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# NUMERICAL ANALYSIS OF THE MINIMIZATION OF FROST FORMATION IN FLAT PLATE WITH DIFFERENT COATINGS

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**Abstract.** *The presence of frost in the most diverse refrigeration systems is a highly relevant problem for commercial refrigeration. The thin layer of ice that forms on a cold surface grows over time, becoming increasingly dense, causing a reduction in system performance due to the increase in the thermal resistance of the layer. The process of formation of ice crystals is very complex to be evaluated due to the different environmental parameters involved on this phenomenon, where the processes of heat transfer and mass occurs simultaneously. Through numerical simulations, based on a mathematical model of this phenomenon, it was possible to determine the thickness and surface temperature of the porous layer of ice formed on flat plates made of brass, copper and zinc, and plates coated with wax and silica. Experimental data available in the literature was used in the validation of the numerical model adopted in this paper. This research is a numerical study of the phenomenon of frost formation and aims to analyze the influence of the coatings on the reduction of frost layer formed on a flat plate, understanding the formation process and analyzing environmental parameters that influence this phenomenon.*

**Keywords:** *Numerical Analysis, Flat Plate, Frost Formation, Frost Reduction, Frost Deposition.*

## 1. INTRODUCTION

Frost is a physical phenomenon that occurs when the flow of the mixture formed by air and water vapor comes into contact with cold surfaces below 0°C. This phenomenon can be commonly found in more diverse applications such as industrial, commercial or even residential. The study of the formation of this phenomenon presents several complexities due to the different environmental parameters involved on the formation of ice layers. Parameters such as relative air humidity, ambient temperature, surface temperature, deposition surface material, among others.

The process of formation of the ice layer is complex to be modeled, due to the diverse environmental conditions involved in this phenomenon, one of the main characteristics of the formation of the porous layer is the simultaneous occurrence of heat and mass transfer processes. The presence of this physical phenomenon in industrial applications as in refrigeration systems, among others, is considered a problem of economic, energetic and even safety relevance, when it occurs in aircraft or in compressor rotors.

When the formation of the frost layer occurs on a heat exchanger this phenomenon becomes a problem for the thermal efficiency of the system because the ice layer acts as a thermal insulation, drastically reducing the rate of heat transfer in the cooling system. This fact is aggravated over time, as the thickness of the ice layer increases and thus the airflow decreases, according to Liu *et al.* (2006), in some exceptional cases the layer increases to the point of completely blocking the flow of air, air in the heat exchanger. Avoiding ice accumulation in heat exchangers is essential for the proper functioning of the system. According to Wu *et al.* (2007), the frost layer in heat exchangers not only increases thermal resistance, but also reduces airflow causing a drop in performance in heat exchangers.

Every refrigeration system is impaired if the heat exchanger does not work properly, preventing the formation of ice buildup in the heat exchanger is essential for the proper functioning of any refrigeration system. New energy efficiency programs are increasingly tight on the efficient use of energy sources, with actions requiring manufacturers to develop new products with high performance and low energy demand.

Due to mass transfer, the boundary of the system grows over time, and with its growth its geometry remains in a state of constant change, directly influencing the conditions of flow and heat transfer. All these challenges make the large part of the studies involving the formation of this phenomenon based on experimental knowledge. According to Silva (2014)

for a complete evaluation of the defrost growth, it is necessary to use models formulated from equations that govern the phenomena of heat transfer and mass allied to the operational and geometric factors involved in the process, obtaining better results on the process of porous ice growth.

Cai *et al.* (2010) studied the effects of surface energy on the phase change of water vapor in the early stage of porous ice growth and performed tests on two surfaces coated respectively by copper and wax, noting that the speed at which nucleation occurs is related to the surface angle. The droplets formed on the wax surface distribute more space to each other, covering less area, than the coated with copper. In addition, the ice crystals need more time to appear on the wax coated surface and their porous ice layer presents low density and weight when compared to the copper coated surface. Finally, it has been found that the wax coating does not totally restrict the growth of ice on the surface.

Kim *et al.* (2016) proposed that a finned surface coated by hydrophobic and superhydrophobic substances may delay the phenomenon of frost formation on the cold surface. This delay occurs due to the prolongation of the nucleation stage of the ice crystals, however the two types of coatings are only effective when the surfaces are overcooled between  $-20\text{ }^{\circ}\text{C}$  and  $-40\text{ }^{\circ}\text{C}$ . In addition, it has been found that the coated heat exchanger has better thermal resistance than the uncoated one and that the deposition time during the nucleation phase is proportional to the contact angle of the surface with the ice crystals.

Okoroafor and Newborough (2000) found that surfaces coated with hydrophilic substances of crosslinked structure reduced the pore ice growth rate from 10% to 30%. According to Dyke and Betz (2014) the results obtained from the reduction in the rate of growth of frost from the use of coatings consisting of hydrophobic or hydrophilic substances can vary considerably since these substances are dependent on surface roughness operating conditions.

Liu *et al.* (2006) tested an ink consisting of the mixture of polymeric and hydrophilic substances in an attempt to retard nucleation and minimize the growth of the ice crystals on the coated surface. Half of a metal plate was coated with this paint and parameters such as surface temperature, ambient temperature and relative humidity were monitored. The results obtained showed that the coating is effective in delaying the formation of frost, where there was a 40% reduction in the thickness of the ice layer in the coated part of the plate and there was also a delay of 15 minutes at the beginning of the nucleation stage.

Liu *et al.* (2007) repeated the previous experiment and evaluated the formation of frost on a paraffin coating as a hydrophilic agent and found that the ice sheets formed on this surface were weak facilitating their manual removal.

Kim and Lee (2011) tested the influence of hydrophobic and hydrophilic coatings on frost formation and compared the results obtained with uncoated plate results and observed that the coatings tested provided a delay on both surfaces, but on the hydrophobic surface the effect is on the hydrophilic surface the ice sheet is thinner and its density is higher.

Liu *et al.* (2016) experimentally investigated the frost formation on a copper plate at cryogenic temperatures, around  $-165\text{ }^{\circ}\text{C}$ . The authors' argument for testing at cryogenic temperatures was based on the fact that most of the studies conducted on the occurrence of this phenomenon are based on ordinary negative temperatures, just below  $-10\text{ }^{\circ}\text{C}$ . They observed that at cryogenic temperatures the frost formation is intensified and the water droplets are more distant from each other on the deposition surface, where the deposition of the ice has been concentrated at some distinct points of the cold plate, not occurring uniformly. This study presented by Liu *et al.* (2016) is very important because it shows the influence of cold surface temperature ( $T_S$ ) on this phenomenon and leaves the questioning whether factors such as relative humidity ( $w_{\infty}$ ) and ambient temperature ( $T_{\infty}$ ), when elevated to extreme cases, can also present peculiar effects on the formed ice sheet.

This paper discusses the numerical study of the formation of frost on a flat plate, testing different types of coatings on the surface of the plate, in an attempt to minimize this phenomenon. This study also show an analysis of the factors that influence the formation of frost in heat exchangers, based on numerical simulations of the flow of moist air on the cooled surface and also provides a comparison between the results obtained for the different types of coatings used in the numerical simulations.

## 2. STAGES OF FROST FORMATION

This section presents concepts necessary in the understanding of the mathematical model used in numerical simulations, but before this one must emphasize the difference between ice and frost, these concepts do not refer to the same substance, since they have different structures and physical properties. The frost is defined as the frozen mixture of air and water vapor, while ice is defined as the solid state of the water. Ice is the result of phase change where water transitions directly from the liquid state to the solid state, the ice structure is generally massive and translucent making it almost always possible to see through it. While the frost is formed in the phase change where the water vapor passes directly into the solid state, thus creating its porous structure formed by irregular crystals of ice. The formation phenomenon can be divided into two stages which will be presented below using Fig. 1 as a guide.

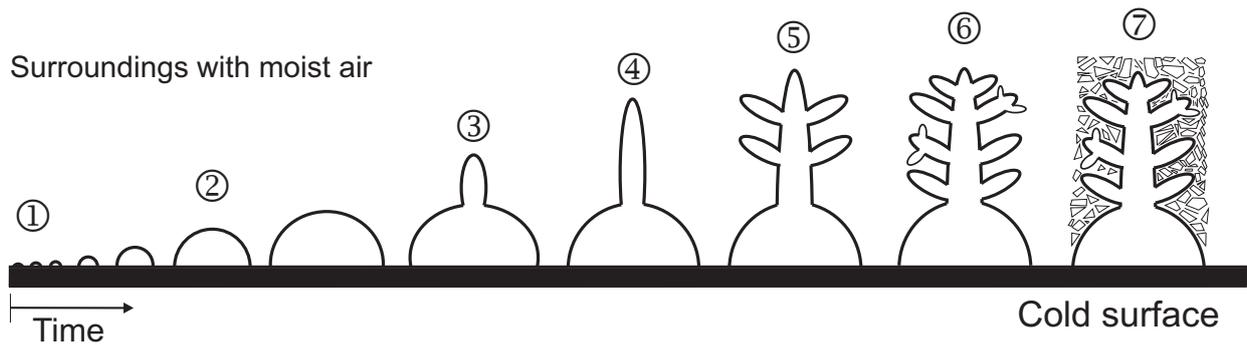


Figure 1. Stages of frost formation

## 2.1 Crystals growth period

The first formation stage is also known as the nucleation period (1) has a short duration and is characterized initially by the emergence of agglomerates of water vapor molecules which are relatively distant from one another, where at the end the freezing of the droplets occurs. During this short-lived phase, a considerable increase in the rate of heat transfer takes place, until more ice crystals are formed on these droplets (2), which are characterized by a growth in the vertical direction, at a constant rate, meanwhile the same ice crystals also grow in the lateral direction. This stage comes to an end when a thin, rough layer of porous ice is formed on the deposition surface.

## 2.2 Period of growth of the porous ice layer

From the thin, rough frost layer formed at the crystal growth stage the process of deposition of ice on the surface continues until the surface energy of the ice droplets no longer supports the adhesion of new molecules, thus creating new nucleations (3) and (4) on the previously formed layer. These new adhesions continue to grow and parallel to this, new branches arise on them as the demand for surface energy is increasing to support its structure.

This stage continues while the crystals are becoming more and more branched (5) and (6), forming a uniform porous layer due to the branches present in the ice crystals. As mass transfer intensifies, while the pores are filled with moist air, the heat transfer rate falls proportionally to this intensification of the deposition, in this way the porous ice sheet begins to behave as a thermal insulation, making it difficult to heat transfer in this layer.

When the surface temperature of the frost approaches the triple point temperature of the water, the water vapor can not be further crystallized because the available surface energy does not provide new branches. Therefore in this latter step (7) a cyclic process of melting, freezing and growing will accelerate the growth of the frost layer.

The division of the growth stages presented in this work is a generalized approach to the formation of frost, where an individual approach to each situation is more effective, since the physical parameters involved must be considered as deposition surface geometry in addition to the environmental variables involved in this phenomenon.

