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Review

Literature Review of Frost Formation Phenomena on Domestic Refrigerators Evaporators

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Abstract: The topic of frost formation on the heat exchanger surface has been gaining interest since the late 1940s. Scientists and industrial engineers from many scientific and R&D units around the world have been trying to understand the nature of frosting and implement solutions to prevent such an unwanted phenomenon from having a significant impact on the performance of heat exchangers (such as a decrease in heat transfer efficiency, mechanical damage, and condensation risk). The aim of this article is to summarize the present state of knowledge dedicated to frost formation types and morphology, review, and discuss the most recent studies relevant to the challenge of frost formation, focusing on the evaporator of the domestic refrigerator. The different types of domestic refrigerators are summarized, as are the different types of evaporators inside them. Common methods of testing frost formation phenomena on the evaporator are revisited in this article, and the analysis of the most recent mathematical models is presented as well. The input and output parameters of these models are grouped, and a similar analysis is conducted for the CFD models.

Keywords: frost; domestic refrigerators; evaporator; CFD

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1. Introduction

Due to the constant tightening of the norms for domestic refrigerator energy labels, it is important to keep energy consumption low without compromising the performance of the refrigerator. The efficiency of the evaporator plays a key role in this process. With high humidity and a large temperature difference in the contact type evaporator, it is possible to observe the formation of a frost on a cold surface. Frost occupies air passages and reduces heat transfer from the cooling effect of the air. Unfortunately, such phenomena occur quite often in domestic refrigerators. Therefore, understanding, predicting, and preventing frost formation is such an important topic.

Frost is a thin layer of ice bound to a solid surface. It forms from water vapour that has an above-freezing temperature and encounters a solid surface whose temperature is lower than the freezing temperature of water [1]. It results in a phase change from water vapour (a gas) to ice (a solid) as the water vapour reaches the freezing point (see Figure 1).

Recently, a great increase of scientific interest has been observed in the topic of frost formation on the surface of a heat exchanger (see Figure 2). Such an increase may be related to the development of better and more precise measurement technologies (such as temperature, humidity, and heat flux sensors, high-speed infrared cameras, DAQ systems, etc.) and numerical models, which may help to better understand the heat transfer characteristics and the whole complexity of the frosting phenomenon.

The phenomenon of frost formation on solid surfaces is important in different fields of science and technology [2] (see Figure 3). It influences the operating conditions of the devices and impacts the physical processes, limiting their performance and efficiency.

Figure 1. Frost formation on a wooden surface [1].

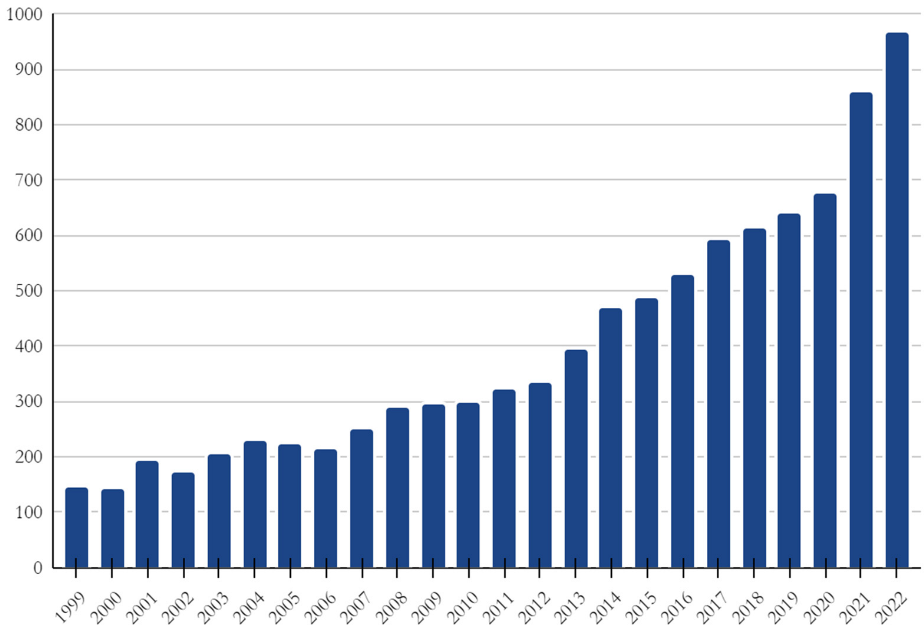


Figure 2. Increase in the number of articles dedicated to the topic of frost formation on the surface of heat ex-changer during the time from 1999 to 2022 (based on www.sciencedirect.com, accessed on 20 January 2023).

