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Frosting model based on phase change driving force

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ABSTRACT

Based on the Gibbs free energy, a non-dimensional phase change driving force for frosting was proposed. A frosting model with the non-dimensional phase change driving force and a criterion for calculating the frost growth was developed. By combining the frosting model into the Euler multi-phase flow method, the local frost formation and the humid air flow characteristics can be simulated. The frosting model was validated by comparing not only the simulated frost thickness but also the corresponding frost weight with experimental data for various conditions. Moreover, the model was also validated by comparing the localized temperature variation with experimental data. The frosting model predicts the frost density distribution, temperature distribution, humid air velocity distribution and the mass transfer rate. The results show that the frost thickness and frost weight grow with time. In the frontal region, the water vapor mass fraction is larger and the mass transfer rate is larger, which leads to denser frost. The different characteristics of heat transfer in the frost layer region and the humid air region can be reflected by the simulated temperature distribution. The simulated velocity distribution shows that the air velocity is close to zero in the frost layer and the velocity in humid air region increases as the frost grows. The simulated localized temperature, localized frost thickness, frost profile, averaged frost thickness and frost weight have a good agreement with experimental results.

1. Introduction

Frosting is a common phenomenon in air conditioning, aerospace and refrigeration industries. Frost buildup on heat exchanger surfaces increases the thermal resistance and blocks the air flow passages, which both reduce the system energy efficiency. In the frosting process, the humid air flows pass the cooling surface and the mass transfer from water vapor in the humid air to ice crystals occurs when the air is supersaturated, which both increases the frost thickness and the frost density. Accurate simulation of frosting on cooling surfaces is required to effectively reduce the frosting experiments.

In order to simulate the frosting processes, the existing calculation methods that only established governing equations for the frost layer region were proposed. Lee et al. [1,2], Kandula [3] and Hermes [4,5] treated the frost growth process as a one-dimensional growth process. The increase of frost density equaled to the water vapor weight diffusing into the frost layer and the frost density was calculated using the empirical correlations. Lee et al. [6–8], Lenic et al. [9,10] and Armengol et al. [11] proposed frosting calculation methods that established governing equations for the humid air flow region at the same time with interface conditions connecting the two regions. Webb et al. [12,13] assumed the humid air was supersaturated at the frost surface and developed a simple equation for calculating the supersaturation degree. Breque et al. [14] studied different frosting models based on heat and mass diffusion through a porous media and pointed out the pathway to improve the frosting predictions. The frost thickness and weight on the flat surfaces have been determined without considering the interaction between the humid air flow field change and the frost growth. Thus, these models may not be adequate to satisfactorily simulate the frost growth on the complicated structure surfaces, such as heat exchanger surfaces.

With the development of the computational fluid dynamics capabilities, multi-phase flow methods were used to solve governing equations for the humid air phase and the ice phase. The frosting processes were simulated by adding the phase change mass source terms to the multi-phase flow method. Zhuang et al. [15] proposed a numerical model based on multi-phase flow to model the condensing droplet formation. Cui et al. [16,17] proposed a frosting mass transfer model based on the nucleation theory to model the frosting processes on flat plates and fin-and-tube heat exchangers surfaces. The nucleation was assumed completely

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Nomenclature

B	correction factor [–]
d	diameter [m]
f	drag function [–]
g	Gibbs free energy [J]
h	heat transfer coefficient [W/(m^2·K)]
H	height [m]
k	Boltzmann's constant
K	momentum transfer coefficient [–]
L	length [m]
m	frost mass [kg]
$\dot{m}$	mass transfer rates [kg/(m^3·s)]
Nu	Nusselt number [–]
p	pressure [Pa]
p^0	atmospheric pressure
Pr	Prandtl number [–]
Q	interphase heat transfer [W/m^2]
Re	Reynolds number [–]
RH	relative humidity [–]
t	time [s]
T	temperature [K]
u	x-velocity component [m/s]
v	y-velocity component [m/s]
w	mass fraction [–]