## 3. METHODOLOGY

The work presented in the document was developed according to this following steps described below:

1. Adapt the mathematical model for the frost formation process, on flat surfaces, developed by Salinas (1996) for plates with different coatings;
2. Implement the mathematical model on the Python 3.6 programming language;
3. validate the numerical model from data available in the literature;
4. Investigate the influence of environmental parameters on the formation of frost. In this step, the influence of the surface temperature ( $T_S$ ), ambient temperature ( $T_\infty$ ) and air humidity ( $w_\infty$ );
5. Simulate numerically the growth of the frost layer for copper, aluminum and brass, through their respective coefficients of thermal conductivity, and from this simulate coatings constituted of wax and silica as agent minimizing this phenomenon.

#### 4. MATHEMATICAL MODEL

The mathematical formulation of the flat plate frost formation phenomenon used in the present paper was developed in the study of Salinas (1996) and Tao *et al.* (1993). Obtaining the equations that model this phenomenon will not be presented again, a complete detail of the obtaining of these equations can be seen in Salinas (1996). As already mentioned in the previous section the frost formation can be divided into two stages and each stage was modeled mathematically differently.

The equations of the first stage are obtained from the basic equations that govern the phenomenon of heat and mass transport. Considering the portion  $dr$  of Fig. 2(a), the energy and mass balance is carried out and through the energy equation the heat balance is carried out. Modeling gives the equations (1) and (2) presented on Tab. 1 that represent the mathematical equations of the first stage of the frost formation process, which is considered as one-dimensional. The boundary condition presented by Eq. (4) it means that on the surface of the flat plate the temperature of the ice surface is equal to the evaporation temperature.

Table 1. Basic equations of the mathematical model.

First stage equations	
Energy equation	$\rho_{\beta} c p_{\beta} \frac{\partial T}{\partial t} \frac{\pi}{4} d^2 dr - \rho_{\beta} h_{sg} \frac{\pi}{4 dt} \left[ \left( d + \frac{\partial T}{\partial t} \right)^2 - d^2 \right] dr = q_r + q_{conv} - q_{r+dr} \quad (1)$
Diffusion equation	$\rho_{\beta} \frac{\partial d}{\partial t} = 2 h_m (w_{\gamma} - w_{\beta}) \quad (2)$
Boundary conditions	$r = 0 \longrightarrow d = d_0 \quad (3)$
	$d = \delta \longrightarrow T_S = T_{evaporation} \text{ and } \frac{\partial d}{\partial r} = 0 \quad (4)$
Second stage equations	
Energy equation	$\rho_{\beta} c p_f \frac{\partial T}{\partial t} + \dot{m} h_{sg} = \frac{\partial}{\partial r} \left( k_{eff} \frac{\partial T}{\partial r} \right) \quad (5)$
Energy equation of the continuity of the ice phase $\beta$	$\frac{\partial \varepsilon_{\beta}}{\partial t} = \dot{m} = w - w_{sat} \quad (6)$
Energy equation of the continuity of the ice phase $\gamma$	$\frac{\partial \varepsilon_{\gamma}}{\partial t} = \frac{\partial}{\partial r} \left( D_{eff} \frac{\partial w}{\partial r} \right) \quad (7)$
Boundary conditions	$h_m (w_{\infty} - w_{\delta}) = D_{ef,\delta} \frac{\partial w}{\partial r} + \rho_{f,\delta} \quad (8)$
	$h_S (T_{\infty} - T_S) = k_{ef,\delta} \frac{\partial T}{\partial r} - \rho_{f,s} \frac{\partial \delta}{\partial t} \quad (9)$
	$r = 0 \longrightarrow T_S = T_e \longrightarrow \frac{\partial \varepsilon_d}{\partial r} = 0 \quad (10)$

In the second phase where the crystallization occurs the ice is considered as porous, increasing the complexity of the modeling, consequently the governing equations for this stage was obtained from heat and mass balances in control volumes. By specifying a volume element  $\Delta V$  within the porous medium as shown in Fig. 2(b), equations (5), (6) and (7) are obtained.

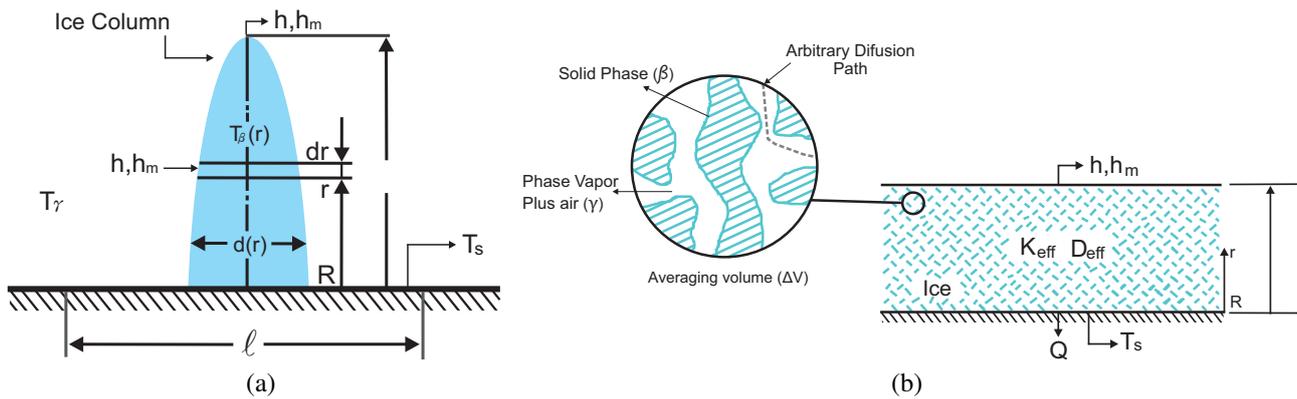


Figure 2. Comparison of frost growth  
Source: Adapted from Tao *et al.* (1993).

