

The local frost density for each time step is computed from equation (1). Also, the local frost thickness is calculated by using equations (1) and (5):

$$y_f^{t+\Delta t} = y_f^t + \frac{m_y''}{\rho_f} \Delta t \tag{6}$$

3.2 Numerical Method

The finite volume method is used in order to discretize the governing equations, and the numerical analyses are performed by using the SIMPLER algorithm (Patankar, 1980). The dependency tests of the time interval and the grid system on the numerical results are investigated by changing the time step (i.e., 5, 10 and 20 seconds) and the number of grid points (i.e., 71×45, 71×55 and 71×65 grid systems). Since the changes of the frost properties calculated from the each grid system and time interval are less than 1.5%, the grid system of 71×55 and the time interval of 10 seconds are adopted in this work, respectively. When the changes of the velocity, the temperature, and the mass concentration of the moist air are less than 10^{-4}%, the solutions are assumed to be converged. Also, the frost surface temperature is iteratively computed until the energy balance in the frost surface is satisfied, and then the density and thickness of the frost layer for each time step are calculated.

4. RESULTS AND DISCUSSION

To validate the present model proposed in this study, the experimental data (Jones and Parker, 1975) for the frost thickness are compared with the numerical results of various models for predicting the frost layer growth, and the results are shown in Figure 4. The previous models (Jones and Parker, 1975, Sami and Duong, 1989, Lee et al.,

1997) and the present model under-predicted the frost thickness at the early stage of the frost formation process. However, the numerical results of this study agree well with the experimental data as compared to those of previous models during the frost formation.
The heat transfer coefficient on the cold plate of the constant temperature without the frost formation is in general calculated as follows (Incropera and DeWitt, 2002):

$$\mathrm{Nu}_x = 0.332\,\mathrm{Re}_x^{1/2}\,\mathrm{Pr}^{1/3}, \qquad \mathrm{Pr} > 0.6,\ \ \mathrm{Re}_x < 5\times10^5 \tag{7}$$

As aforementioned, the correlation of the heat transfer coefficient obtained from the non-frosting conditions has been used by the most of previous researchers. It is not proper to use equation (7) under the frosting conditions because the heat transfer mechanisms of the frosting and non-frosting conditions are considerably different in many respects. To examine the oversight of the previous study (Jones and Parker, 1975, Sami and Duong, 1989, Lee *et al*., 1997, Yun *et al*., 2002) using the correlation of the heat transfer coefficient without analyzing air flow, Figure 5 shows the comparison of the numerical results on the local heat transfer coefficient calculated in this study with those by equation (7) at x=L/2. As shown in the figure, the heat transfer coefficients under the non-frosting conditions are decreased by 30%, compared to those of the frosting conditions. For this reason, the frost layer growth is under-predicted by the previous models (Jones and Parker, 1975, Sami and Duong, 1989, Lee *et al*., 1997).

Figure 6 presents the variations of the local heat and mass transfer coefficients along the flow direction from the inlet at t=180 minutes. The local heat transfer coefficient shows a similar trend with the mass transfer coefficient due to the analogy between heat and mass transfer. However, the variation rates in the heat and mass transfer with respect to the distance from the inlet are slightly different, and those depend on the operating conditions. When the correlation of the heat transfer coefficient, based on the analogy between heat and mass transfer, is applied by the researchers, the prediction on the characteristics of the frost layer growth along the flow direction from the inlet may deviate from the real phenomena.

To verify the mathematical model proposed in this study, Figs 7 to 9 present the comparison of the numerical results with the experimental data on the heat transfer rate, thickness and surface temperature of the frost layer. Figure 7 compares the numerical results with experimental data on frost thickness. As a result, the results of model are in good agreement with experimental data within a maximum error of 10%. Increasing the frost thickness is closely connected with the driving force of the mass transfer on the frost surface, and degrades the thermal performance of the heat exchanger due to the increase of the thermal and flow resistance. The increase in the air velocity and humidity, and decrease in the cooling plate temperature cause the increase in the driving force of the mass transfer on the frost surface, and this, in return, results in the further frost growth.