From the analysis of scientific articles published between 1999 and 2022 (based on www.sciencedirect.com, accessed on 20 January 2023), it can be observed that the most common frost formation issues affect refrigeration, aviation, and HVAC (heating, ventilation, and air conditioning) systems, machines, and devices.

ASHPs (air-to-air heat pumps) provide cooling and heating to conditioned spaces by transferring heat to ambient (outdoor) air. These heat pumps typically work according to the vapour compression cycle with two air-to-refrigerant heat exchangers (i.e., evaporator and condenser): one of them is placed in the conditioned space and the other outdoors [3]. When an ASHP is used for heating in winter, the problem of frost formation on the surface of its outdoor heat exchanger arises. The growth of the frost layer leads to deterioration of the working condition and attenuation of its heating performance [4–8].

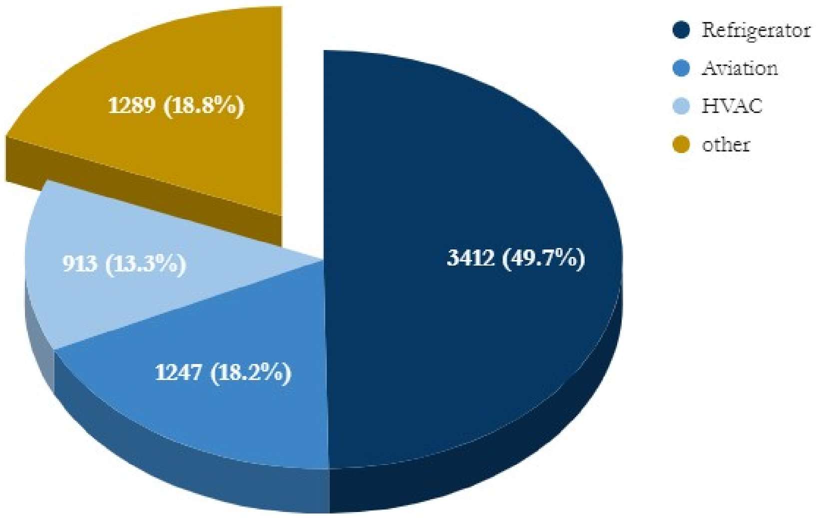


Figure 3. Percentage of articles dedicated to the topic of frost formation on the surface of heat exchanger in different fields of science and engineering, where: 49.7% is related to keywords 'Frost' + 'Refrigerator'; 18.8% is related to keywords 'Frost' + 'Aviation'; 18.2% is related to others; 13.3% is related to keywords 'Frost' + 'HVAC'.

Frost builds up when the temperature of the surface of the outdoor heat exchanger decreases rapidly and reaches a value lower than the dew point temperature (estimated for the temperature and humidity conditions of the incoming air).

As a result, condensation of the steam particles from humid air may be started, and the water vapour particles start to change the phase on the heat exchanger surface. Furthermore, if the ambient temperature drops even lower, the water droplets created after condensation on the coil surface may solidify on the heat exchanger surface, which can even block the air flow passage (see Figure 4).

The same can be observed in air conditioning systems (see Figure 5), whose operating principle is the same as in the case of heat pumps [9]. Frost accumulation within heat and energy recovery devices is among the biggest challenges energy/heat recovery ventilators (ERV/HRV) face. In climate zones with severe winter conditions, frost buildup can block the airflow channels of heat exchangers. This would create an additional drop in air pressure and may potentially damage the device or reduce indoor air quality [1].

Figure 4. Frost fully blocking heat pump. Reproduced with permission from [10], Elsevier, 2022.

Figure 5. Frost fully blocking air conditioning system. Reproduced with permission from [11], Elsevier, 2022.