The mathematical modeling of this phenomenon was implemented in the Python 3.6 programming language using the finite difference method. To develop a discretization was used the finite difference centered method in the derivatives in the space and in the intermediate points, with the implicit formulation for the time. Using fixed mesh properties values are interpolated for each new boundary position through the spline method. All the differential equations were solved through the relaxation method, by means of iterations until a difference of  $10^{-5}$  was obtained between the values of the variables in two successive iterations.

## 5. RESULTS AND DISCUSSION

The modeling of the ice formation process on flat surface exposed at temperatures below  $0\text{ }^{\circ}\text{C}$  and wet air flow was performed considering the division of the phenomenon into two stages, as previously described. The main parameters influencing these results are the initial conditions chosen to initiate the modeling. Here only the environmental parameters were modified for each simulation. Parameters such as air velocity ( $v_{\infty}$ ), cold surface temperature ( $T_S$ ), ambient temperature ( $T_{\infty}$ ), relative air humidity ( $w_{\infty}$ ) and the coefficient of thermal conductivity ( $k$ ) for each numerically simulated material.

Heat exchangers used in refrigeration systems are usually made of materials that have high thermal conductivity like aluminum, copper or brass. The main coatings used to retard the growth of frost are silica and wax. The coefficients of thermal conductivity ( $k$ ) used in this study are shown in Tab. 2.

Table 2. Thermal Conductivity Coefficients.

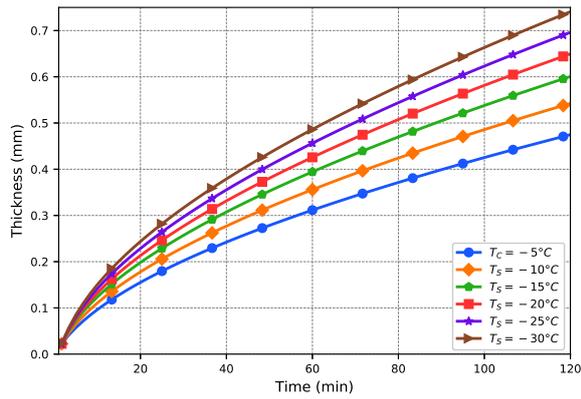
Material	k [W/mk]
Aluminum	204.0
Brass	26.0
Copper	386.0
Silica	1.5
Wax	0.25

Source: ASHRAE (2009).

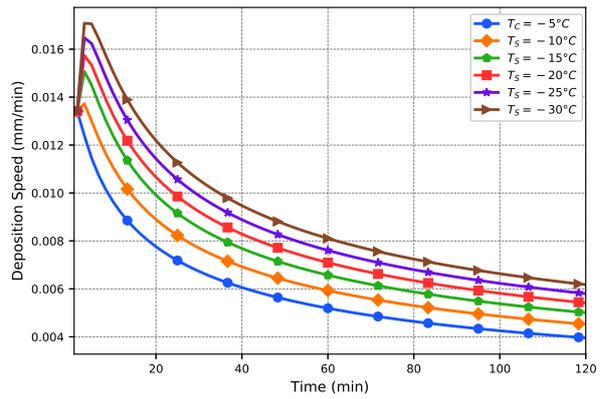
### 5.1 Flat plate coated with wax

In Fig. 3 the results obtained from the simulation are presented considering a plate coated with wax. Figure 3(a) shows how the frost thickness behavior can be influenced when the surface temperature of the plate is varied. It may be noted that the lower the surface temperatures the greater the thickness of the ice layer that forms over time, this is due to the higher temperature gradient which causes as a consequence a greater thermal exchange between the surface of the frost and the air flow, in this way more crystals settle on the surface forming the porous structure and thus increase its thickness.

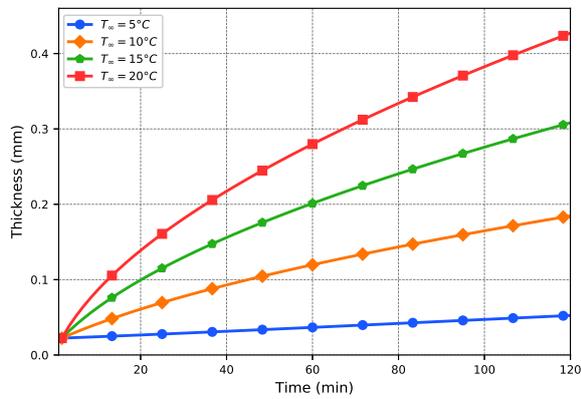
Figure 3(b) shows the variation of the rate of deposition of the frost on the wax coated surface according to the deposition surface temperature. It may be noted that as the plate temperature decreases the deposition rate, the porous ice on the coated plate increases over time. It is also possible to observe a high rate of deposition in the first minutes of this stage, which decreases over time. From the Fig. 3(a), it is observed that as the temperature of the cold surface ( $T_S$ ) is varied this variation affects the thickness of the ice sheet. Based on this, Fig. 3(c) shows how the behavior of the frost thickness is influenced when the ambient temperature ( $T_{\infty}$ ) around the cooled plate is varied.