So far, the frost thickness is mainly focused by the previous researchers. However, the heat transfer rate, density and surface temperature of the frost layer including the frost thickness must be presented all together in order to give the

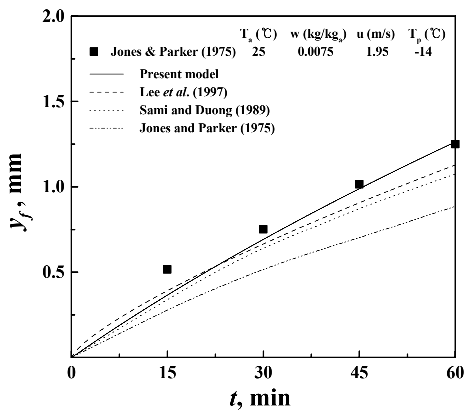

Figure 4 : Comparison of the numerical results of various models with the experimental data on the frost layer thickness

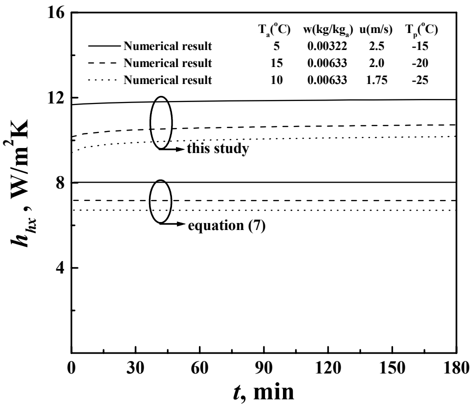

Figure 5 : Comparison of the numerical results with the correlation (equation (7)) on the local heat transfer coefficient at x=L/2

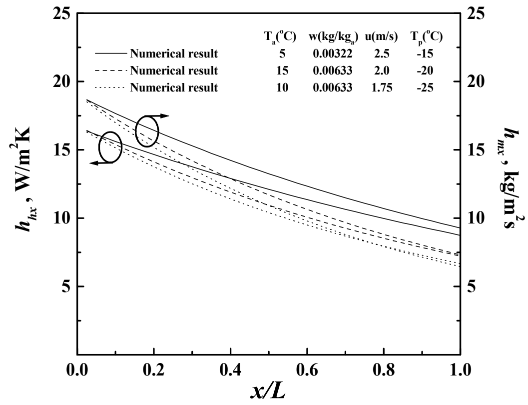

Figure 6 : Variations of the local heat and mass transfer coefficients along the flow direction from the inlet at t=180 minutes

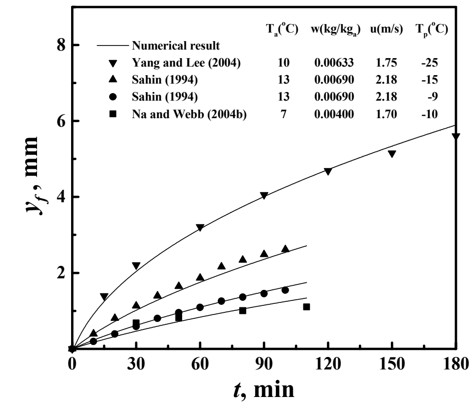

Figure 7 : Comparison of the numerical results with the experimental data on the frost layer thickness with the operating conditions

exact prediction on the frosting behavior. Figs. 8 and 9 compare the numerical results with the experimental data on the frost surface temperature and heat transfer rate during the frost formation. The frost surface temperature shows a close connection with the density and the thickness of the frost layer. Since the present model used in this study accurately predicts the frost thickness, the frost surface temperature agree well with those from the experiment as shown in Figure 8 (The accuracy of the correlation of the frost density is already verified as aforementioned in Figure 1, therefore, the frost density is not presented in this study.). Consequently, the numerical results on the heat transfer rate agree well with the experimental data. The heat transfer rate decreases during the frost formation process. However, the latent heat transfer rate becomes almost invariant because the variation of the saturated humidity on the frost surface is small despite the increase in the frost surface temperature.

Figure 10 presents the temporal variations of the mass flux with the operating conditions. The variation rate of the frost properties is slightly decreased with the frost layer growth, and this is confirmed in Figure 10. The frost thickness and density shows a different behavior depending on the frosting factors for constant air humidity. However, there is little variation in the total mass flux within the frost layer. The effect of air humidity on the mass transfer is dominant as compared to other frosting parameters.

