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Modeling of frost layer growth considering frost porosity

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A B S T R A C T

A numerical model for predicting frost layer growth based on computational fluid dynamics is developed. This model can predict the growth behavior of a highly porous frost layer formed by desublimation. A new volumetric mass transfer rate equation is proposed, which can consider water vapor penetration into a frost layer. The model is validated through experimental results under various operating conditions and used for analyzing the frost layer growth process. The density distribution inside the frost layer is almost linearly changed in the direction perpendicular to the cooling surface under the operating conditions favorable for desublimation, showing different characteristics from the case in the operating conditions favorable for freezing after condensation. In addition, the average mass transfer rate is analyzed as a function of time. As time passes, the porosity of the frost layer decreases and the mass transfer rate due to water vapor penetration decreases gradually.

1. Introduction

When humid air flows over the cooling surface, the humid air near the cooling surface has the degree of supersaturation. At this time, the frost layers are formed on the cooling surface during the phase change of water vapor. These frost layers gradually grow over time and act as heat resistance. Because frosting is an undesirable problem in certain engineering fields, various techniques have been studied to prevent frost formation [1]. However, as the formation of the frost layer cannot be completely prevented, various experimental and analytical studies have been conducted to fundamentally understand the frosting phenomenon. In particular, an effective frosting model can predict frost layer growth behavior under various conditions at the lower cost compared to conducting the experimental studies. Thus, several frosting models have been developed by many researchers.

The frosting models are divided into analytical models and computational fluid dynamics (CFD)-based models. Analytical models predict frost growth by assuming that frost is dominantly formed in one-dimension. Tao et al. [2,3] proposed a frosting model to calculate the mass transfer inside a frost layer. Lee et al. [4,5] established a one-dimensional frosting model to simulate the growth of the thickness and density of a frost layer and developed a model to analyze both the frost layer and the air flow. Le Gall and Grillot [6] calculated the mass transfer within a frost layer more precisely by defining an effective diffusion coefficient. Ismail and Salinas [7] analyzed frost growth behavior on parallel cold plates based on a frosting model. Na and Webb [8,9] increased the accuracy of frosting models by applying a supersaturation degree on a frost layer surface. Yang and Lee [10] proposed a frosting model using new correlations for frost density and thermal conductivity and performed an analysis in laminar flow conditions. Yang et al. [11] developed a frosting model that can be used under turbulent flow conditions and analyzed the growth characteristics of a frost layer under turbulent flow. Kim et al. [12] established a frosting model that can consider the heat conduction of heat exchanger fins. Kandula [13,14] improved the frosting model by developing a new correlation for frost heat conductivity under various operating conditions. On the other hand, a CFD-based frosting model can simulate frost layer growth in two dimensions and provides the advantage of analyzing the distribution of physical properties inside a frost layer. Recently, CFD-based frosting models have been widely studied. Kim et al. [15] proposed a new mass transfer rate by introducing a modified Sauter mean diameter and verified it under various operating conditions. Armengol et al. [16] analyzed two-dimensional frost growth behavior on parallel cold plates using a CFD-based frosting model. Wu et al. [17,18] proposed a volumetric mass transfer rate based on supersaturation and used this result for establishing a frosting model. Kim et al. [19] defined frost formation resistance, which was utilized to propose a new volumetric mass transfer rate and to analyze the growth behavior of a frost layer. More recently, a CFD-based three-dimensional simulation of frost layer growth has also been attempted [20].

In previous models based on analytical solutions [2–14], mass transfer was calculated as the amount of water vapor diffused by

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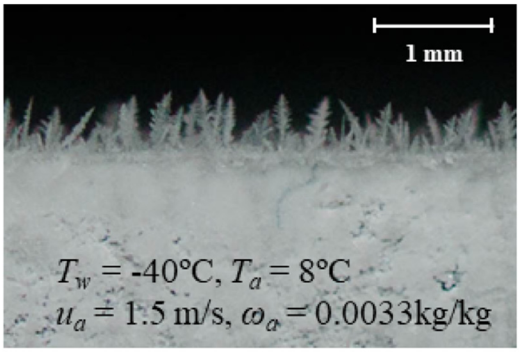
Nomenclature

a	correlation constant
A	area (m^2)
k	thermal conductivity (W/m K)
L	length of cold plate (m)
$\dot{m}'''$	volumetric mass transfer rate (kg/m^3 s)
q''	heat flux (W/m^2)
S	source term
t	time (min)
T	temperature (K or °C)
u, v	velocity components (m/s)
V	volume (m^3)
x, y	Cartesian coordinate components (m)
x^*	dimensionless coordinate in x-axis
α	volume fraction
δ	thickness (m)
ϕ	physical quantity
Γ	diffusion coefficient
ρ	density (kg/m^3)
ω	absolute humidity (kg/kg)

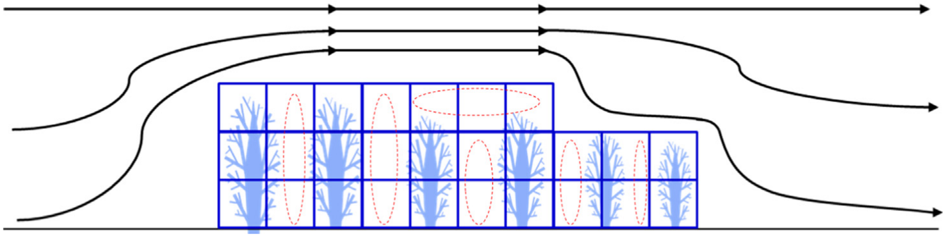
Subscripts

a	air
avg	average
CV	control volume
f	frost
fl	frost layer
fs	frost surface
i	ice phase
in	inlet
R	frost formation resistance
th	threshold
w	cold plate
ψ	water penetration

the humidity gradient from the surface of a frost layer. A few CFD-based models [15,16] used the mass transfer rate from a frost layer surface by converting it into a volume-based transfer rate. However, at low surface temperature, frosting occurs in the desublimation mode [21], and frost crystals do not quickly form a frost layer surface. As shown in Fig. 1(a), frost crystals with extremely high porosity are formed at the beginning of frosting, and the formation of a frost layer surface occurs after these crystals have grown sufficiently. In addition, the frost layer is highly porous. In such conditions, the water vapor diffused from the frost layer surface should not only be considered, but also the water vapor directly penetrating into the frost layer should be considered. Therefore, frosting models that consider only the mass transfer from a frost layer surface are insufficient for predicting the frost layer growth behavior that occurs on a low-temperature cooling surface. Recently proposed CFD-based frosting models [17–20] that use a volumetric mass transfer rate also fail to predict frost layer growth behavior accurately. This is attributed to the fact that in CFD, the spaces occupied by air (the volumes surrounded by a red line in Fig. 1b) can be recognized as frost where air flow into these spaces is blocked. However, when the porosity of a frost layer is large, air flow into the frost layer is not negligible. Such limitations of these



(a) Initial frost layer at a cooling surface temperature of -40°C ([21])



(b) Humid air flow when a highly porous frost layer is formed in a CFD simulation

Fig. 1. Characteristics of a frost layer produced by desublimation.