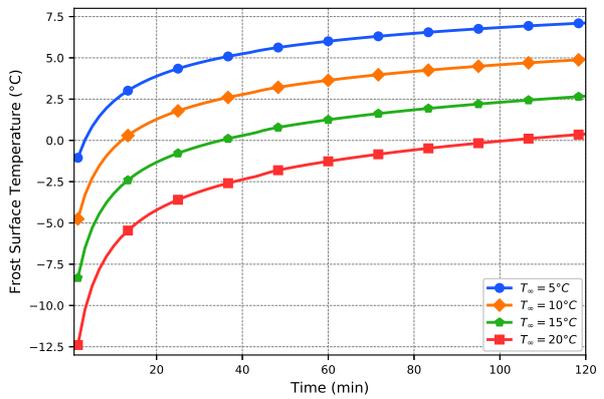
(a)  $T_{\infty} = 22^{\circ}C$ ,  $w_{\infty} = 60\%$ ,  $v_{\infty} = 0.5\text{ m/s}$



(b)  $T_{\infty} = 22^{\circ}C$ ,  $w_{\infty} = 60\%$ ,  $v_{\infty} = 0.5\text{ m/s}$



(c)  $T_S = -5^{\circ}C$ ,  $w_{\infty} = 60\%$ ,  $v_{\infty} = 0.5\text{ m/s}$

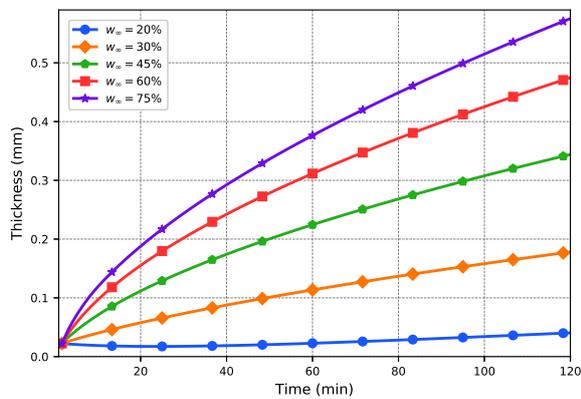


(d)  $T_{\infty} = 22^{\circ}C$ ,  $w_{\infty} = 60\%$ ,  $v_{\infty} = 0.5\text{ m/s}$

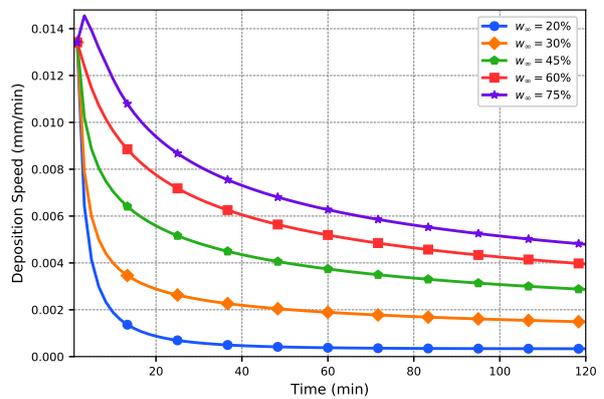
Figure 3. Comparison of frost growth properties on a wax coated plate under different conditions

From the results shown in Fig. 3(a) and Fig. 3(c) it can be observed that the thickness of the ice layer can be related to the temperature difference between the cold surface and the environment around it. The results indicate that the smaller the temperature difference between ( $T_S$ ) and ( $T_{\infty}$ ) the smaller the ice layer formed and the larger that difference, greater the thickness of the ice layer which forms over time.

An important parameter evaluated in the simulation is a surface temperature of the ice sheet which is shown in Fig. 3(d). The results show a rapid growth of the surface temperature of our current stages at this stage until growth is slowing down as the time passes. The surface temperature is one of the most sensitive variables used in the modeling, it is used in determining the flow of heat that is going through the ice sheet and the energy balance of the system.



(a)



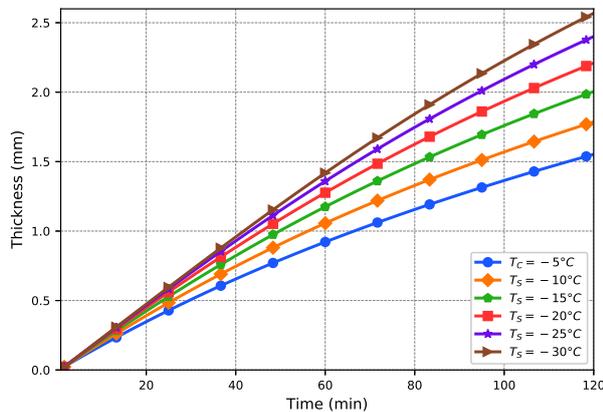
(b)

Figure 4. Comparison of frost growth properties on a wax coated plate varying the relative humidity with the parameters:  
 $T_{\infty} = 22^{\circ}C$ ,  $T_S = -5^{\circ}C$ ,  $v_{\infty} = 0.5\text{ m/s}$

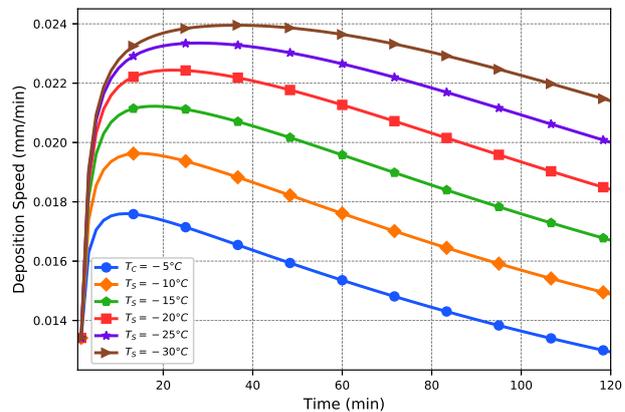
Figure 4(a) shows how the variation of the ambient humidity ( $w_\infty$ ) affects the growth of the frost layer on the cooled plate. It is observed that the higher the relative humidity the greater the frost thickness, this is explained by the increase of water vapor entering the layer and this consequently increases the thickness of the ice layer that soon increases its density as well. And as expected the lower the humidity in the environment the smaller the thickness of the layer because there are no large amounts of steam available to form a thick layer of ice on the plate. One way to reduce frost formation is to control the increase in humidity in the environment. Figure 4(b) shows the influence of the environmental humidity variation on the deposition rate. From the results it can be seen that the higher the relative humidity of the environment the greater the rate of deposition of the frost on the coated plate over time. Once again a high deposition velocity is noticed in the first minutes of this stage, which decreases as the simulation occurs.

