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Frost formation and development on flat plate: Experimental investigation and comparison to predictive methods

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ABSTRACT

This paper proposes new experimental data on frost formation and development on flat plate. The experimental data have been obtained on a 300 × 300 mm^2 aluminum plate, with humid air flowing inside a closed-loop wind-tunnel. The effect of environmental conditions has been studied with a sensitivity analysis. Air velocity ranges between 1 and 4 $m.s^{-1}$, air temperature between 5 and 16 °C, air relative humidity between 50% and 80% and plate temperature between −25 and 0 °C. First, the Lewis analogy boundary layer frequently used to simplify frost phenomenon formulation is checked successfully. Results provided by the sensitivity analysis showed that plate temperature and air relative humidity are the most influential parameters on frost properties (thickness, density and thermal conductivity). Tortuosity, depending on the frost crystal shapes, is also identified as a key parameter which needs deeper investigations. A comparison of experimental data with models from the literature is proposed. Predictive methods have been tested. Reliable predictive methods have been identified for frost thickness and frost conductivity. Correlations for predicting frost density need to be improved. This work also highlights the important role of crystal shape in frost deposition mechanisms.

1. Introduction

Frost represents a real issue for air source heat pump (ASHP) and refrigeration unit optimization. Indeed, in some outdoor air temperature and relative humidity conditions, frost can form on evaporator surface of these devices. Frost layer growth causes air flow obstruction and creates an additional thermal resistance leading to performance decrease [37,6,4]. To remove frost formed on evaporator fins, manufacturers developed defrosting strategies. These energy consuming strategies affects device performance but also cost savings spotlighted by manufacturers. To optimize defrosting strategies, there is a need to understand frost formation phenomenon and the impact of environmental parameters on frost properties.

Frost formation process has been studied by a large number of authors who choose to build experimental benches. Studies have been led on different geometries. Some experimental works have been performed on micro channel evaporators but this geometry was too complicated to observe frost formation phenomenon in depth, and to identify influential parameters. Impact of the geometry and more particularly fin spacing was mainly studied [25,26,23,22,24,40].

Experimental studies led on tube-fin evaporators propose some sensitivity analysis. Air velocity impact has been studied. Nevertheless, some authors identified difficulties related to fin-tube geometry: Kim and Lee [15] underlined that frost does not form uniformly on the evaporator surface (first raw presented a thicker frost layer than secondary raw).

In order to facilitate frost formation study, geometry was simplified to a single cold plate. Most of the studies has been led on horizontal flat plates. Two other geometries were tested: vertical plate to approach fin orientation and two parallel plates to analyze impact of a first frost layer on a second one. A study, proposed by Léoni et al. [21] proposed a gathering of experimental points for the three geometries and used these points to perform a parametric study. The authors found that environmental parameter impact on frost thickness agreed for the three geometries: frost thickness increases with low wall temperature, high relative humidity and high air velocity. Conclusions were not as clear for environmental parameter impact on frost density because of a lack of experimental points. Some contradictory results have been observed. Furthermore, the parametric study of Hermes et al. [9] is particularly interesting. This study enriched thickness and density databases and participated to a better understanding of frost formation.

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Nomenclature

Symboles

c_p	heat thermal capacity ($J.K^{-1}.kg^{-1}$)
H	enthalpy (J)
h	specific enthalpy ($J.kg^{-1}$)
h_{air}	heat transfer coefficient ($W.m^{-2}.K^{-1}$)
h_m	mass transfer coefficient ($kg_{DA}.m^{-2}.s^{-1}$)
$\dot{m}$	mass flow ($kg.s^{-1}$)
m	mass (kg)
q	heat flux ($W.m^{-2}$)
RH	relative humidity (%)
S	surface (m^2)
T	temperature (K)
t	time (s)
V	volume (m^3)
v	velocity ($m.s^{-1}$)

Greeks

δ	thickness (m)
Δ	difference
λ	thermal conductivity ($W.m^{-1}.K^{-1}$)
ρ	density ($kg.m^{-3}$)
ω	absolute humidity ($g_v.kg_{DA}^{-1}$)

Subscripts

air	air
bottom	bottom surface
conv	convective
CP	carbon plate
DA	dry air
dew	dew
f	frost surface
fin	final
lat	latent
plate	plate
sens	sensible
sub	sublimation
top	top surface
tot	total
tube	tube
v	vapor
water	water

Dimensionless number

Le	Lewis number

Acronyms

MAE	mean absolute error
MRE	mean relative error
PERC	percentage of data points included in the error band

Authors identified wall temperature and relative humidity as influential parameters. Yoon et al. [43] completed Hermes et al. [9] study with tests quantifying air velocity and air temperature impacts on frost formation. Lower velocity and lower temperature were identified to facilitate frost growth. The study of Negrelli and Hermes [29] extended frost properties to frost conductivity, analyzing impact of environmental conditions (air velocity, wall temperature, air temperature). Other authors choose to deeply study frost formation, to a microsccopic approach. The study of Fukuta [3] brings some information about crystals morphology formed at different air temperature. This study allows linking temperature and frost crystal shapes. Kobayashi [16] proposed a map classifying crystal shapes under various temperatures and supersaturation degrees. This study shows the impact of relative humidity on crystal shapes. To complete these first investigations, Wu et al. [39] proposed a detailed study on frost formation, separating important steps of the frost formation (based on [5] study). Authors proposed to classify crystal shapes in four groups, according to their form and appearance. According to the authors, crystals shapes are particularly related to relative humidity and cold surface temperature.

Lots of predictive methods have been proposed in the literature. Léoni et al. [21] and Iragorry et al. [11] presented a complete summary and an evaluation of prediction capacity of the predictive methods.

To sum-up the literature survey, we can say that:

- Only a few authors tried to combine their results on the impact of environmental parameters with frost morphology (Chrystal shape) to explain the phenomena occurring during frosting;
- Based on Iragorry et al. [11] and Léoni et al. [21] studies, we see that the current prediction methods are not so accurate in particular for frost density and conductivity. One of the reasons could come from the lack of experimental data available in the literature (may be only a few thousands which is not so large);
- Lewis number equals unity is often used but almost never checked experimentally in the literature (only by [19] to our knowledge).

The idea of this paper is thus to provide new experimental data, to check the Lewis analogy, to try to explain the phenomena occurring during frosting thanks to frost morphology and to compare the results with existing prediction methods.

2. Description of the test facility and the test section

2.1. Description of the test facility

Fig. 1 shows a schematic representation of the test facility. The facility is conceived as a closed-loop wind-tunnel. A cold room (a) is used to cool the air. Air temperature is controlled from 5 to 16 °C thanks to thermal resistances located in the wind-tunnel. The air is

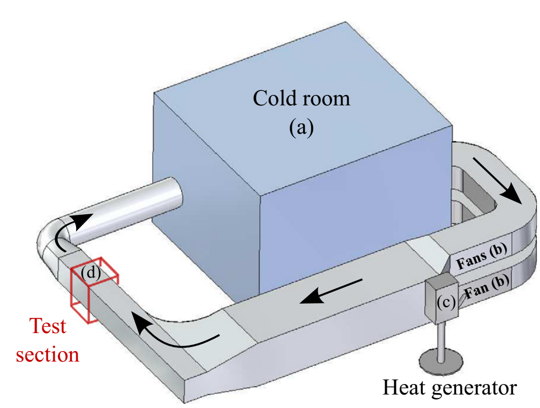

Fig. 1. Test facility description. (a) Cold room, (b) fans, (c) heat generator, (d) test section.