The literature analysis indicates great scientific interest in this topic [12–15]. In fact, out of 561 articles relevant to efficiency problems in HVAC, almost half of these articles focus on the topic of ice accumulation on the surface of a heat exchanger (see Figure 6).

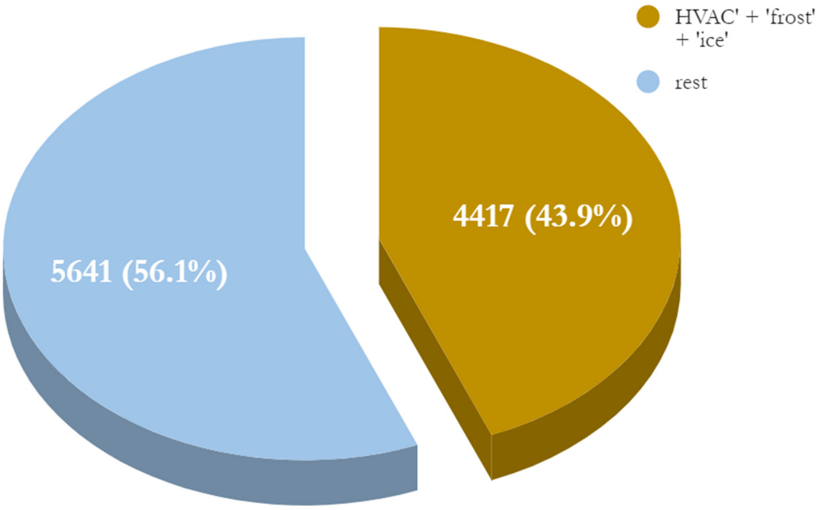


Figure 6. Percentage of articles including the word 'frost' or 'ice' after 'HVAC' comparing to the overall number of relevant to the energy issues in HVAC systems, during the period from 1999 to 2022 (based on www.sciencedirect.com, accessed on 20 January 2023).

Commercial aircraft operate in a wide temperature range, from −40 °C to +50 °C (during takeoff). The environmental control system (ECS) is used in pressurized gas turbine-powered aircraft. It is quite common to supply such aircraft with two refrigeration units, the air cycle machine (ACM), which operates at even more extreme conditions, that is, from subzero temperatures (the outlet temperature of the ACM turbine) to temperatures exceeding 100 °C (the inlet temperature of the ACM compressor). The main difference between such a refrigeration system and the evaporator of a domestic refrigerator is that the first one uses air as the cooling component instead of the refrigerant (cooling by convection, no phase change). Such operating conditions can cause condensation of water on the surface of the ACM machine, which can lead to further frost formation [16] (see Figure 7).

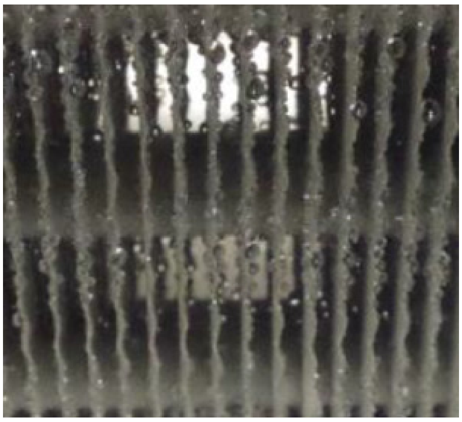


Figure 7. Frost formation on the ACM machine. Reproduced with permission from [16], Elsevier, 2022.

In the next part of this article, the authors pay attention to frost formation in domestic refrigerators.

In order to estimate the impact of frost formation on the heat transfer of the heat exchanger, it is required to understand how much of the air passage through the fin channels the first one is blocking. To do so, the thickness of the frost layer has to be known. There are different techniques to measure this parameter, which can provide a thickness value with low error (up to 0.2 mm [17]); however, it depends on the configuration of the evaporator (how small are the fin pitches and the possibility of installing certain measuring equipment). The methods can be divided into two categories:

- Direct;
- Indirect.

Both methods are based on observation of the phenomenon with a high-speed camera [18–21]. If resources are limited and/or research is conducted on a refrigerator with ducts, a small endoscope can be used to video record the process. However, it should be kept in mind that such devices usually have diodes on the camera, which, during long-term usage, will emit heat. On the contrary, photo capture helps to omit such an issue. For some studies [22,23], for this purpose, CCD cameras with digital microscopes were used, which recorded the frost image every 2 s.