## 5.2 Flat plate coated with silica

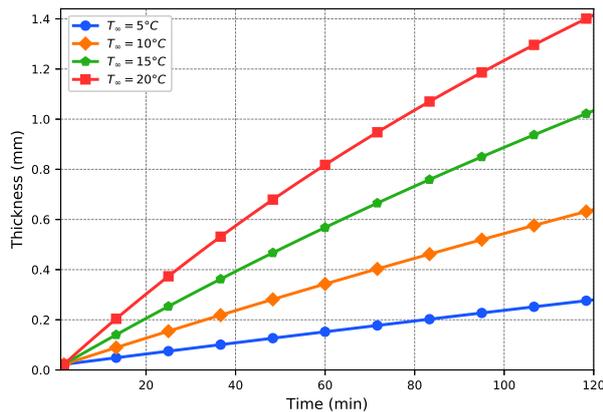
In Fig. 5 the results obtained from the simulation are presented considering a plate coated with silica. In Fig. 5(a) the results obtained from the thickness of the frost layer to the silica coated plate, when varying the surface temperature of the plate ( $T_S$ ) are presented. From this result, one can note the difference in ice sheet thickness when comparing different materials. The results obtained for the frost deposition rate for silica coated plate when varying the surface temperature of the plate ( $T_S$ ) are shown in Fig. 5(b). Here again the deposition velocity at the beginning of the simulation is high in the first minutes and then decreases as the simulation occurs.



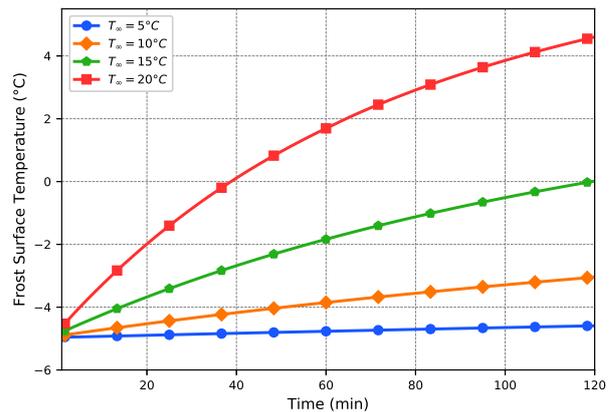
(a)  $T_\infty = 22^\circ\text{C}$ ,  $w_\infty = 60\%$ ,  $v_\infty = 0.5\text{ m/s}$



(b)  $T_\infty = 22^\circ\text{C}$ ,  $w_\infty = 60\%$ ,  $v_\infty = 0.5\text{ m/s}$



(c)  $T_S = -5^\circ\text{C}$ ,  $w_\infty = 60\%$ ,  $v_\infty = 0.5\text{ m/s}$



(d)  $T_S = -5^\circ\text{C}$ ,  $w_\infty = 60\%$ ,  $v_\infty = 0.5\text{ m/s}$

Figure 5. Comparison of frost growth properties on a silica coated plate under different conditions

Figure 5(c) shows the variation of the thickness of the ice sheet according to the variation of the ambient temperature. Here again the results indicate that the smaller the temperature difference between ( $T_S$ ) and ( $T_\infty$ ) the smaller the ice layer formed over time. In Fig. 5(d) the results are presented for the surface temperature of the frost, here again the results show a rapid rise in surface temperature in the first few minutes of this stage until growth slows down as time goes by. However, a greater variation in frost surface temperature is observed for the silica coated plate than for the wax coated plate. The variation is very abrupt when compared to the case presented in Fig. 3(d). Figure 6(a) shows how the variation of the ambient humidity ( $w_\infty$ ) affects the growth of the frost layer on the cooled plate. As expected it is observed that

the higher the relative humidity the greater the frost thickness. Figure. 6(b) shows the influence of the environmental humidity variation on the deposition rate. The velocity variation on the silica coated plate is much sharper than the wax coated plate when the relative humidity is varied, a high deposition velocity is noticed in the first minutes of this stage which decreases as the simulation occurs.

