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Review

# State-of-the-art review of frost deposition on flat surfaces

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ABSTRACT

This paper presents a comparative study of predictive methods of frost growth and densification on horizontal, vertical and parallel flat surfaces. The study treats two aspects of frost formation: thickness and density. It focuses on the comparison between four different existing theoretical models or empirical correlations and a database gathering almost 382 test points available in the literature for average frost thickness. Furthermore, five correlations are compared to 149 data points for average frost density. Impacts of air velocity, relative humidity and wall temperature are studied. The latter is found to have a significant impact on frost development. Quantitative and qualitative analyses of the predictive methods are proposed. This study leads to the identification of the main issues in the field of modelling of frost deposition on horizontal, vertical and parallel flat plates.



# Synthèse de l'état de l'art du dépôt de givre sur des surfaces planes

*Mots clés :* Givre ; Densité ; Épaisseur ; Corrélation ; Modèle

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**Nomenclature**

| | |
|---|---|
| $a_1$ | coefficient (Hermes, 2012) |
| $A_0$ | plate surface [m$^2$] |
| $c_p$ | specific heat capacity of air [J kg$^{-1}$ K$^{-1}$] |
| $d_0$ | coefficient (Hermes, 2012) |
| $d_1$ | coefficient (Hermes, 2012) |
| $D$ | diffusivity of water vapour in air [m s$^{-1}$] |
| $D_f$ | diffusivity of water vapour in air in the frost layer [m s$^{-1}$] |
| $F_t$ | empirical function: $F_t = 1 + 0.052 \cdot \frac{T_a - T_M}{T_M - T_W}$ |
| Fo | Fourier number: $F_0 = \frac{\alpha t}{l_c^2}$ |
| $h_{sub}$ | specific latent heat of sublimation [J kg$^{-1}$] |
| $Ja$ | Jakob number |
| $k$ | thermal conductivity [W m$^{-1}$ K$^{-1}$] |
| $l$ | plate length [m] |
| $l_c$ | characteristic length [m] |
| $m$ | mass [kg] |
| $m_g$ | mass flux of growth [kg m$^{-2}$ s$^{-1}$] |
| $m_w$ | mass flux of water vapour [kg s$^{-1}$] |
| $m_\rho$ | mass flux of densification [kg m$^{-2}$ s$^{-1}$] |
| $Nu$ | Nusselt number |
| Q | heat flux [W] |
| $p$ | partial pressure of water vapour [$Pa$] |
| $Re$ | Reynolds number |
| $Re_c$ | critical Reynolds number |
| RH | relative humidity [%] |
| $T$ | temperature [K] |
| $t$ | time [s] |
| $v$ | velocity [m s$^{-1}$] |
| V | volume [$m^3$] |
| $w$ | humidity ratio [$kg_v \cdot kg_a^{-1}$] |
| x | distance [m] |
| z | thickness [m] |

*Greek symbols*

| | |
|---|---|
| $\alpha$ | thermal diffusivity [m$^2$ s$^{-1}$] |
| $\alpha_w$ | absorption factor [kg m$^{-3}$ s$^{-1}$] |
| $\gamma$ | tortuosity |
| $\varepsilon$ | porosity |
| $\pi$ | pressure ratio: $\pi = \frac{p_a - p_{f,sat}}{p_{a,sat} - p_{f,sat}}$ |
| $\rho$ | density [kg m$^{-3}$] |
| $\tau$ | dimensionless time: $\tau = \frac{k_f \cdot t}{\rho_f \cdot C_p \cdot l^2}$ |
| $\mu$ | diffusion resistance factor |

*Subscripts and superscripts*

| | |
|---|---|
| a | humid air |
| c | critical |
| f | frost |
| i | ice |
| m | melting |
| sat | saturation |
| tp | triple point |
| v | vapour |
| w | wall |

## 1. Introduction

In certain environmental conditions, frost can form and develop on the surface of air refrigeration system evaporator. When surface temperature is below the dew point and above the triple point of water, liquid droplets will condense on the surface. If the dew point is kept positive and the surface temperature is reduced below the triple point, liquid droplets begin to freeze. Frost can also appear by desublimation: water vapour changes directly into frost. Desublimation occurs when surface temperature and dew point are below the triple point of water. The frost layer acts as (i) a thermal insulator between the humid air and the cold surface and (ii) significantly reduces air flow area between the fins of the evaporator, increasing the air pressure drop. Consequently, the energy performance of the system is reduced. A defrosting operation is needed to recover regular performance. This operation is energy consuming and makes the coefficient of performance lower.

In the last decades, lots of surveys investigated frost formation. Hayashi et al. (1977) divided the frost formation process into three steps: (1) the crystal growth period, (2) the frost layer growth period and (3) the frost layer full growth period. This study proposed a first empirical correlation to calculate frost density. Later, Tao et al. (1993) completed this survey, gathering the two last periods. The first stage corresponds to a one-dimensional growth of ice column and the second to a three-dimensional growth of the ice column. Hayashi et al. (1977) and Tao et al. (1993) proposed to model the fully developed growth as a homogeneous porous medium in which diffusion leads to the frost growth and densification. Jones and Parker (1975) developed a model based on molecular diffusion of water vapour at the frost interface and using energy and mass balances. Based on the previous model, Sami and Duong (1989) developed a correlation to determine heat transfer coefficient and used Lewis analogy to calculate mass transfer coefficient. Schneider (1978) proposed an empirical correlation for the frost thickness growth. O'Neal and Tree (1984) suggested another frost thickness correlation based on experimental data for parallel plates. Facing the large differences between experimental data and predictions, Lee et al. (1997) developed a model considering a molecular diffusion of water-vapour and heat generation due to sublimation from the frost layer, assuming water-vapour in a saturated state at the frost surface. The numerical model was validated with experimental data. Cheng and Cheng (2001) proposed a semi-empirical model considering the Lewis analogy and using the Hayashi et al. (1977) frost density correlation. The theoretical model, compared to the experimental data of Yonko and Sepsy (1967), showed good agreement. Lee et al. (2003) developed a new mathematical model to predict the behaviour of frost layer, without employing any experimental correlation. Compared