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The effect of surface wettability on frost melting

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ABSTRACT

Frost melting on a vertical surface is divided into three stages: absorption, accumulation and draining, and the effect of surface wettability on melting is investigated analytically. The ratio of the volume flux of water to the melting rate is the key factor that determines meltwater motion. In the absorption stage, the ratio is greater than unity with meltwater is absorbed into the frost layer by capillary force. The volume flux of water depends on porosity and permeability of the frost layer, which are affected by the surface wettability. When the frost layer is saturated, meltwater accumulates on the surface, and the retention water is related to surface wettability. In the draining stage, meltwater flows along the surface, and the draining velocity depends on boundary conditions at the interfaces. Draining velocity increases on hydrophobic surfaces compared to that on hydrophilic surfaces owning to the presence of a slip velocity.

1. Introduction

Frost formation occurs on aircraft, wind turbines, power lines and heat exchangers. In refrigeration systems, frost deposition on evaporators blocks air flow and degrade thermal performance, so periodic defrosting is necessary to maintain the normal operation. Defrosting techniques include active, passive and system methods [1]. Electric heating and hot gas defrost are active methods. Surface treatment has attracted attention as a passive defrost method. The influence of surface treatment on both anti-frosting performance and defrost processes have also been investigated experimentally.

Surface treatment has been shown to tune surface wettability [2,3] and consequently, to delay frost initialization. Liu et al. [4] examined frost formation on an anti-frosting paint with no frost observed for up to 3 h. They further showed that frost formation was delayed for 55 min on a superhydrophobic surface [5]. The resulting frost structure was looser and easily removed from the surface. He et al. [6,7] fabricated superhydrophobic surfaces with micro- and nanometer structures to show that frost formation was greatly retarded. Bahadur et al. [8] presented a model to predict ice formation on superhydrophobic surfaces resulting from super cooled water droplets. The model was validated by predicting the experimental findings that droplets froze upon impact at temperatures below −20 to −25 °C. Kim et al. [9] reported an ice-repellent material based on slippery, liquid-infused porous surfaces (SLIPS). In their experiments, the SLIPS-coated aluminum was shown to reduce ice accumulation, and ice adhesion was reduced by 1–2 orders of magnitude. Wang et al. [10] presented the anti-icing performance of an aluminum coupling agent surface with a 147° static contact angle. The hydrophobic surface was shown to reduce the water condensation and delay frost deposition for 60 min compared to the neat aluminum surface at low temperature.

The influence of surface treatment on the defrost process has been focused on the experimental study of defrosting properties and the modeling of retention water geometry and distribution. Wu and Webb [11] investigated the possibility of frost release from hydrophobic surface by mechanical vibration. The frost could not be removed from the test surface, and the water droplets were retained on the hydrophobic surface by surface tension. Jhee et al. [12] reported the effect of surface treatment on the frosting and defrosting behavior of a fin-tube heat exchanger and showed that hydrophilic and hydrophobic surfaces had little improvement on thermal performance during the frosting cycle. Defrosting time and efficiency were improved on hydrophobic surfaces compared to hydrophilic surfaces. Kim and Lee [13,14] presented measurements on frosting and defrosting characteristics with respect to surface wettability on a fin of the heat pump. Frost retardation on the hydrophobic surface was not noticeable. After melting, retention water on the hydrophilic surface was smaller compared to the other surfaces. Wang et al. [15] investigated the frosting and defrosting behaviors on three types of fin-tube heat exchangers. The results showed that only small droplets were retained on the superhydrophobic surface after frost melting. The geometries and distribution of condensate droplets were shown to vary with surface wettability [16–19]. EI Sherbini and Jacobi [17] presented a model predicting condensate distribution on plain fin heat

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Nomenclature

b	slip length [m]
c_p	specific heat at constant pressure [J kg^{-1} K^{-1}]
g	gravitational acceleration [m s^{-2}]
k	thermal conductivity [W m^{-1} K^{-1}]
p	permeability power law constant
q	capillary pressure power law constant
q''	heat flux [W/m^2]
t	time [s]
u	velocity in x-direction [m s^{-1}]
v	velocity in y-direction [m s^{-1}]
y	direction normal to the surface [m]
C	entry capillary pressure [Pa]
Fr	Froude number, $v/(g\delta_w)^{1/2}$
K	permeability or intrinsic permeability [m^2]
L_f	latent heat of fusion [kJ kg^{-1}]
P_c	capillary pressure [Pa]
T	temperature [K]
Re	Reynolds number
S	water saturation, the volume fraction of water to the pore volume
V	volume flux [m s^{-1}]
W	width of the test plate [m]