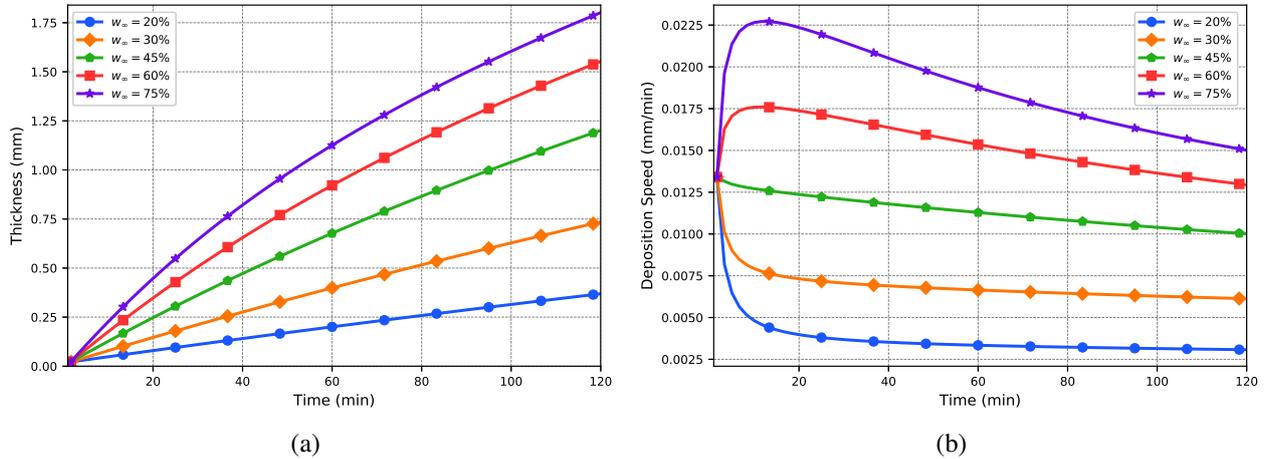


Figure 6. Comparison of frost growth properties on a silica coated plate varying the relative humidity with the parameters:  $T_\infty = 22^\circ C$ ,  $T_S = -5^\circ C$ ,  $v_\infty = 0.5 m/s$

### 5.3 Analysis of results

Figure 7(a) shows the thickness of the ice sheet for all materials numerically simulated in this study. It is observed that of all the simulated materials, for the considered environmental parameters, the wax presents the thinner ice sheet with a thickness of approximately  $0.5 mm$ . The silica also has a thin layer of ice about  $1.5 mm$ . Aluminum, copper and brass are the materials most used in the manufacture of heat exchangers in commercial refrigeration. It is observed that the aluminum and brass surfaces, which is a metallic alloy composed of copper and zinc, presented very similar results for the conditions of this simulation a thicker layer of ice formed on these materials having a thickness of more than  $2.5 mm$  for the layer of ice formed on the surface of the plate. The results indicate that among all the materials tested in this simulation the wax is more effective containment of ice sheet growth under the conditions mentioned in Fig. 7(a).

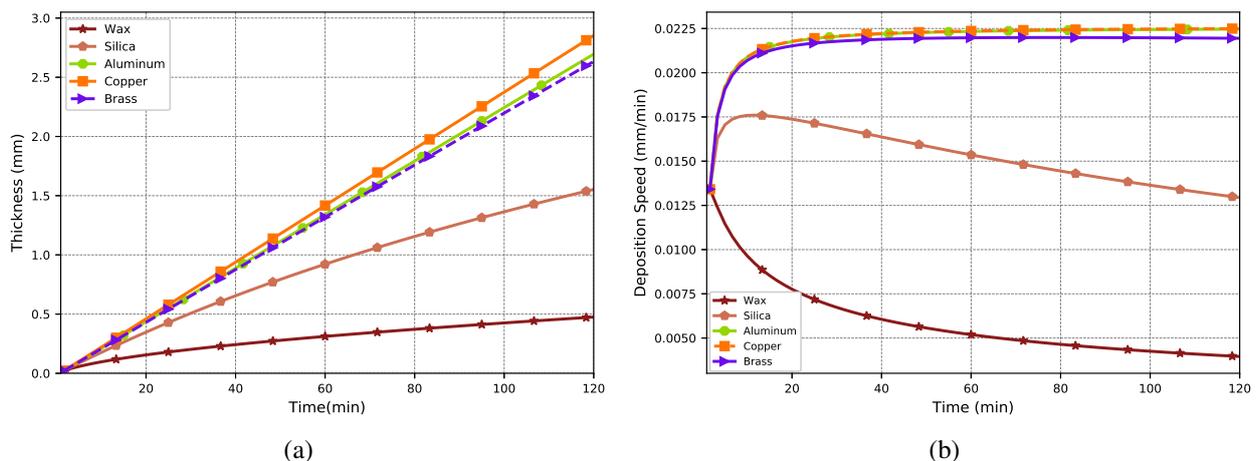


Figure 7. Comparison of frost growth properties on a aluminum, copper and brass coated plate with the parameters:  $T_\infty = 22^\circ C$ ,  $T_S = -5^\circ C$ ,  $v_\infty = 0.5 m/s$ ,  $w_\infty = 60\%$

It is possible to observe a relation between the coefficient (k) and thickness of the porous ice layer, a thickness increase, in this simulation, as (k) assume higher values. Figure 7(b) presents a comparison of the deposition rate of the frost layer for the materials tested in this study. This result is very interesting because it shows that for materials with higher thermal conductivity the deposition of the ice crystals runs at a higher speed than the materials of low thermal conductivity, it is observed that the deposition occurs more quickly for the copper and the aluminum and more slowly for the wax and the

silica. It is important to note that the rate of deposition does not start at zero, since we consider only the second stage of formation in this result, because as mentioned earlier the first stage is of very short duration.

Figure 8 shows a comparison of the surface temperature of the frost layer. It is understood that wax and silica have higher surface temperatures than aluminum, copper and brass. This result apparently reflects directly on the thickness of the formed ice layer, since the higher the frost surface temperature the smaller the thickness of the layer formed.

This result is essential on determining the flow of heat through the ice sheet and in the energy balance of the system. This information will not be calculated here because they are not the objective of the present study.

