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Analysis of the frost growth on a flat plate by simple models of saturation and supersaturation

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Abstract

When humid air comes in contact with a cold surface maintained below the freezing temperature, heat and mass transfer occur and a frost layer begins to grow. Simple models for the growth of the frost layer on a flat plate are presented and they focus on diffusion and phase change inside the porous media. A simple model was built on the assumption that the water-vapor concentration at the frost surface is saturated, and that the gradient of vapor pressure is the same as the value obtained from the Clausius–Clapeyron equation. It was found that initial porosity of the frost layer affected the characteristics of frost growth. In order to solve the inconsistency of the diffusion resistance of water-vapor in the region of high porosity, the model was modified with the assumption that the concentration of water-vapor at the frost surface was in supersaturation. Two parameters controlling the densification and thickness growth of the frost layer were obtained.

Keywords: Frost layer; Heat and mass transfer; Porous media; Saturation; Supersaturation

1. Introduction

Frost is a porous medium composed of humid air and ice crystals. The formation of frost has affected various fields, such as cryosurgery, meteorology, agriculture, aerospace industry, refrigeration industry, civil engineering, etc. In the cryosurgery, when diseased tissue is removed, frost can form in healthy tissue or on surgery tools. Frost formation hinders meteorological measurements made on tall radio and television masts, particularly at northern latitudes. Furthermore, when plant tissue freezes, internal and external ice crystals, called "frost damage", form. In the aerospace industry, frost forms when the lower surface of the wing is cooled by cold-soaked fuel in the wing tanks or wings come in contact with cold air. This frost in the leading edge region can have severe negative effects on airfoil and wing performance. Before take-off, an expensive petroleum solvent is used to sweep off the frost developed on the outer surface of the planes. Frost formation on the external tank of a space shuttle and space vehicles may shed and damage the surface tiles of the vehicle during take-off. The effect of frost formation on refrigeration systems also cannot be disregarded. Here, frost reduces the airflow passage area and act as a thermal resistance layer. Defrosting is the only way to return the system to its rated performance. Methods such as hot gas defrost, reversing the cycle, coil spray defrost, air defrost, electric defrost, and condensing unit on/off control, etc. have been used for defrosting [1]. Effective defrosting, which reduces energy use and achieves better protection of refrigeration equipment, is possible only when the growth characteristics of the frost layer are known. For several decades, there have been various numerical,

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Nomenclature

A	area [m^2]
C	shape coefficient
C_p	specific heat [J/kg K]
d	diameter of pore [m]
D_{eff}	effective mass diffusivity [m^2/s]
d_h	hydraulic diameter [m]
D_v	mass diffusivity [m^2/s]
h	enthalpy [J/kg]
h_c	convective heat transfer coefficient [W/m^2 K]
h_{ig}	latent heat of sublimation of water-vapor [J/kg]
h_m	mass transfer coefficient [m/s]
k	thermal conductivity [W/m K]
l	thickness [m]
m	mass [kg]
M	molar mass [kg/kmol]
$\dot{m}''$	mass flux [kg/m^2 s]
Nu_D	Nusselt number
P	perimeter [m]
p	pressure [kPa]
Pr	Prandtl number
$\dot{q}''$	heat flux [W/m^2]
Re	Reynolds number
R_u	universal gas constant [J/kmol K]
S_{sf}	specific surface area [m^2/m^3] $\frac{C(1-\varepsilon)}{d}$
T	temperature [K]
u	internal energy [J/kg]
w	humidity ratio [kg/kg_{DA}]
x	distance from the leading edge [m]
y	spatial coordinate [m]

Greek symbols

ε	porosity, $(\rho_i - \rho_f)/(\rho_i - \rho_a)$
κ	parameter [s^{-1}]
μ	diffusion resistance factor
ρ	density or concentration [kg/m^3]
τ	time [s] or tortuosity
ψ	coefficient for phase change [m/s]

Subscripts

a	air
cal	data from calculation
cond	conduction
conv	convection
cry	ice crystal
d	diffusion
eff	effective
exp	data from experiments
f	frost
fs	frost surface
i	ice
in	inlet
l	latent
m	mean
par	parallel, in Eq. (14)
per	perpendicular, in Eq. (14)
s	sensible
sat	saturated
sf	solid–fluid interface
t	total
v	water-vapor
w	surface of cooling wall
0	initial

Superscript

*	dimensionless

experimental, and semi-empirical studies about the frost formation on a plate, cylinder, parallel plates, complex heat exchangers, systems, etc.

Brian et al. [2] tried to develop a variable density model and found that their model was unsuccessful in predicting the densification of the frost in the region near the cold wall. Padki et al. [3] and Sherif et al. [4] developed a semi-empirical model for predicting frost formation. Tao et al. [5] attempted to establish a mathematical model that can predict both spatial and temporal variation of the frost density and temperature, using the local volume averaging technique. They used correction factors to match the experimental data. Fukada and Inoue [6] developed an experimental method for determining the internal mass flux through frost layer and found that the profile of the local frost density is almost flat in the direction of depth, regardless of the cooling wall temperature and the total pressure. Şahin [7] found that the effective thermal conductivity of the frost layer was not the only parameter related to frost density. Yun et al. [8] developed a physical model of frost growth, and Stoney and Jacobi [9] studied the effect of vortices on the frost growth rate. Mao et al. [10] and Le Gall and Grillot [11] attempted to determine the empirical correlations for frost formation. Despites a fairly large number of studies dealing with frost formation, growth characteristics of frost layer cannot yet be accurately predicted and explained.

In this study, two simple models of saturation and supersaturation are proposed and verified by comparing the results of analysis and existing experimental data. The models can predict transport phenomena and the