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Frosting model for predicting macroscopic and local frost behaviors on a cold plate

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ABSTRACT

A computational fluid dynamics (CFD)-based model to predict macroscopic and local frost behaviors on a cold plate is described. The model was validated by comparing its results with a range of experimental data. The effects upon the model of various factors that affect frost formation were studied, including the inlet velocity, relative humidity, and cold plate temperature; the numerical predictions agreed very well with experimental data, with a maximum deviation of 0.3 mm in the average frost thickness. Similarly, the modeled average frost density was in good agreement with experimental data, with an error of 10% after 60 min and a maximum error of 25% during the early stages of frost formation. The model outlined herein is able to describe the localized details of frost growth, including the distribution of frost density and the absolute humidity along the *y*-axis, in contrast to existing approaches.

1. Introduction

Frost formation and growth are natural and usually undesirable phenomena that occur in a wide range of engineering fields, including refrigeration, heat pumps, cryogenics, and aeronautics. In particular, frost forms on the heat exchangers used in refrigeration applications when the surface temperature of the heat exchanger is below the freezing point, which causes the water vapor in humid air to freeze onto the surface, forming a porous structure. This frost increases flow resistance in the heat exchanger, and decreases thermal performance by increasing the thermal resistance between the air and the surface of the fin. Models that describe frost growth are useful for predicting frost formation and growth to optimize the thermal performance of heat exchangers.

Over the past two decades, several models have been reported to describe frost formation and growth. Tao et al. [1–3] proposed a one-dimensional model of the frost layer and Lee et al. [4] established a model to describe the growth and densification of the frost layer. There are a number of models that solve the governing equations only in the frost layer, without taking the air side into account [5–11]. When using these approaches, it is necessary to describe frost formation and growth based on the heat transfer coefficient of the air side. However, the results of these models typically deviate from measured data because correlations are employed to calculate the heat transfer coefficient, rather than modeling the air side directly. In the 2000s, the accuracy of frosting models was improved by solving the governing equations for both the air side and the frost layer. Lee et al. [12,13] divided the simulation domain into two subregions, one for the air side and one for the frost layer. They calculated the thickness and density of the frost layer by solving the governing equations for the air side and the frost layer, without employing a correlation for the heat transfer coefficient. Such dual-domain models of frosting have become more established recently [14–17]; Na and Webb developed a frost model by assuming that the humid air at the surface of the frost was supersaturated, and validated the approach in a number of experiments [18–20].

These models all assume that the density of the frost layer is uniform. However, frost is typically more dense near the cold plate and less dense near the surface of the frost layer. Existing frosting models split the simulation domain into the frost layer and the air side, and matching conditions are used to balance the flow of energy and mass between the two subdomains. Furthermore, water vapor is assumed to be saturated or supersaturated near the surface of the frost layer, which may result in errors.

In this paper we describe a CFD-based model of frost growth. This model can describe both the macroscopic behavior of the frost layer, including its thickness and density, as well as localized phenomena, including the frost density distribution and the distribution of absolute humidity in the frost layer.

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Nomenclature

A	area [m^2]
D	diffusivity [m^2/s]
h	enthalpy [kJ/kg]
k	thermal conductivity [W/m K]
L	cold plate length
N	total number of grid in frost layer
M	total number of grid in frost surface
m_w	mass concentration of water vapor
m''_ρ	mass flux for frost density [kg/m^2 s]
m''_y	mass flux for frost thickness [kg/m^2 s]
m'''_f	mass transfer rate at each node [kg/m^3 s]
$\dot{m}_f$	total mass transfer rate at each control volume [kg/m^3 s]
p	pressure [Pa]
Pr	Prandtl number
S	volumetric source terms
T	temperature [K] or [°C]
u, v	velocity components [m/s]
V	volume
x	Cartesian coordinate in x-axis [m]
y	frost thickness [m]
Greek symbols	
α	volume fraction
β	modified Sauter mean diameter
ϕ	arbitrary scalar used in Eq. (4)
Γ	diffusivity coefficient
ρ	density [kg/m^3]
μ	viscosity [kg/m s]
Superscript	
$*$	dimensionless
$t + \Delta t$	next time step
Subscripts	
air	air side
avg	average value
eff	effective value
f	frost
fl	frost layer
fs	frost surface
i	ice phase
in	inlet
init	initial value
j	tensor index
local	local value
n	index of summation
max	maximum
s	cold plate
sub	sublimation
v	water vapor phase
0.5	value at $x^* = 0.5$

2. Numerical model

Mass transfer and phase change are the important physical phenomena in the process of frost growth and densification (Fig. 1). Water vapor in humid air is transferred from the air side to the frost layer due to the concentration gradient of the water vapor, and frost grows via a phase change of this water. There is a concentration gradient between the water vapor remaining in the porous frost and the ice particles in the frost layer. We establish a mathematical model to describe both the macroscopic and localized behavior during frost growth on a cold plate at a constant temperature. The dimensionless length along the flow direction is introduced as follows:

$$x^* = \frac{x}{L}, \tag{1}$$

where L is the length of the cold plate.

2.1. Governing equations and assumptions

In contrast to existing approaches, in which the simulation domain is divided into two subdomains, herein we use CFD to solve the governing equations in a single domain. A Eulerian two-phase model is used to separate the air side and the frost layer, which distinguishes the primary (i.e., water vapor) and secondary (i.e., ice) phases in each control volume, so that each phase is represented by the volume fraction, α. This volume fraction can be expressed as follows [21,22]:

$$\frac{\partial \alpha_i}{\partial t} + \frac{\partial}{\partial x_j}(u_j \alpha_i) = S_V, \tag{2}$$

where S_V is a volumetric source term. Two phases exist in each control volume, and are related by

$$\alpha_i + \alpha_v = 1. \tag{3}$$

If we have $\alpha_i = 0$ (and therefore $\alpha_v = 1$), this corresponds to only water vapor in the control volume, whereas $\alpha_i = 1$ (and hence $\alpha_v = 0$) corresponds to only ice in the control volume. Any intermediate states $0 < \alpha_i < 1$ and $0 < \alpha_v < 1$ correspond to a mix of water vapor and ice in the control volume; this state is considered to be frost, which is a porous medium consisting of a mix of ice and water vapor.

CFD software packages solve the general transport equation by discretizing it, and solving for an arbitrary scalar ϕ; i.e., [22]

$$\frac{\partial \rho \phi}{\partial t} + \frac{\partial}{\partial x_j}(\rho u_j \phi) = \frac{\partial}{\partial x_j}\left(\Gamma \frac{\partial \phi}{\partial x_j}\right) + S, \tag{4}$$

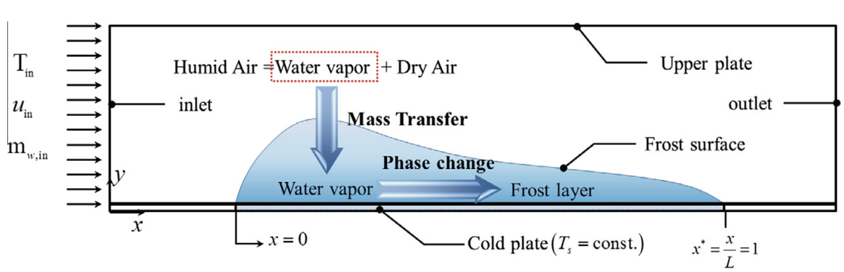

Fig. 1. Schematic diagram showing the physical processes involved in frost formation and densification.