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An experimental study of defrost on treated surfaces: Effect of frost slumping

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ABSTRACT

Experiments of defrost processes are reported for superhydrophilic, plain and superhydrophobic surfaces which are vertically placed. On the superhydrophobic surface, the frost layer falls off as a rigid body. On the superhydrophilic and plain surfaces, the frost melts, and part of the frost layer falls off with the draining meltwater. Defrost time is thus less for the superhydrophobic surface compared to that for superhydrophilic and plain surfaces. Frost slumping conditions are analyzed with a static force balance, and criteria for frost release are presented. Meltwater motions are suggested as the key factor of the defrost mechanism. When the volume flux of meltwater in the frost is greater than the melting rate, the meltwater is absorbed into the frost. When the volume flux of meltwater is less than the melting rate, it accumulates and drains on the surface. Water accumulation favors frost slumping because the adhesive force becomes weak. Frost slumping generally shortens defrost time and improves defrost efficiency based on our measurements.

1. Introduction

Frost forms on refrigeration equipment, aircraft, wind turbines and power lines under proper conditions and generally reduces thermal and aerodynamic performance. Common defrosting methods include electrical heating and hot gas heating. With the advances of the material science, surface treatment methods were investigated by many researchers in the study of retarding frost formation and improving defrost efficiency. Liu et al. [1] reported that frost formation delayed for up to 3 h on the surface with anti-frosting paint. Cold plate temperature and ambient humidity had a strong influence on performance of the anti-frosting paint. They further examined the influence of hydrophobicity on frost formation [2]. It was observed that frost thickness on the hydrophobic surface was smaller than that on a hydrophilic surface at the beginning of frost growth. When the surface was covered by frost, however, frost thicknesses were almost the same. Fabrication methods of superhydrophobic surfaces were studied, and the influences of the surfaces on rapid drop removal and frost retardation were presented [3,4,6]. Some researchers suggested that the application of superhydrophobic surfaces on frost retardation should be cautioned. Varanasi et al. [5] investigated frost formation and ice adhesion on superhydrophobic surfaces. They showed that frost nucleation occurred indiscriminately on all areas of the superhydrophobic surface. Farhadi et al. [7] studied the anti-icing performance of superhydrophobic surfaces. The results showed that the anti-icing performance was significantly lower in a humid atmosphere and deteriorated during icing/de-icing cycles. Bahadur et al. [8] proposed a physics-based model for ice formation on superhydrophobic surfaces. The model provided a tool for the design and analysis of surfaces for ice reduction.

The effect of surface wettability on frost release and defrosting behaviors were investigated experimentally. Min et al. [9] investigated the long-term wetting characteristics of dehumidifying heat-exchangers with and without hydrophilic coatings. The wet/dry pressure drop ratio increased linearly with the receding contact angle. Wu and Webb [10] presented a study of frost release from the cold surface by mechanical vibration, and their experiments showed that frost on hydrophobic surfaces could not be released by surface vibration. Droplets on the hydrophobic surface stood up on the surface by surface tension. Jhee et al. [11] reported the effect of surface treatment on the performance of heat exchangers during frosting and defrosting processes. Defrost efficiency increased by 3.5% for the hydrophilic surface and by 10.8% for the hydrophobic surface compared to plain surface. Condensate retention on treated surfaces was investigated analytically and experimentally [12,14]. A model was developed with the study of volume fraction, maximum drop diameter and size-distributions. The model could be applied to predict the mass of condensate

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Nomenclature

A	area (m^2)
c_p	specific heat at constant pressure (J/kg-K)
CA	contact angle
F	force (N)
FR	force ratio
g	constant of gravitational acceleration (m/s^2)
G	gravity (N)
L	length of test plate (m)
L_f	latent heat of fusion (kJ/kg)
m	mass (kg)
P	power (W)
q''	heat flux (W/m^2)
RH	relative humidity (%)
t	time (s)
T	temperature (°C)
W	width of test plate (m)
y	direction normal to the surface (m)

Greek symbols

δ	thickness (m)
ε	porosity
θ	contact angle (°)
ρ	density (kg/m^3)
γ	surface tension (N/m)
η	efficiency

