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A semi-empirical correlation for the thermal conductivity of frost☆

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ABSTRACT

The present work is aimed at advancing an improved correlation for the thermal conductivity of frost. The analysis was conducted based on the weighted geometric mean of the thermal resistances of moist air and ice crystals, thus setting the theoretical background for a dimensionless model for the thermal conductivity as a function of the porosity of the frosted medium. Experimental data obtained elsewhere for a wide wall surface temperature span (from −30 °C to −4 °C) were employed to fit the model, coming up with a semi-empirical correlation for the thermal conductivity of frost valid for porosities ranging from 0.5 to 0.95. Comparisons of the proposed correlation with the experimental data showed that it is able to predict 81% of the data points (153 out of 188) within the 15% thresholds. Comparisons with other correlations available in the open literature are also reported.

Une corrélation semi-empirique pour la conductivité thermique de givre

Mots clés : Givre ; Conductivité thermique ; Corrélation

1. Introduction

Frost often builds-up on evaporators of small-capacity refrigerating appliances, resulting in an increased energy input to accomplish the same refrigerating effect. To mitigate the issues caused by the evaporator frosting, simulation-based designs have been carried out by means of mathematical models for the growth and densification of frosted media in various geometries, such as flat surfaces (Sami and Duong, 1989; Tao et al., 1993; Lee at el., 1997; Na and Webb, 2004; Hermes et al., 2009; Hermes, 2012), parallel plate channels (O'Neal, 1982; Ismail and Salinas, 1999; Luer and Beer, 2000; Cui et al., 2011; Loyola et al., 2014), and tube-fin heat exchangers (Tso et al., 2006; Huang et al., 2008; Silva et al., 2011).

Most models, however, rely on empirical correlations for the thermophysical properties of frost, particularly the density and the thermal conductivity, which limit their range of

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Nomenclature

Roman

A	Parameter of Equation (2)
a, b	Coefficients of Equations (18) and (19)
B	Shape factor of Equation (12)
C	Blending factor of Equation (6)
D_v	Water vapor diffusivity in air, $m^2\ s^{-1}$
E, F	Parameters of Equation (5)
Fo	Fourier number, dimensionless
h_{sv}	Latent heat of sublimation, $J\ kg^{-1}$
k	Thermal conductivity, $W\ m^{-1}\ K^{-1}$
L	Binary parameter of Equation (4)
M	Molecular weight, $kg\ mol^{-1}$
p_{atm}	Atmospheric pressure, Pa
p_v	Vapor pressure of water, Pa
r	Radius, m
Re	Reynolds number, dimensionless
R_v	Gas constant for water vapor, $J\ kg^{-1}\ K^{-1}$
S	Surface area, m^2
T	Temperature, K
t	Time, s
X	Dimensionless frost thickness

Greek

α, β, γ	Coefficients of Equation (1)
δ	Thickness
ε	Frost porosity
ρ	Density, $kg\ m^{-3}$
ω	Humidity ratio
ξ	Blending factor of Equation (10)
ζ	Dimensionless thermal conductivity

Subscripts

0	Reference state
a	Moist air
air	Dry air
c	Turbulent convection
eff	Effective
f	Frost
g	Geometric mean
i	Ice
m	Molecular diffusion
max	Maximum
min	Minimum
p	Parallel association
s	Serial association
t	Thermal diffusion
tp	Triple point
v	Water vapor
w	Wall surface

operation. The former was assessed in prior studies, when empirical and semi-empirical correlations were put forward for the frost density (Hayashi et al., 1977; Mao et al., 1992; Yang and Lee, 2004; Kandula, 2011; Hermes et al., 2014; Nascimento et al., 2015). The latter is at the aim of the present paper.

Several studies are available in the open literature focused on the thermal conductivity of frost. The most influential ones are described in Table 1, whereas Table 2 summarizes the key parameters evaluated in the studies reported in Table 1. They are detailed as follows.

Yonko and Sepsy (1967), in a pioneering study, advanced an empirical correlation for the thermal conductivity of frost as a quadratic polynomial function of the frost density. The correlation was not able to predict the experimental data satisfactorily, suggesting that the thermal conductivity is dependent on parameters other than the density. Despite of that, their approach influenced the works of Ostin and Andersson (1990) and Sturm et al. (1997), which also employed quadratic polynomials to correlate the thermal conductivity as a function of the frost density, as follows:

$$k_f = \alpha + \beta\rho_f + \gamma\rho_f^2 \tag{1}$$

where k_f is the thermal conductivity of frost in [$W\ m^{-1}\ K^{-1}$], ρ_f is the frost density in [$kg\ m^{-3}$], and the coefficients α, β and γ are summarized in Table 3.

Pitman and Zuckerman (1967) put forward a semi-empirical correlation assuming the ice crystals as small spheres connected to each other by ice cylinders. The correlation predictions were compared with experimental data for wall surface temperatures of −88, −27 and −5 °C, disregarding the dense frost media typical of the plate-shaped ice crystals observed for wall surface temperatures between −27 and −5 °C, as depicted in Fig. 1, which reproduces the frost morphology map due to Kobayashi (1958). Their correlation is as follows:

$$\frac{1}{k_f} = \frac{1-r}{(k_i - k_a)S + k_a} + \frac{4\ln(A+1)/(A-1)}{2A\pi r(k_i - k_a)} \tag{2}$$

where k_a and k_i are the thermal conductivities of moist air and ice, respectively, r is the radius of the spheres, and S is the surface area of the cylinders. The parameter A is defined as follows:

$$A = \left\{1 + \frac{4}{\pi[(k_i/k_a) - 1]r^2}\right\}^{1/2} \tag{2.a}$$

A few years later, Brian et al. (1969) noticed the frost density and the wall surface temperature are key independent parameters that affect the thermal conductivity of the frost media, thus coming up with the following empirical correlation based on their own data, which is valid for frost densities lower than 250 $kg\ m^{-3}$:

$$k_f = 2.401 \times 10^{-5} T_w^{1.272} + 3.921 \times 10^{-8} \rho_f T_w^{1.74} \tag{3}$$

where T_w is the wall surface temperature in [K], ρ_f is the frost density in [$kg\ m^{-3}$], and k_f is the thermal conductivity of frost in [$W\ m^{-1}\ K^{-1}$].

One year later, Biguria and Wenzel (1970) advanced theoretical models to predict the effective thermal conductivity of frost based on the crystal morphology (e.g., spheres, plates, columns, needles), as depicted in Fig. 1. They found out that none of the theoretical models were able to predict the experimental data satisfactorily using the frost density as the only parameter. In order to improve the model prediction capabilities, they included other key heat and mass transfer parameters into correlation, as the air velocity and humidity, as follows: