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Densification of frost on hydrophilic and hydrophobic substrates – Examining the effect of surface wettability

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ABSTRACT

The properties of a growing frost layer were analyzed and compared for surfaces of different wettability to determine the effect that the surface energy has on the frost mass, thickness, and density. Three surfaces were tested – an uncoated, untreated aluminum plate (Surface 1), an identical plate coated with a hydrophobic coating (Surface 2), and a plate containing a hydrophilic coating (Surface 3). For these experiments, the frost layer was grown for a three-hour period inside a Plexiglas environmental test chamber where the relative humidity was held constant (i.e. 60%, 80%) using an ultrasonic humidifier. The surface temperature of the plate was fixed using a thermoelectric cooler (TEC) and monitored by four thermocouples affixed to the surface and stage. Frost thickness was determined from images of the frost layer taken using a CCD camera mounted directly overhead. A reduction in frost density of 37–41% was observed on the hydrophobic surface (Surface 2), whereas an increase of 20–26% was consistently observed on the hydrophilic surface (Surface 3) as compared to the baseline surface. Frost layer property data were also compared against models found in the literature. Reasonably good agreement was observed when comparing against data from the baseline surface; however, the agreement was not generally as good when compared against the hydrophilic and hydrophobic surfaces suggesting the need for surface wettability to be included as a parameter in future frost densification models.

1. Introduction

The study and continued development of super-hydrophilic and super-hydrophobic surfaces represents a valuable step in advancing our current understanding and design of more energy efficient and frost tolerant systems. For example, in refrigeration systems, heat exchanger fin spacing is often quite large to mitigate frost blockage of the air flow passage, and thus the convective heat transfer coefficient is typically low. Because of the requirement for periodic defrosting, refrigerator evaporators tend to be rather inefficient due to this periodic downtime. Furthermore, because the frost layer acts as an additional thermal resistance, the cooling capacity of the evaporator tends to decrease with ongoing frost layer growth. Thus, the development of more accurate frost growth and densification models represents an important issue for the HVAC&R industry; however, it is also expected that this research would benefit the aerospace and automotive industries where these models might be used to help mitigate surface drag, improve wing de-icing, etc. It is also important to note that while methods currently exist for creating water repellent and/or frost tolerant surfaces, these approaches typically rely upon chemical coatings which break down over time due to the thermal cycling and large temperature gradients experienced in these systems.

Over the years, numerous frost studies and frost densification models have been published. For example, O'Neal and Tree [1] and Padki et al. [2] have each performed an extensive review of the literature and tried to summarize the effect that various environmental parameters have on frost properties. Östin and Andersson [3] concluded that the plate surface temperature and the air relative humidity both affect frost thickness; whereas, the density of the frost largely depends on the air velocity and to a lesser extent on the relative humidity. Density, however, was independent of surface temperature. Similarly, the mass deposition rate of the frost was shown to have considerable dependence upon the relative humidity and air velocity. Östin and Andersson [3] also examined the contribution of the mass flux of condensed vapor to frost density and frost thickness and found that the condensing water vapor contributes nearly equally to the increase of frost density and frost thickness. Rite and Crawford [4] examined the impact that various environmental parameters have on the frost rate of an evaporator and found that a theoretical frost deposition rate based on measured upstream and downstream relative humidities was reasonably accurate. They also observed that the average frosting

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Nomenclature

A	heat transfer area (mm^2)
c_p	specific heat of air ($J\ kg^{-1}\ K^{-1}$)
CA	contact angle (°)
F_t	function defined by Eq. (5) (–)
i_{sv}	latent heat of sublimation ($J\ kg^{-1}$)
k	thermal conductivity ($W\ m^{-1}\ K^{-1}$)
m	frost mass (g)
p	vapor pressure (Pa)
RH	relative humidity (%)
t	time (sec)
T	temperature (°C)
V	voltage (V)

Greek Symbols

δ	frost thickness (mm)
Λ	modified Jakob number
Π	ratio defined by Eq. (4)
ρ	density ($kg\ m^{-3}$)
ω	humidity ratio ($kg_v\ kg^{-1}$)

Subscripts

a	air
f	frost
m	melting point
sat	saturation
w	plate surface

rate flux was essentially the same after 10 h as it was after 5 h, whereas Senshu et al. [5] had suggested that the frosting rate decreased with increasing air velocity. Other relevant works include Hayashi et al. [6] who derived a correlation to calculate the frost density, and Brian et al. [7] who developed a correlation for calculating the effective thermal conductivity of the frost layer based on the mean frost surface temperature and the average frost density. Other published methods for predicting frost properties on conventional surfaces (esp. thermal conductivity) include Yang and Lee, Yang et al., Yonko and Sepsy, and Lee et al. [8–11].

