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A generalized simple model for predicting frost growth on cold flat plate

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ABSTRACT

With the aim to develop a generalized model for predicting the frost growth on cold flat plate, experiments were conducted in a suction-type open-loop wind tunnel under variant frosting conditions. Based on the Hayashi correlation, a modified correlation of initial frost density was developed by the experimental results. After validating this proposed correlation, dynamic frosting characteristics, such as the frost thickness, density, frost surface temperature and heat flux were predicted under a wide range of frosting conditions. Compared with 25 groups of experimental results taken from this paper or previous open literatures, the average simulating errors were found to be limited within ±10%. The validation results indicate the proposed model is suitable to predict the dynamic heat and mass transfer process of the frost growth under a wide range of frosting conditions.

Modèle général et simple pour la prévision de la formation de givre sur une plaque plate refroidie

Mots clés : Formation de givre ; Expérimentation ; Mesure ; Modélisation ; Corrélation

1. Introduction

The frost formation and growth on cold surface influences the performance of heat exchanger, and then exerts a negative effect on the performance of the air source heat pump or refrigeration unit. It is a valuable work to understand the frost characteristics, such as the frost thickness, density, frost growth rate, frost surface temperature and heat flux. However, these frost characteristics are various under different frosting conditions, like different air temperature, humidity, flow rate, cleanness, temperature and the property of the cold surface. Though a lot of literatures have been published to investigate the frosting characteristics by conducting experiments, it is still difficult to comprehensively

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Nomenclature

$c_{p,a}$	Specific heat at constant pressure, J kg^{-1} K^{-1}
D	Diffusivity of water vapor in air, m^2 s^{-1}
D_H	Hydraulic diameter, m
h_d	Mass transfer coefficient, m s^{-1}
h_h	Heat transfer coefficient, W m^{-2} K^{-1}
l	length of the plate, m
Le	Lewis number
L_h	Latent heat of desublimation, J kg^{-1}
M	Frost Mass, kg
m	Mass flux, kg m^{-2} s^{-1}
q	Heat flux, W m^{-2}
Re	Reynold number
T	Temperature, °C
v	Air velocity, m s^{-1}
w	Absolute humidity, kg kg$_a^{-1}$
z	Orthogonal coordinate, thickness, m

Greek symbols

α_f	Absorption factor, s^{-1}
λ	Thermal conductivity, W m^{-1} K^{-1}
ρ	Density, kg m^{-3}
φ	Relative humidity

Subscripts

a	Air
f	Frost layer
f,s	Frost surface
$f0$	Initial frost condition
lat	Latent
t	Time
tot	Total
sen	Sensible
p	Cold plate
sat	Saturation
w	Water vapor
z	Thickness
Δt	Time increment
ρ	Density

understand the frosting mechanism only by experimental data. A simple and generalized model is required to predict the characteristics of frost growth under different conditions. Quite a few scholars have put forward some models to investigate the heat and mass transfer between moist air and frost surface. O'Neal and Tree (1985) proposed a theoretical model to predict frost growth and densification. The frost was supposed to be a porous medium which is now widely accepted. Hayashi et al. (1977) divided the frost formation into three steps and proposed an empirical correlation to calculate the frost density. Jones and Parker (1975), Sami and Duong (1989) analyzed the diffusion equation of water vapor and adopted correlations of the heat and mass transfer between moist air and frost layer surface to predict the growth of frost layer. Yun et al. (2002) proposed a simple model to predict frost growth and calculate the average frost density in the process of frost formation. Lee et al. (1997) built a one-dimensional model to simulate frost growth by assuming the water vapor to be saturated at the frost surface and validated it by conducting experiments. Na and Webb (2003, 2004a,b) considered that the water vapor was supersaturated at the frost surface and proposed a supersaturated model for predicting the frost growth. The proposed model was proved to be superior to the saturated models by comparing the numerical results to previous investigators' results. Cheng and Cheng (2001) introduced a semi-empirical model for predicting the frost growth and densification rates by applying the correlation of frost density proposed by Hayashi et al. (1977).

Despite large efforts have been expended on developing the models for predicting frost growth, an important problem about the initial condition of frost density was still controversial in the current models. Jones and Parker (1975) considered that the initial frost density in the range of 8–48 kg m^{-3} would not bring large influence to the predicted results. Web (2004) fixed it as 30 kg m^{-3} in his theoretical model. Lee (1997) set it from experimental results. According to the results of Lee (2005), the initial frost density has a great effect on the predicted result of frost thickness. Hermes (2009) also pointed out that the predicted results of most models are strongly depended on the initial condition of the frost density. Cheng and Cheng (2001) calculated the initial frost density by Hayashi correlation. Hermes et al. (2009) modified Hayashi's correlation by considering the influence of cold plate temperature. However, the initial frost density is also related to the environmental temperature. Therefore, to build a generalized model for predicting the frosting process, the correlation for predicting the initial frost density is required first.

This paper modified the Hayashi correlation to calculate the initial frost density by considering the frost layer temperature, cold plate temperature and the environment temperature. Abundant experiments were conducted to provide the database both for building up the model and then validating it. The numerical results indicate that the modified model agree with the experimental results both from this paper and previous open literatures.

2. Experiment

A number of frosting experiments are conducted under various operating conditions. The experimental results, such as frost thickness, frost density and frost growth rate, are applied as a database to develop the correlation for calculating the initial frost density, and further to validate the numerical results.

2.1. Experiment apparatus

The frosting experiments are conducted in a suction-type open-loop wind tunnel, which is shown in Fig. 1 a). The