Subscripts

0	initial
adv	advancing
ch	chamber
df	defrost
dp	dew point
f	frost
i	ice
rec	receding
s	surface

retained on plain-fin heat exchangers. Zhong et al. [13] presented a review of methods to produce superhydrophobic surfaces, and they created a superhydrophobic surface with contact angle of 148° to observe the condensation and wetting behaviors on surfaces with micro-structures. Huang et al. [15] studied frost release on fin-and-tube heat exchangers and demonstrated long anti-frosting time of the coated heat exchanger. Kim and Lee [16] showed that frost retardation was not significant on the hydrophobic fin, and the effect of surface treatment on defrosting time was insignificant. Antonini et al. [17] proposed a way of reducing energy by promoting the shedding of liquid water on superhydrophobic surface. Some researchers devoted efforts in utilizing surface morphology for facile defrosting. Kim et al. [18] reported an ice-repellent material based on slippery and liquid infused porous material that enable easy removal of the accumulated ice and melted water. Jing et al. [19] examined frosting and defrosting on a rigid superhydrophobic surface, and the frost layer was shown to detach from the surface during defrosting. Chen et al. [20] presented a hierarchical surface that had nano-grassed micro-truncated cone architecture, which was shown to suppress freezing wave propagation during frost formation and increase lubrication and mobility of frost during defrosting. Boreyko et al. [21] reported a nanostructured superhydrophobic surface that promotes frost growth in the Cassie state. The frost layer was removed by dynamic defrosting driven by a low contact angle hysteresis of the meltwater.

Analytical studies on the defrost process are focused on the defrost modeling and properties. Krakow et al. [22] presented an idealized model of reversed-cycle hot gas defrosting. The work included the description and analysis of major components consisting of evaporator, reversing valve and receiver. The model provided a way of simulating system operating characteristics during the defrost cycle. Sherif and Hertz [23] presented a defrost model of an electrically heated cylinder tube using a lumped system analysis. The meltwater was assumed to drain away continuously from the coil surface. The model provided a method for describing the frost/air interface temperature and the frost thickness as functions of time. Hoffenbecker et al. [24] developed a transient model to predict the defrost time and efficiency of a hot gas defrost cycle. Instead of solving a moving boundary domain, mass and volume at each mode were assumed to be constant. When ice melted, water was assumed to drain away, and the volume formally occupied by water was replaced by air. Qu et al. [25,26] presented the defrosting process with 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 and then flowed downwards due to gravity at 90 s which was obtained experimentally. A lumped parameter model was applied. Mohs [27] developed a defrost model that consists of vapor diffusion, permeation and dry-out of the retention water. During the permeation stage, meltwater was assumed to be absorbed into the frost layer. The effect of vapor diffusion was shown to be insignificant during the initial stage and significant when the surface dried out.

The present work investigates the defrost process on surfaces with different wettability and the effect of frost slumping on defrost time and efficiency. Frosting and defrosting tests are run on superhydrophilic, plain and superhydrophobic surfaces. The frost slumping criterion is formulated based on static force analysis, and the relations with respect to surface wetting properties are investigated. Meltwater motion is proposed as an important factor that influences the defrost behaviors and facilitate frost slumping. Defrost processes vary depending on the surface wettability, and defrost time and efficiency are shown to have significant improvement when frost slumping occurs during the defrost period.

2. Apparatus and procedure

The objective of the experiment is to investigate the defrost process on surfaces with different wetting properties. The apparatus and associated instrumentation are shown in Fig. 1. The apparatus consists of the test section, air humidifying system, imaging system and data acquisition and analysis system. The test chamber provides an enclosed space for frost growth and humidity control, and test plates of 38 × 38 × 3.8 mm are used. Humidity inside the chamber is controlled by the air humidifying system, which consists of a water flask, a rotameter and air pump. Air is circulated through the water flask to add moisture into the chamber. The relative humidity is measured with Omega HX94C humidity transmitter with an accuracy of ±2%. Thermoelectric modules are used to cool down the test surface and the chamber. The performance of thermoelectric modules depends on the hot side temperature. A water cooling block is used to remove heat from the hot side of thermoelectric modules. In the experiments, the maximum temperature difference between the hot and cold sides is ~40 °C. The temperatures of test surface are measured with three type-T thermocouples with an accuracy of ±0.5 °C. One is located at the