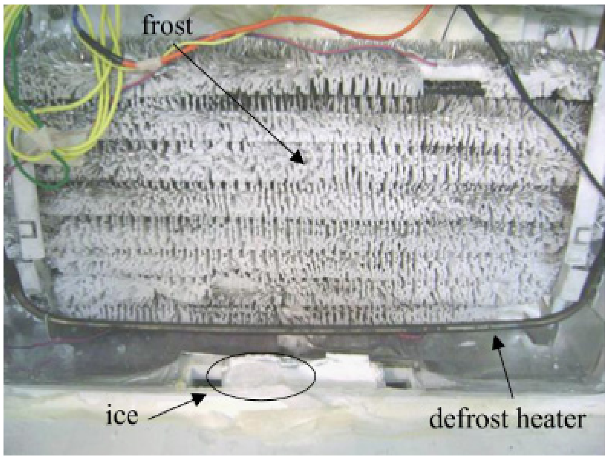
In order to obtain the thickness value, one of the direct methods suggests placing the ruler orthogonal to the surface of the fin [24–27] while recording with a regular digital camera. Other methods suggest a digital micrometer [28], which is more suitable for measuring the frost layer when the geometry is only considered on the flat fin.

Indirect methods suggest measurements of the frost thickness after the experiment is carried out, based on photographic data. This technique has been used for various investigations [29,30]. Furthermore, software with the AI tool was developed that automatically recognized the thickness value in the picture and provided the data as the value [31].

Currently, laser measurements are used for such purposes [32]. Disregarding the fact that they allow for high-precision measurements, the emitted heat may impact the process and even lead to the frost being melted [33]. To summarize, there are different techniques and methods to measure the frost thickness; each has its pros and cons; hence, all the details should be taken into consideration and the one should be chosen based on the type of experiment.

2. Frost Formation in the Domestic Refrigerators

In domestic refrigerators, the region where a flow of humid air covers the solid metal surface of the fin and tube evaporator is usually a potential area of risk of frost formation due to the relatively large temperature difference between the warmer air (+4 °C) and the colder surface of the evaporator (−25 °C). Due to the very small distance between the fins (ca. 4 mm [34]), a frost layer formed on the surface of the fin (see Figure 8) can, in the worst case, easily block the entire air passage. Thus, convective heat transfer from the warmer airflow to the colder surface of the evaporator may be significantly limited or even eliminated. Such effects can negatively impact the performance of the evaporator and therefore reduce the efficiency of the whole product.



(**a**) (**b**)

Figure 8. Clogged evaporator: (**a**) Vertical FoT (fin on tube) evaporator [35]; (**b**) Horizontal FoT evaporator. Reproduced with permission from [36], Elsevier, 2015.

In order to overcome such issues and remove the additional thermal resistance caused by the frost layer, evaporators are designed with a defrost heater [37,38] designed to melt the frost and improve heat transfer [39–41]. Such heaters consume additional energy and cannot always fully defrost the surface, leading to the formation of ice blocks that are stacked on the metal surface.

Preventing and reducing the potential risk of frost growth is another key point for improving product efficiency. Therefore, research on this topic is important. In domestic refrigerators, frost formation occurs mainly on surfaces whose temperature differs significantly from the temperature of flowing air. Therefore, a high temperature gradient occurs between the surface of the heat exchanger and the humid air. 90% of frosting cases are observed in the riskiest zone—very near the heat exchanger—because they usually correspond to the previously described conditions. However, frost can also be observed on the surface of the liner (the plastic part of the refrigerator chamber that is visible to the user) as well [36,37] (see Figure 9).

Figure 9. Frost formation on the surface of liner. Reproduced with permission from [37], Elsevier, 2011.

The frost formation on the surface of the liner is usually a random event that can be caused by low manufacturing quality (for example, damaged seals or gaps) or most likely due to physical deformation of the gasket and, as a consequence, infiltration of moist, warmer air into the RC (refrigerator compartment [38]). On the other hand, frost formation on the evaporator is a much more important problem. Therefore, the following part of this paper considers a review of articles focused on this area.