Greek symbols

β	dimensionless parameter characterizing the structure of permeable material
δ	thickness [m]
ε	porosity
μ	dynamic viscosity [N s m^{-2}]
ρ	density [kg m^{-3}]
ω	filtering velocity [m s^{-1}]
Ω	average volumetric flow rate [m^3 s^{-1}]

Subscripts

0	initial
avg	average
B	boundary
f	frost
m	melt
p	permeation
s	surface
w	water

Superscript

$*$	dimensionless

exchangers. Condensate retention was predicted by integrating the volume functions and size distribution over the drop diameters. The model was restricted to droplet contact angles from 45° to 120°.

Analytical modeling of the defrost process has been presented for electric defrosting and hot-gas defrosting [20–27]. Alebrahim and Sherif [21] described a defrost model calculating the defrost time and temperature distribution for a finned tube evaporator coil using the enthalpy method. Defrosting was divided into pre-melting and melting phases. Frost was assumed to collapse when a water layer was formed between the frost and the coil. The results showed that for low heat input rate, the defrost time decreased when the heat input rate increased for different air and refrigerant temperatures. Liu et al. [22] presented a defrost model for air-source heat pump during hot gas defrost. They modeled the defrost process with four stages: preheating, melting, vaporizing and dry heating. Defrost time was calculated and agreed with measurements. The heat storage in the compressor was not included in the model. Dopazo et al. [24] presented a defrost model with six stages: preheating, tube frost melting start, fin frost melting start, air presence, tube-fin water film and dry-heating. A finite difference method was used to find the defrost time and energy distribution during the defrost process. Qu et al. [25,26] divided the defrosting process into three stages: frost melting without water flow, frost melting with water flow and water layer vaporization. The melted frost was held to the surface at first due to surface tension until the mass of the melted frost reached the maximum point and then flow downwards due to gravity. A lumped parameter modeling was applied. Mohs and Kulacki [27] presented a multi-stage defrost model that consists of vapor diffusion, permeation and dry out of the retention water. Meltwater was assumed absorbed into frost layer, and the permeation layer consisted of water and ice crystals. Heat and mass transfer through sublimation were investigated for each stage. System level testing showed that drainage was enhanced on super hydrophobic surfaces during the defrost process.

The influence of surface wettability on defrost processes has not been extensively investigated analytically in the literature whilst surface wettability has been shown to affect defrost properties in experimental investigations. The defrost process has generally been divided into three stages: preheating, melting and evaporation. Theoretical work on the effect of surface wettability has been limited to the evaporation stage. The present investigation therefore builds an analytical model to examine the effect of surface wettability on frost melting. We divide frost melting into three stages: absorption, accumulation and draining based on meltwater motion. The effect of surface wettability is investigated in each.

2. Model formulation

The process of frost melting depends on the meltwater motion. It has been observed in laboratory studies that meltwater could be absorbed into the frost layer, accumulate on the test surface, and drain away [28]. However, the factors affecting meltwater motion have not been thoroughly investigated. The following model development is restricted to a one-dimensional melting process.

The melting process consists of three stages, which are absorption, accumulation and draining, and the formulation of the three stages is based on several assumptions. In the absorption stage, it is assumed that the volume flux of water is greater than the melting rate and that all the meltwater is absorbed in the frost layer by capillary force. In the accumulation stage, the frost is assumed to be saturated with meltwater, and the structure consists of a thin water film and a permeation layer. In the draining stage, it is assumed that gravity dominates, and meltwater drains along the test plate. The draining velocity varies only across the water film and depends on the boundary conditions at the solid/water and water/permeation interfaces. The no slip boundary condition applies to plain and hydrophilic surfaces, and the slip boundary condition applies to hydrophobic surfaces.

2.1. Absorption

A permeation layer forms between the test surface and the frost layer (Fig. 1). The mass balance on a control volume (CV) is formulated with respect to the water saturation S, which is the volume fraction of water in the pore volume,