Greek symbols

α	volume fraction [–]
δ	frost thickness [m]
λ	thermal conductivity [W/(m·K)]
υ	kinematic viscosity coefficient [m^2/s]
ρ	density [kg/m^3]
τ_v	time relaxation coefficient [s^{-1}]

Subscripts

a	air
i	ice
s	saturated
v	water vapor
w	cooling wall
x	x axis [m]
y	y axis [m]
ai	from air to ice
ia	from ice to air
in	inlet
cal	calculation
exp	experimental

homogeneous and the mass transfer rate from water vapor to ice included the mass increase caused by new ice crystals formation and mass addition at the stage of ice crystals growth. Kim et al. [18] assumed that the mass transfer at the frost surface occurs due to the water vapor concentration gradient and used their frosting model to predict frost formation on flat plates. Their simulation was able to describe localized frost density and the absolute humidity. Wu et al. [19,20] assumed the driving force for the water vapor condensation into ice was the difference between the water vapor partial pressure in the humid air and the water vapor saturation pressure corresponding to the frost surface temperature. The phase change mass transfer rate was related to the driving force and the effective density of humid air. Wu et al. [19,20] used their model to simulate frost formation on a flat plate with local cooling and fin-and-tube heat exchanger surfaces. The frost distribution and cooling surface temperature were in good agreement with experimental results.

The frosting simulation using the multi-phase flow method with phase change mass source terms added in can reflect the interaction between the humid air flow field change and the frost growth. Thus, the localized frost and humid air flow characteristics can be obtained. These frosting calculation methods had more advantages to simulate the frost growth on the complicated structure surfaces compared with previous frosting calculation methods [1–11]. Based on our previous work [19], a non-dimensional phase change driving force for frosting was proposed in this paper. A frosting model with the driving force and a frost growth calculation criterion was developed. The frosting processes on flat plates were simulated using FLUENT based on the Euler multi-phase flow method with the frosting model added. The frosting experiments were conducted to valid the accuracy of the frosting model. The simulations results were compared with Lenic's experimental results [9] on localized frost thickness and temperature and compared with experimental results in present paper on frost morphology, averaged frost thickness and frost weight. The simulation results were in good agreement with experimental results and the frosting in this paper can describe the frost morphology, temperature distribution, velocity distribution and phase change mass transfer rate in frosting processes.

2. Physical model

Fig. 1 shows the simulation domain of frosting on the flat cooling plate, including the cooling wall, air inlet, air outlet and adiabatic walls. There are two simulation objects in this paper, the first has the same size with the experimental object in Lenic's research [9] and the second has the same size with the experimental object in the present work. The channel height H_y, the entrance region length L_{x1} and the cooling wall length L_{x2} are 10 mm, 20 mm and 140 mm for the first simulation object and 5 mm, 25 mm and 50 mm for the second simulation object.

Rectangular mesh was used and the cell size was set as $\Delta x = 0.1$ mm, $\Delta y = 0.05$ mm after the mesh independence tests. The simulation conditions were listed in Table 1. Case_1 in Table 1 is for the first simulation object and Case_2–Case_9 are for the second simulation object.

3. Mathematic model and numerical method

The frosting process is complicated and unsteady. Based on the mass transfer from water vapor in the humid air phase to ice phase, the momentum transfer and energy transfer from water vapor to ice occur. The interface between the frost layer and the humid air changes with the frost growth, which changes the flow field and the temperature field. The same assumptions [19] were considered.

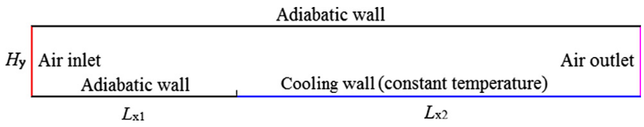

Fig. 1. Simulation domain of frost formation on the flat cooling plate.