2.1. Frost Morphology, Classification, and Nucleation Development on the Heat Exchanger Surface

The variety of full natural crystals, their structure, shape, and sizes, have been described in detail and classified according to temperature in [39,40]. The authors of [41] were the first scientists to recreate frost crystals in the laboratory. From the perspective of frost formation on the flat surface of the heat exchanger, not all possible frost crystals should be considered due to the temperature and humidity range restrictions. The typical patterns for the evaporator surface are discussed below and visualized in Figure 10.

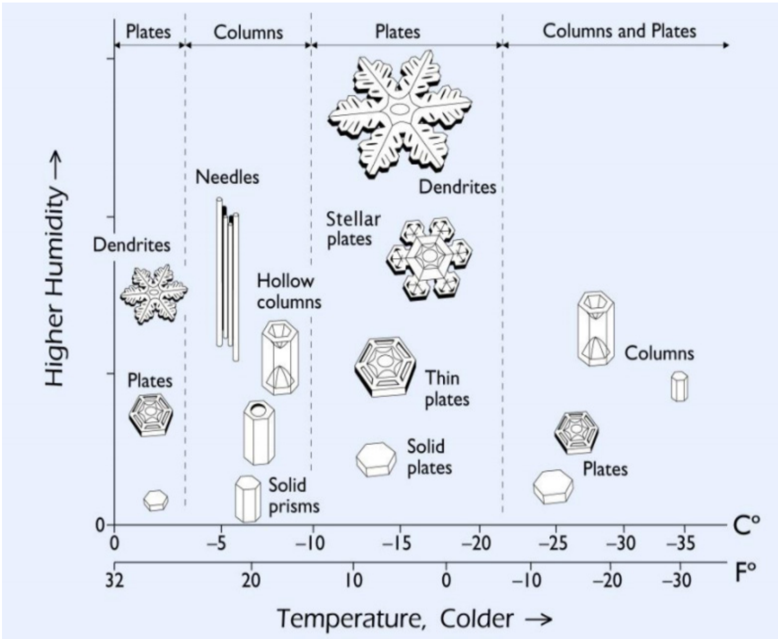


Figure 10. Frost flakes pattern depending on different temperature and humidity ranges. Reproduced with permission from [42], Elsevier, 2022.

In the diagram (see Figure 10), it is shown that the frost structure changes with increasing humidity and decreasing temperature. The simplest frost agglomerations, which begin to appear shortly after the temperature level reaches 0 °C, consist of regular plates, while with an increase in humidity, they obtain a more sophisticated shape called dendrites. The difference is in the cutouts on the edges for the higher humidity case. In general, the same trend can be observed for other temperature levels: the higher the humidity, the more complex the shape of a single frost flake.

In addition, another similarity (for the temperature ranges of −5–0 °C, from −10 to −20 °C) had been observed. The shape for both cases is similar to the plates, while for other temperature ranges (from −5 to −10 °C), the shape of frost corresponds more to columns: starting from solid prisms and hollow columns for lower humidity and changing to the needles with the humidity increase. With a further decrease in the temperature below −25 °C, the structure becomes even more complex and consists of both columns and plates. Having such a mixed type of structure leads to a point of porosity, which consequently results in changes in thermal properties (see Figure 11).