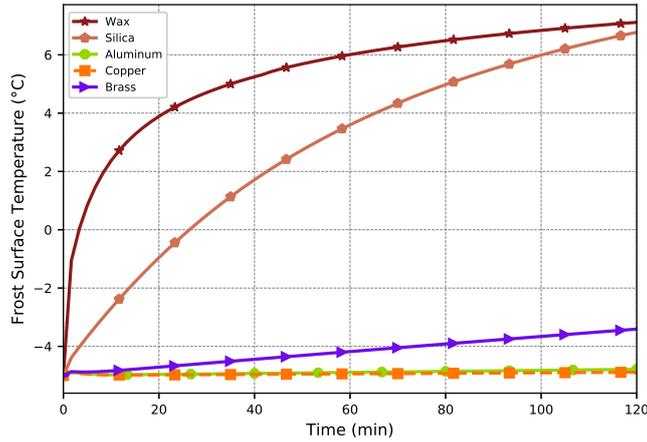
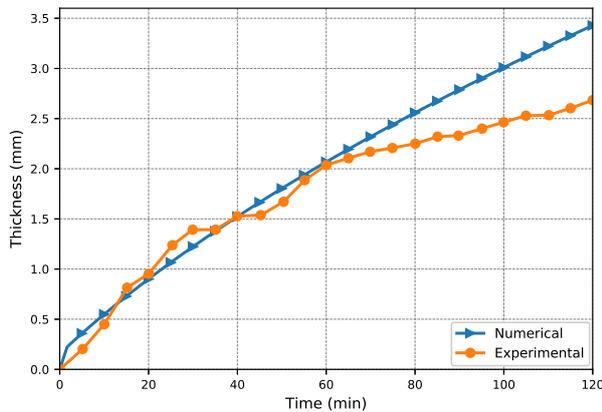


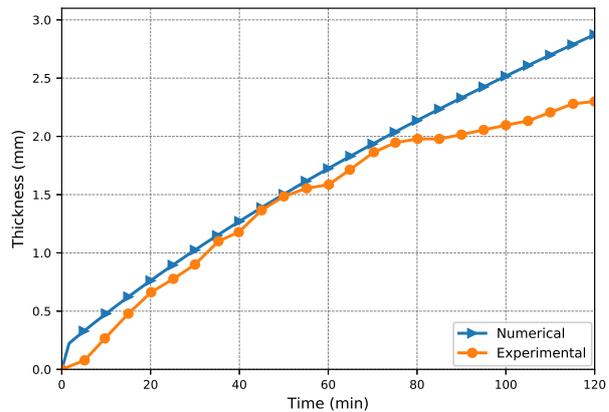
Figure 8. Frost surface temperature for different coatings with the parameters:  $T_{\infty} = 22 \text{ }^{\circ}\text{C}$ ,  $T_S = -5 \text{ }^{\circ}\text{C}$ ,  $v_{\infty} = 0.5 \text{ m/s}$ ,  $w_{\infty} = 60 \%$

#### 5.4 Validation of the numerical model

For a qualitative validation of the mathematical model used in this study, the experimental data obtained in the work of Liu *et al.* (2007) for a frost formation on a paraffin coated surface were used. Figure 9 shows a comparison between the numerical result and the experimental data, it can be observed that the mathematical model shows good agreement with the experimental result in up to 60 minutes and after that the model is not able to predict the results with a good precision in two situations with different environmental conditions as shown in Fig. 9(a) and Fig. 9(b). Of course that the Liu *et al.* (2007) experiment may be subject to errors, due to all the complexities involved in this process, even though the use of such data is sufficient to provide a satisfactory indication of the validity of the numerical model used.



(a)  $T_{\infty} = 21.0 \text{ }^{\circ}\text{C}$ ,  $T_S = -9.4 \text{ }^{\circ}\text{C}$ ,  $w_{\infty} = 68 \%$



(b)  $T_{\infty} = 20.4 \text{ }^{\circ}\text{C}$ ,  $T_S = -7.1 \text{ }^{\circ}\text{C}$ ,  $w_{\infty} = 63 \%$

Figure 9. Comparison between numerical results and experimental measurements of frost growth

The root mean square (RMS) technique was used to obtain an average of the absolute error between numerical and experimental data. The results presented in Tab. 3 confirm that in up to 60 minutes the mathematical model has a "low" error of around 6% taking into account all the complexities involved in this phenomenon. Between 60 and 120 minutes, the model considerably escapes reality with an average error of about 38% for both situations.

Table 3. Average of the absolute error between numerical and experimental data.

Time interval [min]	0 – 60	60 – 120	0 – 120
RMS of Fig. 9(a)	6.89 %	38.34 %	38.96 %
RMS of Fig. 9(b)	6.36 %	27.49 %	28.21 %

## 6. CONCLUSIONS

It has been shown numerically that the thickness of the frost sheet and the rate of deposition increase with the decrease of the surface temperature of the flat plate. The wax coated plates retarded the frost formation phenomenon more effectively than the other coatings. Moreover it is observed that the deposition occurs more quickly for the copper and the aluminum and more slowly for the silica and the wax due to the influence of the thermal conductivity on the deposition rate.

The mathematical model used was validated through experimental data available in the literature and it can be concluded that the numerical code used are able to predict the properties of frost ice sheet in up to 60 minutes with good accuracy. By testing only two coatings it was already possible to observe a considerable reduction in the thickness of the frost layer in both tests. Further studies testing new coatings are necessary due to the economic relevance of this problem in commercial refrigeration systems. The results obtained in the numerical simulation for the flat surfaces coated with different materials and the mapping of the thickness and speed of deposition around the flat plate were the contributions of this study.

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## 8. RESPONSIBILITY NOTICE

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