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The role of surface wettability on natural convection frosting: Frost growth data and a new correlation for hydrophilic and hydrophobic surfaces

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ABSTRACT

In refrigeration systems, frost accumulation on the evaporator demands periodic defrosting. Chemical coatings (either hydrophilic or hydrophobic) are sometimes used to mitigate frost build-up and/or improve drainage during the defrost cycle. Although several studies have been performed on frost growth behavior, relatively few studies have specifically examined the effect of surface wettability on the frost growth rate. This paper focuses on the influence of environmental operating conditions on the growth of a frost layer on surfaces which span a wide range of contact angles under natural convection conditions. A new semi-empirical correlation which includes the surface contact angle θ and the modified Jakob number Λ as parameters is reported with an average predictive error of 11.7% (N = 930) for all non-zero experimental data. The correlation was developed using multivariable regression analysis and data which span different surface temperatures (−13 °C to −5°C), relative humidities (40–80%), and static contact angles ranging from 45° (hydrophilic) to 160° (hydrophobic).

1. Introduction

Under frosting conditions, refrigerator evaporators tend to be rather inefficient because of the requirement for periodic defrosting. Moreover, the frost layer acts as an additional thermal resistance and increases the air-side pressure drop by reducing the free flow passage, thus decreasing the cooling capacity of the evaporator. This in turn leads to longer run cycles for the compressor to achieve the same desired cooling effect. Chemical coatings (either hydrophilic or hydrophobic) are sometimes used to mitigate frost build-up and/or improve drainage during the defrost cycle. Although several studies have been performed on frost growth behavior, relatively few studies were found which have specifically examined the role of surface wettability on the frost growth rate.

The literature contains several models for predicting frost growth and frost properties including Tokura et al. [1], Tao et al. [2], Le Gall and Grillot [3], Inaba and Imai [4], Ogawa et al. [5], White and Cremers [6], Brian et al. [7], Hayashi et al. [8], and Schneider [9]. More recent works/review articles include Shin et al. [10], Kandula [11,12], Hermes et al. [13], Yun et al. [14], Iragorry et al. [15], Yang and Lee [16], Cheng and Cheng [17], and Cheng and Wu [18]. Additionally, O'Neal and Tree [19] and Padki et al. [20] have each performed an extensive review of the literature in an effort to summarize the various key parameters which affect frost growth properties.

Relatively few papers were found, however, which specifically examined the effect of surface wettability on a growing frost layer despite the existence of numerous studies which have attempted to model frost properties. Instead, previous research on frost has largely focused on the influence of environmental parameters. For example, in examining frost growth on a flat plate, Cheng and Wu [18] distinguished between three different time periods and called them the crystal growth period, frost layer growth period, and full growth period, respectively. According to Cheng and Wu, a slight decrease in frost thickness periodically occurs during this last period due to the melting of frost crystals on the surface, the collapse of the frost layer, and the penetration of melted water. The range of the examined environmental parameters were $2 \leq V \leq 13$ m/s, $20° \leq T_a \leq 35$ °C, $40\% \leq \phi \leq 80\%$, and $-13 \leq T_w \leq -2$ °C. Cheng and Wu [18] also offered several reasons for the disparity of results in the literature concerning the effects of air temperature on frost thickness. One explanation was that when warmer air arrives at the frost surface, it may not be cooled immediately to

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Nomenclature

c_p	specific heat of moist air, J kg^{-1} K^{-1}
h	droplet height, mm
i_{sv}	latent heat of sublimation, J kg^{-1}
L	plate height, m
t	time, s
T	temperature, °C
V	droplet volume, μL
Greek symbols	
δ	frost thickness, mm
θ	static contact angle, °
ρ_a	density of moist air, kg m^{-3}
ρ_i	density of ice, kg m^{-3}
ρ_f	density of the fresh frost, kg m^{-3}
$\bar{\rho}_f$	average density of the frost layer, kg m^{-3}
ω	humidity ratio, kg$_v$ kg^{-1}
Λ	Modified Jakob number
Subscripts	
a	air
i	ice
f	frost surface
sat	saturation
w	plate surface

below the freezing point but may enter the frost layer and aid in densification instead of surface-level deposition. A second explanation offered by Cheng and Wu [18] was that the higher temperature air raises the frost surface temperature and in this way promotes the melting of the frost columns and branches at the surface. It was also noted, however, that higher temperature air usually can hold more moisture.

Östin and Andersson [21] observed that the plate surface temperature and relative humidity of the air stream both affect frost thickness, whereas the density of frost largely depends on the air velocity, and to a lesser extent on the relative humidity. Likewise, the frost mass deposition rate was shown to depend upon the relative humidity and air velocity. Östin and Andersson [21] also found that for times greater than 60 min, the contribution of the water vapor mass flux that went towards increasing the frost thickness varied between 41% and 65% with an average value of 49%. This fact suggests that under quasi-steady conditions, the vapor contributes nearly equally towards increasing frost density and frost thickness.

In Rite and Crawford [22,23], a trade-off concerning the effect of velocity on the frosting rate of a domestic refrigerator evaporator was examined by considering four parameters linked to the airflow rate, namely the mass transfer coefficient, surface temperature, air temperature, and moisture capacity of the air. They showed that the mass transfer coefficient, air temperature, and moisture capacity of the air all increase with the airflow rate which tends to promote the mass driving potential. The surface temperature, on the other hand, also increases with the airflow rate, but this effect serves to decrease the driving potential.

Kandula [11] reported a one-dimensional frost growth and densification model for laminar flow over a flat surface. Kandula found that while the air velocity contributed significantly to frost densification, it had no appreciable effect on the frost thickness. Kandula [12] later performed follow-up testing with the model under variable humidity conditions. In Hermes et al. [13], frost density is presented as a function of time and the modified Jakob number. It is worth noting that their model is independent of the frost surface temperature, but still provides an explicit relationship between frost density and time. This is noteworthy since previous correlations have used the frost surface temperature which can be difficult to measure in predicting either the frost density or frost thickness [8,9]. It should also be pointed out that most models until only recently have treated the air-frost interface condition as saturated [24,25], despite the known importance of the supersaturation degree in the frost nucleation and accretion processes and its influence on model accuracy [26–30].

With regards to frost layer thickness specifically, several researchers have suggested that the growth of the frost layer is nearly proportional to the square root of time during the mature growth period including Schneider [9], Östin and Andersson [21], Okoroafor and Newborough [31], and Hoke et al. [32]. In the work by Schneider [9], frost thickness was found to be largely independent of certain parameters that are often considered 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%.

As mentioned earlier, relatively few papers were found which have investigated the influence of surface wettability on frost growth and frost properties. In the work by Okoroafor and Newborough [31], 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.

In Shin et al. [10], surfaces with different 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 on the surface energy, and the process of frost growth was affected by the DCA. Low DCA surfaces showed uniform and regular crystals resulting in low frost thickness and high density, whereas 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. Although at later stages the frost formation tended to be influenced more by the environmental conditions, this finding nonetheless suggests that the growth of frost crystals is indeed controlled by surface energy during the early stages of frost growth. In a follow-up work by the same group, Lee et al. [33] studied the DCA surfaces of 23° and 88° in more detail. Frost structures were classified, and frost maps were proposed. It was found that the lower DCA surface at lower humidity produced a denser frost due to a shifting in surface structure formation type.

Kim and Lee [34,35] investigated the effect of fin surface contact angle on the frosting/defrosting performance of a heat pump. Static