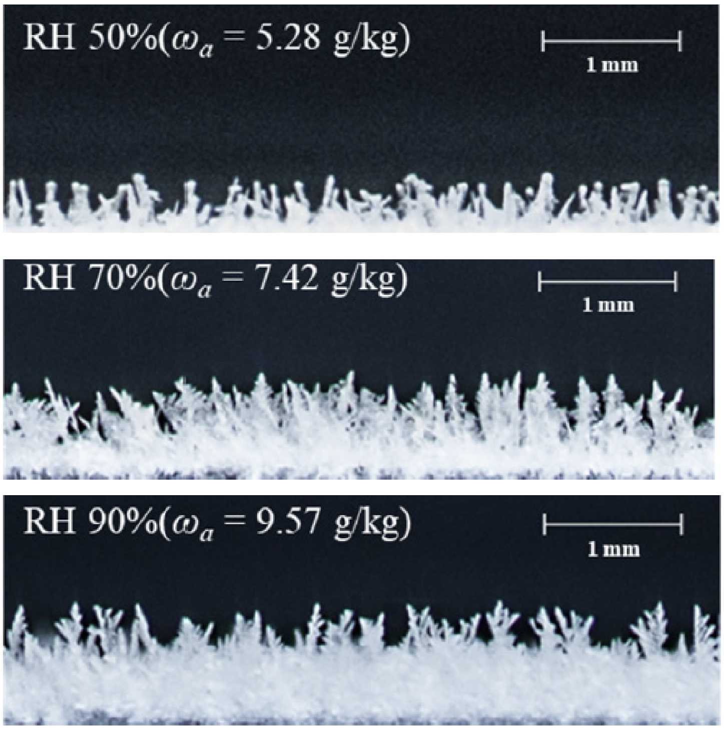


Figure 11. Frost pattern for different humidity ranges. Reproduced with permission from [42], Elsevier, 2022 [42].

Furthermore, it has been observed that the shape and properties of frosts evolve with time from a simple droplet to a fully developed hollow frost with an ice layer. First, such an observation had been made by [2]. Recent studies [43–46] reported and further postulated that there are 3 main periods of frost growth: the crystal growth period, the growth period of the frost layer, and the full growth period of the frost layer.

However, a more detailed classification (see Table 1) was proposed by [47,48], which has the only difference of an additional fourth period. Tao et al. [49] paid more attention to the early frosting process and divided the crystal growth period into two periods: the drop-wise condensation period and the solidification and tip growth periods.

Table 1. Frost growth periods change with time. Reproduced with permission from [50], Elsevier, 2022.

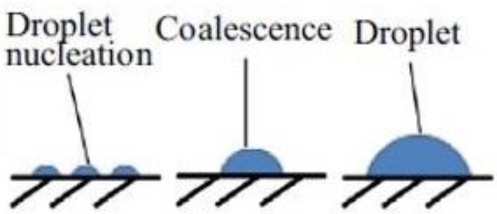
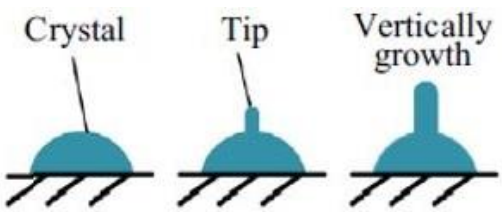
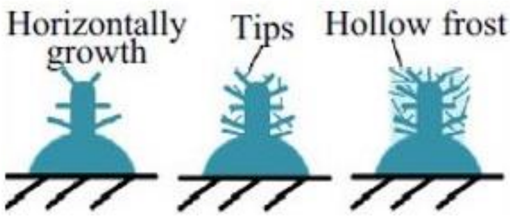
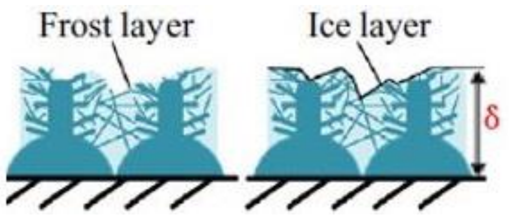
Schematic Illustration	Name of the Period
	Droplet condensation
	Solidified liquid tip-growth

Table 1. *Cont.*

Schematic Illustration	Name of the Period
	Frost layer growth
	Frost layer full growth

During the first stage, tiny droplets (condensation of water from the humid air) start to cover the cold surface.

During the second period (crystal growth), a slight 1-dimensional growth of rod-type crystals is observed [48]. With time, such crystals start developing in three dimensions. This is frost layer growth. After the frost layer is formed and its surface temperature reaches 0 °C, it starts melting, and thus the ice layer on top is formed.

This scenario occurs for the first frost formation in the evaporator in the fridge or after the evaporator has been completely cleaned of the ice and the surface has dried. However, if, after defrosting or restarting, such conditions are not fulfilled, the frost layer will develop in a different way (see Figure 12).

