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Phase change mass transfer model for frost growth and densification

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ABSTRACT

A frosting mechanism was used to develop a phase change mass transfer model to predict the frost layer growth and densification. The model with a criterion can describe the mass transfer of water vapor from the humid air to increase the frost thickness and the frost density. Frost formation on a cold surface with local cooling was simulated by using the model as a source term in FLUENT to predict the frost morphology, temperature distribution and frost weight which are all in good agreement with the experimental results. The results show that the frost first forms around the cooling block and then extends gradually to other directions, with the frost above the cooling block having the greatest density. The average frost thickness increases gradually with time with the growth rate slowing down, while the average frost density increases with the increases rate getting faster. The temperature distribution in the computational domain is related to the frost layer morphology and the frost surface temperature is usually lower than the freezing point temperature. As the frost layer grows, the average air velocity increases with the maximum local velocity located above the thickest part of the frost layer.

1. Introduction

Frosting is a common phenomenon in refrigeration and cryogenic systems. Frost layers are porous structures containing ice crystals and air gaps which can increase the heat transfer resistance and block the flow channel and reduce a decrease of the heat transfer rate, and even lead to a system failure. Thus, we have done some experimental investigation of frost formation on cold surfaces [1–3], but accurate simulations of the frost morphology, growth rate and properties are also needed to design heat exchangers under frosting conditions.

There have been many theoretical studies of frosting with three types of frost growth models. In the first type, the mass transfer during frost formation simultaneously increases the frost thickness and the frost density [4–7]. O'Neal et al. [4] modeled the diffusion of molecules in a porous media to calculate the mass transfer for increasing the density with the mass transfer for increasing the thickness obtained from the difference between the frost growth data measured in experiments and the mass for increasing the density. This model was improved by Webb et al. [5], Lee et al. [6] and Yao et al. [7]. In the second type, the frost layer thickness and density at the early stage are given as initial conditions, for example, Lenic et al. [8] used this method. In the third type, a semi-empirical quasi steady model was proposed by Padki et al. [9] where the mass transfer rate is obtained using Lewis' analogy with the heat transfer rate calculated using the experimental correlations [10].

Computational methods for modeling frost formation can also be classified into three groups. The first group only focuses on the frost region with no account of the influence of the air flow; they calculated the heat and mass transfer using empirical correlations for the diffusion on the air side [5,11–14]. Barron et al. [14] assumed that the humid air near the frost surface was saturated with the assumption used by many others [11,13]. While Webb et al. [5,12] assumed that the humid air was supersaturated and proposed new models to calculate the frost growth.

The second group considers both the frost region and the humid air region with interface conditions to connect the two regions [6,8,15–17]. Lee et al. [6,15–16] used this method to calculate the frost growth on a cold plate with laminar and turbulent flow. Lenic et al. [8,17] calculated the frost formation between two fins of a finned tube exchanger using a transient state model and a self-programming method to solve the governing equations for the boundary layer region that include the frost and air regions as well as a boundary condition at the air-frost interface.

The third group solves governing equations for each phase simultaneously in the computational region in a multiphase flow

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Nomenclature

A	area [m^2]
B	correlation coefficient
D_{H_2O}	diffusivity [m^2/s]
g	gravitational acceleration [m/s^2]
h	enthalpy [kJ/kg]
K	momentum transfer coefficient
l	latent heat [kJ/kg]
$\dot{m}$	mass transfer rates [kg/s]
P	pressure [Pa]
$\vec{q}$	heat flux [W/m^2]
Q	interphase heat transfer [W/m^3]
S	source terms
t	time [s]
T	temperature [K]
$\vec{u}$	velocity vector [m/s]
W	aluminum plate width [m]
w	mass fraction
x	x axis [m]
y	y axis [m]

Greek symbols

α	volume fraction
ρ	density [kg/m^3]
$\bar{\bar{\tau}}$	stress tensor [Pa]
τ_v	time relaxation coefficient [s^{-1}]
χ	humidity ratio [kg/kg dry air]

Subscripts

a	air
i	ice
s	saturated
in	inlet
ai	from air to ice
ia	from ice to air
ma	air mass
mi	ice mass
ha	air enthalpy
hi	ice enthalpy
ua	air velocity
ui	ice velocity
va	vapor
0	initial

model [18–21]. Cui et al. [18,19] proposed a model to predict frost formation based on the nucleation theory and they simulated frost growth on a horizontal cold surface and on the fins of a finned tube exchanger using the multiphase flow model in FLUENT. Kim et al. [20] used the Euler multiphase flow model for both the ice phase and the humid air phase in the frost to predict the average frost thickness and the average frost density. Zhuang et al. [21] presented a condensation model for simulating water condensation using FLUENT.

Among three frost formation models, the ones that have the mass transfer during the frosting process contributing to increase both the frost thickness and the frost density agree best with the frosting data. However, there are some limitations in these models because the total frost quantity is based on experimental data and experiments are difficult to conduct on some frosted surfaces with complicated structures.

Although there have been numerous frosting calculations, few studies have used CFD models to simulate the frost formation. CFD can help illustrate the heat and mass transfer processes during the frost formation and is also suitable for heat exchangers with complex structures to give more researches to supplement limited experimental frosting data for various working conditions.

This study used a frosting mechanism to develop a phase change mass transfer model with a criterion that illustrates the frost growth and the densification processes. FLUENT was then used to simulate frost growth on a cold surface with local cooling. The obtained frost morphology, temperature distribution and frost weight data are all in good agreement with Kwon's experimental results [22].

2. Physical model

Fig. 1 shows the details of the test section of Kwon et al. [22]. The air flow channel was 110 mm long, 100 mm wide and 4 mm high with an aluminum plate installed at the bottom of the channel, with a 10 mm long cooling block under the plate.

A two-dimensional numerical simulation of the test section was conducted for the computational domain shown in Fig. 2. The length of the Y axis enlarged 10 times to show the results more clearly.

The inlet and boundary conditions listed in Table 1 are consistent with the experimental conditions.

3. Mathematical model

The frost layer is a porous media made of ice crystals and air gaps. The frosting process is a complicated, unsteady process with simultaneous heat and mass transfer. Some assumptions were made to simplify the calculations.

(1) The ice framework of the porous frost was assumed to be motionless so that convection heat transfer could be neglected and the frost layer temperature was assumed to be so low that radiation heat transfer could be neglected.
(2) The humid air was assumed to be an incompressible Newtonian fluid due to the small velocities.

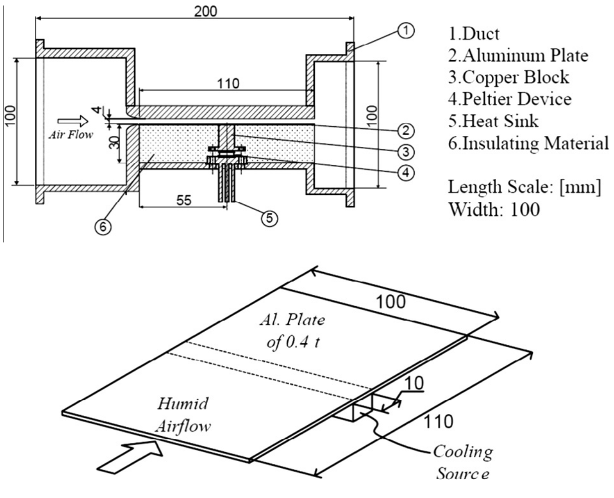

Fig. 1. Test section [22] (length scale: [mm]).