Many previous researchers in the field of the frost formation have applied the initial frost properties obtained by either the numerical calculation or the experimental observation from the specific frosting conditions. However, this study applies the correlation of the local frost density derived by considering the related frosting parameters and

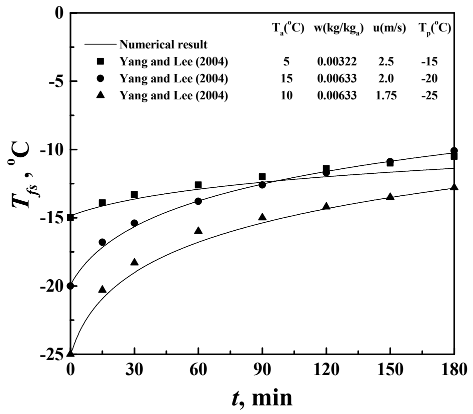

Figure 8 : Comparison of the numerical results with the experimental data on the frost surface temperature with operating conditions

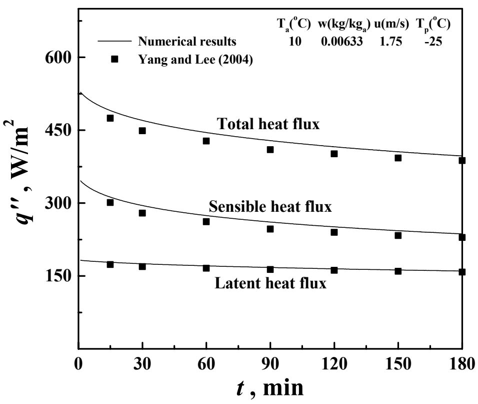

Figure 9 : Comparison of the numerical results with the experimental data on the heat fluxes

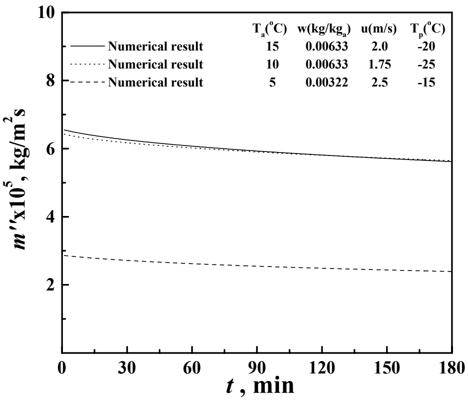

Figure 10 : Temporal variations of the mass flux with operating conditions

obtained from the various experimental conditions. Therefore, the present model established in this study gives a relatively better prediction for the frost properties that include the heat and mass transfer with the various frosting conditions. Also in the case of the arbitrary geometry with the unknown heat transfer coefficient, the application of the mathematical model for frost growth prediction proposed in this study is feasible.

5. CONCLUSIONS

This study presents a mathematical model to predict the characteristics of the heat and mass transfer within the frost layer by analyzing the frost growth. The laminar flow equations for the air flow are analyzed, and the correlations of the local frost density and the effective thermal conductivity are employed to predict the frosting behavior on the cold plate. The experimental data, obtained from the various frosting conditions, are rearranged to derive the correlation, and the correlations for the local frost properties are proposed by considering the various frosting parameters. Through this process, the limitation of the application range of the model by the correlation is relatively minimized. The present model predicts the experimental data on the heat and mass transfer with the frost properties within a maximum error of 10%. With the unknown heat transfer coefficient in the analyzing geometry, on which the frost is formed, the present model can be applied to predict the frost growth.

NOMENCLATURE

c_p	specific heat at constant pressure	(kJ/kg K)
D	mass diffusivity	(m^2/s)
h_{hx}	local heat transfer coefficient	(W/m^2 K)
h_{mx}	local mass transfer coefficient	(kg/m^2 s)
h_{sv}	latent heat of sublimation	(kJ/kg)
k	thermal conductivity	(W/m K)
L	length of cooling plate	(m)
m''	mass flux	(kg/m^2 s)
m''_y	mass flux for frost thickness	(kg/m^2 s)
m''_ρ	mass flux for frost density	(kg/m^2 s)
m_w	mass concentration of vapor	(kg/m^2 s)
Nu_x	local Nusselt number ($h_x x/k_a$)	(–)
n	normal direction	(–)
p	pressure	(Pa)
Pr	Prandtl number	(–)
q''	heat flux	(W/m^2)
Re_L	Reynolds number ($\rho vL/\mu$)	(–)
Re_x	local Reynolds number ($\rho vx/\mu$)	(–)
S	Source term	

Greek symbols

Δ	increment
ϕ	scalar variable
μ	viscosity (kg/ms)
ρ	density (kg/m^3)

Subscripts

a	air
eff	effective value
f	frost
fs	frost surface
ice	ice
in	inlet
i, j	tensor indexes
p	cooling plate
sat	saturation
t	time
tp	triple point of water
w	water-vapor

T	Temperature	(K)		
t	time	(s)	**Superscripts**	
u, v	velocity components	(m/s)	t	time
w	absolute humidity	(kg/kg_a)	Δt	time increment
x, y	cartesian coordinates			
y_f	frost layer thickness	(mm)		

REFERENCES

Chen, H., Besant, R. W., Tao, Y. X., 1999, Frost characteristics and heat transfer on a flat plate under freezer operating conditions: Part II, Numerical modeling and comparison with data, *ASHRAE Trans.*, vol. 105, no. 1: p. 252-259.