Using the frost property models of Hayashi et al. [6] and Brian et al. [7], Cheng and Cheng [12] proposed a theoretical model for predicting the frost growth rate on a flat plate. Assumptions inherent to this model included uniform frost density throughout the frost layer at any instant, orthogonal growth of the frost layer relative to the plate surface, uniform frost thickness, and constant heat and mass transfer coefficients (h and h_m) on the frost surface. Comparisons were made with other existing theoretical models by Jones and Parker [13] and Sherif et al. [14]. Cheng and Wu [15] examined frost formation on a flat plate subjected to atmospheric air flow in an open-loop wind tunnel using a CCD camera. They distinguished between three different time periods in the formation of frost as was done previously by Hayashi et al. [6] and called them the *crystal growth period*, *frost layer growth period*, and *full growth period*, respectively. More recent models for the prediction of the frost growth rate use supersaturated water vapor at the frost surface instead of saturated vapor such as Na and Webb [16,17]. Other relevant models of frost growth and densification include Cheng and Cheng [12], Cheng and Wu [15], Schneider [18], Tao et al. [19], White and Cremers [20], Yun et al. [21], Inaba and Imai [22], Le Gall and Grillot [23], and Ogawa et al. [24].

One of the best recent works that was found on frost layer densification is by Hermes et al. [25]. In this work, the authors presented a first-principles based model for predicting the time-evolving porosity of a frost layer. This theoretical model was then combined with experimental data (obtained elsewhere) to produce a semi-empirical correlation for frost layer densification as a function of time and the modified Jakob number. It is also worth noting that most correlations for frost density in the literature rely upon the frost surface temperature such as Hayashi et al. [6] which is difficult to obtain. The model by Hermes et al. [25] was independent of the frost surface temperature while still providing an explicit relationship between frost density and time. In a follow-up work by the same group, Nascimento et al. [26] extended this work to create a model for frost build-up between two parallel plates in channel flow.

With regards to predicting frost layer thickness, several researchers have suggested that the increase in frost thickness is nearly proportional to the square root of time during the mature growth period including Östin and Andersson [3], Schneider [18], Hoke et al. [27], and Okoroafor and Newborough [28]. In the work by Schneider [18], frost thickness was found to be largely independent of certain parameters that are often important in mass transfer such as the Reynolds number and the vapor pressure difference between the air stream and the frost surface. Instead, the frost thickness followed crystal growth behavior which is affected by the ratio of supersaturation and the conduction of the heat of sublimation that is delivered when the water molecule is built into the lattice. An equation based on a simplified model of frost growth was derived and compared against measured experimental data. The equation was found to be in good agreement with the data with a probable error of ±3.7% and a maximum error of ±10%. In the work by Okoroafor and Newborough [28], crosslinked hydrophilic polymeric coatings were examined as a possible means of retarding frost growth as compared to an uncoated aluminum surface. In this study, tests were performed at two plate temperatures (i.e. −5 °C and −10 °C) and two relative humidities (i.e. 40% and 70%), and then a regression analysis was performed to determine the constants that best fit their experimental data. The extent of the reduction in frost growth appeared to vary with the water absorbing potential of the polymeric coating.

Although many studies have been performed to model frost properties, relatively few papers were found which specifically examined the effect of surface wettability on the growing frost layer. In fact, in most published work on frost properties, the effect of the substrate surface energy has been largely ignored which may explain some of the scatter that has been reported in the literature. Some papers, however, have examined the impact of surface wettability on frost growth [29–31]. In a paper by Shin et al. [29], three different surfaces having advancing dynamic contact angles (DCA) of 23°, 55°, and 88° were installed in a wind tunnel and exposed to a humid air flow. They found that during the initial period of frost formation, the shape of the micro droplets depended upon the surface energy, and the process of frost growth was affected by the advancing DCA. High DCA surfaces showed the presence of irregular and rough crystals during the initial period of frost deposition, which resulted in high frost thickness and low frost density. By comparison, low DCA surfaces showed uniform and regular crystals resulting in low frost thickness and high density. This suggests that the growth of crystals is strictly controlled by surface energy during the early stages of frost growth. However, when the frost thickness was observed to reach a certain level, frost formation tended to be influenced instead by the environmental conditions rather than by the surface characteristics. One of the main limitations of this paper (and their associated model) is that this work