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Modeling of frost formation over parallel cold plates considering a two-dimensional growth rate

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ABSTRACT

In this study, a frost formation model is presented based on a new two-dimensional approach for the growth rate. For modeling the frost formation over parallel cold plates, the basic transport equations of mass, energy and momentum have been discretized using the finite volume method in a two-dimensional domain in which air and frost are considered. A fixed grid formulation is used to deal with the air–frost moving boundary. An extended domain in the inlet boundary has been considered in order to study the frost formation in the leading edge of the plate. The numerical results have been validated against experimental data in which frost growth and temperature as a function of time are reported as local values. The model predictions of the frost thickness as a function of time agree with the experimental data within 10% of deviation for the case of intermediate plate temperature.

1. Introduction

Frost formation consists in a phenomenon in which water vapor from moist air flow is deposited in a cold surface whose temperature is lower than the freezing temperature of water. Frost is a porous structure which consists of ice containing air gaps, so it presents a considerable thermal resistance. In addition, frost formation in the heat exchanger channels increases the pressure drop by flow restriction. Therefore, heat exchangers thermal performance decreases when frost formation appears. Many researchers have studied this phenomenon. One of the first among them was Hayashi et al. [1], who divided the frost growth process in three different periods.

The first one is associated with the crystal growth, which is relatively short when compared with the whole process, the frost layer does not experience a significant thickness increase in this period. During this early stage, the frost cannot be considered a porous medium since the structure might be understood as ice columns where convective heat and mass transfer are the main mechanisms for frost growth, rather than diffusion within the frost layer.

In the second stage, known as the frost layer growth period, frost is treated as a porous medium in which molecular diffusion of water vapor occurs. The total mass flux of water vapor coming from the air contributes in two different processes: the densification of the frost layer and the frost growth.

Finally, in the frost layer full growth period, the frost surface temperature reaches the triple point of water, and so it begins a cyclic process in which the condensed vapor at the frost surface permeates into the frost layer and gradually freezes because of the inner temperature gradient. A study of this stage is presented in Aoki et al. [2].

In the last decades, many models for frost growth on flat plates have been proposed. A review of frost formation in simple geometries is found in Óneal and Tree [3]. One can classify the theoretical models into two groups, depending on the use or not of empirical correlation for the air–frost interaction.

In the first group, the models use empirical correlations for the air side effect and they apply energy and mass transfer equations within the frost layer to predict frost formation. Tao et al. [4] developed a mathematical model based on the frost structure analysis done by Hayashi et al. [1] using the local volume averaging technique to deal with the frost as a porous media. Based on that model, Ismail and Salinas [5] determined the best initial values of the diffusivity, initial radius and geometry of ice crystals. Using the local volume averaging technique, Le Gall et al. [6] proposed an interface balance to predict frost growth rate. In

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Nomenclature

$\dot{m}$	water vapor mass flux, kg m^{-2} s^{-1}
A	area, m^{2}
c_p	specific heat capacity, J kg^{-1} K^{-1}
D	mass diffusivity coefficient, m^{2} s^{-1}
E, W, N, S	respective east, west, north and south computational nodes
e, w, n, s	respective east, west, north and south control volume faces
H	distance, m
P	pressure, Pa
q_{sub}	specific heat of sublimation, J kg^{-1}
T	temperature, °C
t	time, s
u	horizontal velocity, m s^{-1}
V	volume, m^{3}
v	vertical velocity, m s^{-1}
x	coordinate, m
y	coordinate, m

Greek symbols

λ	thermal conductivity, W m^{-1} K^{-1}
μ	dynamic viscosity, Pa s
ω	humidity ratio, kg$_{\text{v}}$ kg$_{\text{a}}^{-1}$
ρ	density, kg m^{-3}
ε	porosity

Subscripts

0	initial value
diff	diffusing through the frost layer
a	air
CS	control surface
ef	effective
f	frost
i	ice
in	inlet
s	plate surface
v	vapor

their work, Na and Webb [7–9] proposed a model considering supersaturated water vapor density at the frost surface. Yang et al. [10] reported an effective frosting model for predicting the thermal performance of a fin–tube heat exchanger. More recently, Hermes et al. [11] developed a mathematical model whose predictions of the frost thickness agreed within 10% error bands when compared with experimental data. Kandula [12,13] proposed new frost correlations for the flat plate and studied the effects of the environment parameters in the frost characteristics. Even though one-dimensional models based on empirical correlations can predict frost formation with reasonable precision, they require experimental determination of the empirical correlations for every different geometry.

The second group, consists in an attempt to avoid empirical correlations by simulating the air flow and the frost formation simultaneously. As frost formation is a common phenomenon which takes place in different surface geometries, it is required a better understanding of the two-dimensional frost growth without using empirical correlations. Lee et al. [14] proposed a two-dimensional model that shows good agreement with experimental data for different working conditions. However, the model assumes that the frost density in the direction normal to the cooling plate is constant. Recently, Cui et al. [15] and Kim et al. [16] simulated frost formation with a commercial Computational Fluid Dynamic (CFD) package getting results with good agreement with experimental data. These models can determine local properties of the frost layer such as density, humidity and temperature. In these models, it was found that frost layer at the leading edge of the plate presents larger values of density and thickness when compared with the values at the trailing edge. Lenic et al. [17] proposed a two-dimensional mathematical model based on the assumptions of Na and Webb [7] and modeled it using the finite volume technique. The model of Lenic is similar to the one proposed in this work, except for the treatment of the frost growth rate.

The main goal of this investigation is to establish a mathematical model for the frost growth in two dimensions, which means that a frost element not only increases its height but also its width. Such approach is developed in the context of the second group, so it has been modeled the air and the frost subdomains.

2. Mathematical and physical model

2.1. Physical model of the fin-and-tube heat exchanger

The frost formation is here modeled in the region between parallel cold plates. Such configuration represents the air channels of a fin-and-tube heat exchanger, which is very common in refrigeration systems. In the heat exchanger, represented in Fig. 1a, a refrigerant fluid flows in the finned tube in order to cool a mass of air flowing through a parallel plates arrangement. If one considers the temperature of the cold plate as constant, there is no need to simulate the refrigerant fluid domain. Due to the symmetry of the problem, the computational domain (Fig. 1b) corresponds to the lower half region between the cold plates. All prior two-dimensional models set the west inlet air boundary in the origin of the plate ($x = H_{x,1}$ in Fig. 2), whereas in this study it has been considered an extended domain in order to (1) avoid unrealistic physical boundary conditions, and to (2) permit horizontal frost growth in the leading edge.

2.2. Physical assumptions

It is assumed that frost formation is symmetric with respect to the mid line between the parallel plates. In addition, it is assumed that the plate has null thickness in order to apply a symmetry condition in the south air boundary.

The following physical assumptions are made for the air subdomain: (1) humid air is treated as an incompressible Newtonian fluid in laminar flow; (2) density (ρ_{a}), mass diffusivity coefficient (D_{a}) and specific heat capacity ($c_{p,\text{a}}$) of air are assumed constant; and (3) inlet air velocity is large enough so that natural convection is negligible.

The following physical assumptions are made for the frost subdomain: (4) the size of the frost porous are small enough that heat transfer by natural convection is negligible; (5) atmospheric pressure is considered as the total gas pressure of the humid air within the frost layer [6]; and (6) humid air within the frost layer is considered saturated [12].

The local humidity is calculated in the center of the control volumes, whereas frost–air interface is placed in the control