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A lattice Boltzmann study of frost growth on a cold surface

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ABSTRACT

A two-dimensional Lattice Boltzmann model was established to study the dynamic physical process of frost growth on a cold flat surface. It is verified that the theoretical results are in good agreement with the experiment data with better accuracy. The frost morphology is explored by showing two-dimension density distribution with different cold surface temperatures. The results also include dynamic characteristics of frost properties such as thickness, deposition weight, volume fraction, density, temperature. According to the results, it is found that the nearer it is from the cold flat plate, the larger of frost crystal volume fraction and density are. The frost surface temperature increases rapidly at the early period of frosting and then increases gradually towards the triple point temperature of the water. The frost internal temperatures rise in a linear tendency with the frost thickness and decrease at the same frost layer location with frost growth. Super-saturation degree of moist air has non-negligible effect on frost growth parameters such as frost thickness, frost crystal deposition mass, frost deposition rate and frost crystal volume fraction.

1. Introduction

Frost is very common in many engineering fields such as refrigeration and cryogenic fields. Frost on evaporators not only increases the heat resistance but also blocks the air flow area through fins of evaporators. Thus, many efforts have been made to alleviate these problems in past several decades. Though numerous experiments have been carried out on frosting on cold surfaces [1–3], accurate model is also essential not only to reveal frost morphology, dynamic properties and other parameters related to frost formation mechanism but also to provide suggestions for defrost strategy.

In the last several decades, there have been a lot of models for frost growth. Depending on semi-empirical correlations, many one-dimension models simulating frost growth were primarily proposed [4–8]. All these studies assumed the frost layer as a homogeneous porous media. According to their studies, it has been demonstrated that the humid air at the frost surface is in supersaturated state. Furthermore, some two-dimensional models were established to study frost growth without using frost empirical correlations in recent years. To study frost growth, two-dimensional models were presented by literatures [9,10] based on conservations law or finite volume method. Without adopting any experimental correlations, Lee et al. [11] developed a transient two-dimensional model of frost layer formation on a cold plate with agreement of about 10%. In this model, the frost density in the direction vertical to the cold flat surface is hypothesized as a constant value. Lenic et al. [12] proposed a two-dimensional model with the assumption of supersaturated air theory presented by literature [5], which is suitable for frost growth and fully developed frost period. More recently, CFD models were used to predict frost formation within acceptable uncertain threshold [13–15]. These models are capable of predicting frost layer local parameters. Concurrently, the frost effective thermal conductivity of frost has been investigated thoroughly by Negrelli et al. [16] by means of fractal theory. Compared to the experimental data, the theoretical results have ± 15% deviation.

Though models available in literatures can predict frost thickness satisfactorily to some extent, many parameters associated with frost growth are still not clear. Take frost surface temperature for example, it is difficult to measure frost surface temperature and few literatures can provide an effective mean to determine it. Moreover, the humid air near frost crystal has already been verified to be supersaturated. However, there is no report that how the super-saturation degree of the humid air affects the frost growth. Besides, although the present models show good agreement with experimental points, the deviations (about 10% in most models) are still desired to be lower.

The lattice-Boltzmann (LB) method has achieved many successes in many areas where traditional calculation methods are difficult to

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Nomenclature

c_s	isothermal sound velocity, m/s
c_0, c_1	parameter of auxiliary velocity
c_p	specific heat at the constant pressure
C_0,F_μ,k	diffusion resistance factor
d_p	Diameter of the solid particle
e	discrete velocity, m/s
f	velocity distribution function
F_ε	geometric function
h_{sg}	specific enthalpy in the gas-solid phase transition, J/kg
J	nucleation rate
J_0	kinetic constant of nucleation rate, /m^{2}s
k_B	Boltzmann constant, J/K
K	permeability
δm	increase of frost crystal mass, kg
M	water molecular mass, kg
n_c	nucleation correction factor
P	freezing probability
p	pressure, Pa
r_c	critical radius, m
R	universal gas constant, J/(mol·K)
S	water vapor super-saturation degree
T	temperature, K
u	velocity, m/s
v	auxiliary velocity

Greek symbols

α	water vapor saturation ratio
α_m	thermal diffusivity
δx	lattice spacing
δt	time step
θ	contact angle, rad
ν	kinematic viscosity, m^2/s
ρ	density, kg/m^3
σ	interface energy, J/m^2
τ,τ_c	dimensionless relaxation time
φ	air relative humidity
ω	weight coefficient
γ	specific heat capacity ratio
ζ	non-isothermal correction factor
ϑ	heat capacity ratio
ε_i	frost crystal volume fraction
ε_p	porosity
ϕ_t	discretized source term
$\mu(\varepsilon_i)$	nucleation parameter

Subscript

a	air
f	frost
fs	frost surface
ice	ice
i	direction
s	water vapor in saturated state
v	water vapor in local state
w	cold flat surface

Superscript

eq	equilibrium state

perform, such as porous media and multiphase flow [17–20]. Frost layer consisting of a great number of frost crystals acts as a porous media. We have been focusing on frost growth for many years [21–24]. We also established an effective LB model to investigate frost growth and acquired some preliminary findings [23]. Based on our previous study, this study presents a two-dimensional LB model to study the dynamic behavior of frost growth on a cold flat surface considering the frost layer as a heterogeneous medium. The theoretical results are in good agreement with the experiment data with mean relative error 1.34%. The results include the dynamic variation rules of frost layer properties such as frost surface temperature and so on. The influence of super-saturation degree of humid air on frost growth has also been analyzed in detail.

2. Numerical model and theory

Frosting is a complex problem involving the flow and heat transfer in a variable porous structure consisting of frost crystals and humid air. In order to simplify the numerical model, some assumptions are made as follows:

(1) The nucleation process of frost crystals is treated as the homogeneous nucleation. The crystal nucleus with a critical size formed by the water vapor condensation directly deposited on the existing frost crystals.
(2) The humid air was treated as an incompressible Newton fluid because of its small velocity. In one simulation condition, water vapor super-saturation and relative humidity are assumed to be fixed.
(3) The melting and sublimation of frost crystals in some areas were neglected.

On the basis of the above assumptions, the frost layer growth process is simulated in a two-dimensional plane by the LB model based on the fractal theory (DLA model). According to DLA, a certain number of seed particles are randomly generated firstly on the X-axis (cold surface), and then a certain number of random particles (used to simulate the frost crystal after the phase transition nucleus of water vapor) are generated in the calculation region using a random function. The probability of random particle generation is related to the freezing probability in Eq. (6). The random particles generated at the frost top layer calculation area are preferentially attached to the frost crystal growth main trunk, which has the strong longitudinal growth characteristics. The calculation process is: The distance between random particles and the seed particles is firstly calculated, and the minimum distance is determined. Then the random particles will attach to the main frost crystal at the seed position with the smallest distance. In addition, in order to simulate the phenomenon that water vapor bypasses around the main frost crystals and condenses at the inside of the frost layer, random particles are also generated inside the frost layer and move towards downward, left and right directions with equal probability. Then these random particles will attach to the nearest cold surface or existing frost crystals. On the basis of this DLA, the frost layer growth process can be simulated by our LB model.

2.1. The mass of frost layer

According to nucleation theory, the change in frost crystal mass within the controlled volume is calculated as follows [25]:

$$\delta m = \frac{4}{3}\pi r_c^3 \rho_{ice} J P \mu(\varepsilon_i)\delta t \tag{1}$$

where the critical radius of the nucleus r_c is:

$$r_c = \frac{2\sigma}{\rho_{ice} R T_w \mathrm{In}(\alpha)} \tag{2}$$