Hayashi, Y., Aoki, A., Adachi, S., Hori, K., 1977, Study of frost properties correlation with frost formation types, *ASME J. of Heat Transfer*, vol. 99: p. 239-245.

Hosoda, T., Uzuhashi, H., 1697, Effects of frost on the heat transfer coefficient, *Hitachi Review*, vol. 16, no. 6: p. 254-259.

Incropera, F. P., DeWitt, D. P., 2002, *Fundamentals of Heat and Mass Transfer*, Chapter 7, John Wiley and Sons Inc.: p. 393-394.

Ismail, K. A. R., Salinas, C. S., 1999, Modeling of frost formation over parallel cold plates, *Int. J. Refrig.*, vol. 22, no. 5: p. 425-441.

Ismail, K. A. R., Salinas, C. S., Goncalves, M. M., 1997, Frost growth around a cylinder in a wet air stream, *Int. J. Refrig.*, vol. 20, no. 2: p. 106-119.

Jones, B. W., Parker, J. D., 1975, Frost formation with varying environmental parameters, *J. Heat Transfer*, vol. 97: p. 255-259.

Le Gall, R. J., Grillot, M., Jallut, C.,1997, Modelling of frost growth and densification, *Int. J. Heat and Mass Transfer*, vol. 40, no. 13: p. 3177-3187.

Lee, K. S., Jhee, S. Yang, D. K., 2003, Prediction of the frost formation on a cold flat surface, *Int. J. Heat and Mass Transfer*, vol. 46, no. 20: p. 3789-3796.

Lee, K. S., Kim, W. S., Lee, T. H., 1997, A one-dimensional model for frost formation on a cold flat surface, *Int. J. Heat and Mass Transfer*, vol. 40, no. 18: p. 4359-4365.

Lüer, A., Beer, H., 2000, Frost deposition in a parallel plate channel under laminar flow conditions, *Int. J. Therm. Sci.* vol. 39, no. 1: p. 85-95.

Na, B., Webb, R. L., 2004, Mass transfer on and within a frost layer, *Int. J. Heat and Mass Transfer*, vol. 47, no. 5: p. 899-911.

Na, B., Webb, R. L., 2004, New model for frost growth rate, *Int. J. Heat and Mass Transfer*, vol. 47, no. 5: p. 925-936.

Östin, R., Anderson, S., 1991, Frost growth parameters in a forced air stream, *Int. J. Heat and Mass Transfer*, vol. 34, no. 4/5: p. 1009-1017.

Parish, H. C., Sepsy, C. F., 1972, A numerical analysis of frost formation under forced convection, *Semiannual Meet.*, ASHRAE: p. 236-251.

Patankar, S. V., 1980, *Numerical Heat Transfer and Fluid Flow*, Hemisphere/McGraw-Hill, Washington, DC.

Raju, S. P., Sherif, S. A., 1993, Frost formation and heat transfer on circular cylinders in cross-flow, *Int. J. Refrig.*, vol. 16, no. 6: p. 390-401.

Sahin, A. Z., 1994, An experimental study on the initiation and growth of frost formation on a horizontal plate, *Experimental Heat Transfer*, vol. 7, no. 2: p. 101-119.

Sami, S. M., Duong, T., 1989, Mass and heat transfer during frost growth, *ASHRAE Trans.*, vol. 95, no. 1: p. 158-165.

Yang, D. K., Lee, K. S., 2004, Dimensionless correlations of frost properties on a cold plate, *Int. J. Refrig.*, vol. 27, no. 1: p. 89-96.

Yonko, J. D., Sepsy, S. F., 1697, An investigation of the thermal conductivity of frost while forming on a flat horizontal plate, *ASHRAE Trans.*, vol. 73, no. 2: p. 1.1-1.11.

Yun, R., Kim, Y., Min, M. K., 2002, Modeling of frost growth and frost properties with airflow over a flat plate, *Int. J. Refrig.*, vol. 25, no. 3: p. 362-371.

ACKNOWLEDGEMENT

This research was supported by The Center of Innovative Design Optimization Technology (iDOT), Korea Science and Engineering Foundation and the Brain Korea 21 Project.