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A semi-empirical correlation for predicting the frost density on hydrophilic and hydrophobic substrates

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ABSTRACT

A new semi-empirical correlation for the prediction of frost density on hydrophilic and hydrophobic surfaces is proposed. The proposed correlation is a function of the modified Jakob number and contains two correction terms, one for surface contact angle and another for relative humidity. Whereas most frost correlations exclude surface wettability as a parameter, our research has shown that the surface contact angle can be important when trying to accurately predict the properties of a growing frost layer. The correlation was developed using data from three different surfaces. On each surface, the frost was grown for three hours and then defrosted. The proposed correlation predicted more than 93% of the data to within a ±20% error band and is proposed for use on surfaces with contact angles $45° < \theta < 160°$, relative humidity $0.40 < \phi < 0.80$, and plate temperatures $-13\ °C < T_w < -5\ °C$ under natural convection conditions.

Une corrélation semi-empirique pour prédire la densité de givre sur des substrats hydrophiles et hydrophobes

Mots clés : Croissance de givre ; Aluminium ; Angle de contact ; Mouillabilité de surface ; Densité de givre ; Hydrophile ; Hydrophobe

1. Introduction

The study of frost formation and frost properties on surfaces remains an important consideration when designing new frost-tolerant heat exchangers and systems. In most cases, frost formation is undesirable because it forms a thermal barrier on the heat exchanger surface due to its porous structure and low overall thermal conductivity. As a result, frost growth typically reduces the heat transfer rate and can block the flow of

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Nomenclature

A	heat transfer area [mm^2]
c_p	specific heat of air [J kg^{-1} K^{-1}]
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 [s]
T	temperature [°C]
u	air velocity [m s^{-1}]

Greek symbols

δ	frost thickness [mm]
ϕ	relative humidity [–]
Λ	modified Jakob number
ρ	density [kg m^{-3}]
θ	contact angle [°]
ω	humidity ratio [kg$_v$ kg^{-1}]

Subscripts

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

air through the heat exchanger thereby degrading its performance. Moreover, most refrigerator evaporators require periodic defrosting which further increases their inefficiency due to this periodic downtime. And while super-hydrophilic and super-hydrophobic surfaces have been studied extensively in other contexts, relatively few papers could be found which have examined the influence of surface wettability on a growing frost layer. Furthermore, most correlations ignore surface wettability when seeking to predict frost density on metallic surfaces. 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.

Over the years, numerous frost studies and frost densification models have been published. For example, O'Neal and Tree (1985), Padki et al. (1989), and Iragorry et al. (2004) have each performed a critical review of the literature and tried to summarize the effect that various environmental parameters have on frost properties and frost growth models. Östin and Andersson (1991) concluded that the plate surface temperature and the air relative humidity both affect frost thickness. They also examined the contribution of the mass flux of condensed water vapor to frost density and frost thickness and found that the mass flux contributes nearly equally to increasing the frost density and frost thickness. Other seminal works include Hayashi et al. (1977) who derived a correlation to calculate the frost density, and Brian et al. (1970) 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. O'Neal and Tree (1985) and Padki et al. (1989) also reported that frost formation during forced convection has been studied extensively, while only a limited number of studies have explored frost formation during natural convection. It is worth noting therefore that this study helps to fill this gap in the literature. Possible applications of frost formation under natural convection conditions include natural draft roll-bond evaporators, refrigerated drawers and shelves, inner liners of refrigerated cabinets, and equipment used for the gasification of cryogenic liquids.

Other recent works in this area include Kandula (2011a, 2012), Wang et al. (2012), and Janssen et al. (2016). Kandula (2011a) developed a one-dimensional frost growth and densification model for laminar flow over a flat surface. Recent improvements with respect to frost density and thermal conductivity prediction were incorporated into the model. Kandula found that air velocity has no appreciable effect on frost thickness but does contribute significantly to frost densification. In a subsequent work, Kandula (2012) performed follow-up testing to check the accuracy of his frost growth model (Kandula, 2011a) under variable humidity conditions. In a separate work, Wang et al. (2012) developed a generalized correlation for predicting the initial frost density on cold flat plates (a value that is often difficult to predict accurately) based on the Hayashi et al. (1977) correlation and by incorporating additional frost data. Janssen et al. (2016) reported a new experimental technique for obtaining quantitative information about frost thickness with faster data acquisition and higher accuracy than traditional approaches. Other papers focused on the prediction of frost properties on conventional surfaces (especially thermal conductivity) include Tokura et al. (1983), Yang and Lee (2004), Yonko and Sepsy (1967), Lee et al. (1997), and Negrelli and Hermes (2015).

A recent study that was found on frost layer densification is by Hermes et al. (2014). 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 (from an earlier work) 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. (1977) which is difficult to obtain. The model by Hermes et al. (2014) 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. (2015) extended this work to create a model for frost build-up between two parallel plates in channel flow. In a paper by Cheng and Wu (2003), frost formation on a flat plate was examined under forced convection in an open-loop wind tunnel using a charge-coupled device (CCD) camera. They distinguished between three different time periods in the formation of frost as was done previously by Hayashi et al. (1977) and called them the crystal growth period, frost layer growth period, and full growth period, respectively. As shown in Na and Webb (2004a, 2004b), most frost growth models now use supersaturated water vapor at the frost surface instead of saturated vapor. Other relevant models on frost growth and densification include El El Cheikh and Jacobi (2014), Cheng and Cheng (2001), Schneider (1978), Tao et al. (1993), White and Cremers (1981), Yun et al.