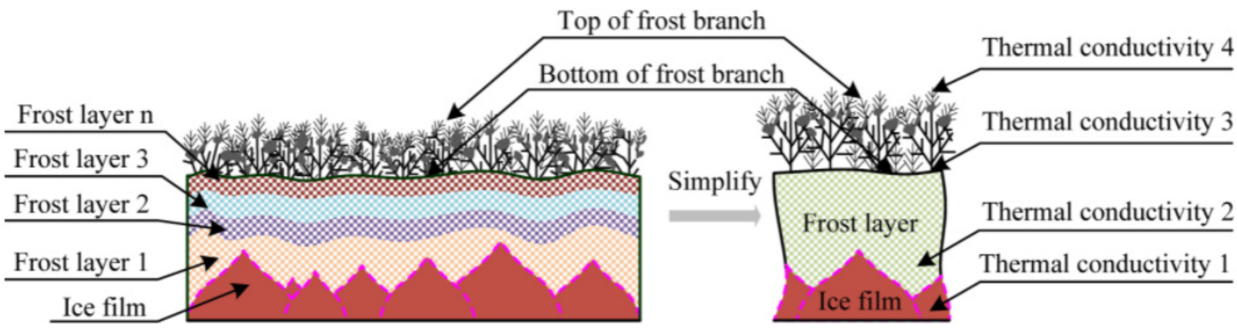


Figure 12. Morphology of frost formation on not properly clean heat exchanger surface [47].

The first layer with the higher density and lower thermal conductivity has a triangular shape with radiuses on the sides and is called ice film. Visualizing the freezing of a single drop of water was described in [43] and is presented in Figure 13.

It may appear after the water covers the cold surface and is not able to be removed, then it just solidifies on the surface, creating a very 'hard-to-clean' layer on the heat exchanger surface. On top of this layer, the frost starts to grow, which is also divided into a couple sublevels according to its height depending on the geometry and other thermal conditions.

The upper layer of frost (see frost layer n in Figure 12) is the most complicated; it consists of two groups: the bottom of the frost branch and the top one. Although they both have a porous nature, the porous coefficient and flow resistance will be different than those for the top layer.

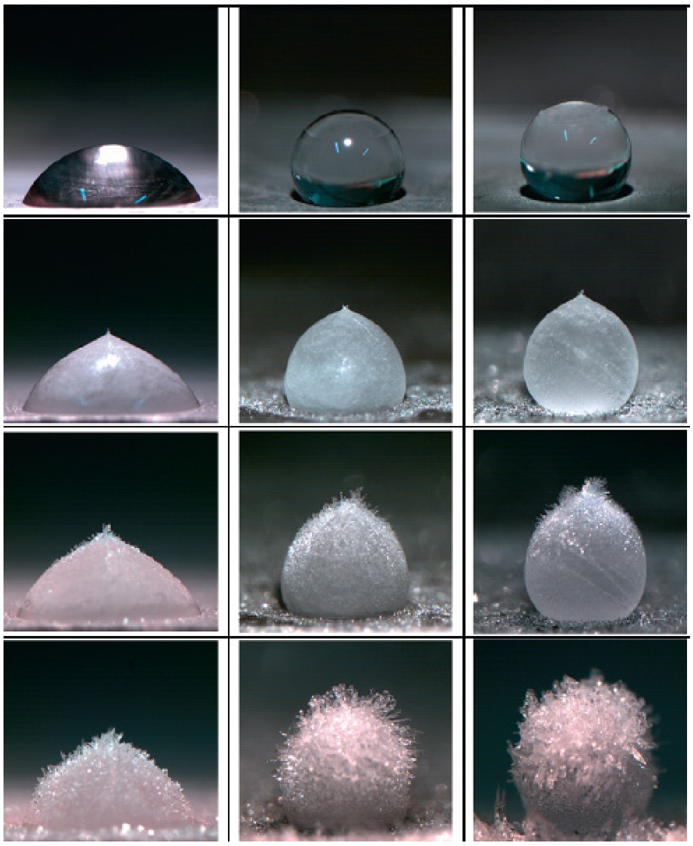


Figure 13. Water droplet freezing with farther crystal growth. Reproduced with permission from [43], Elsevier, 2022.

Based on the there-phase diagram (see Figure 14), frost formation is divided into 4 groups:

- neither frosting nor condensation;
- condensation;
- condensation frosting;
- sublimation frosting.

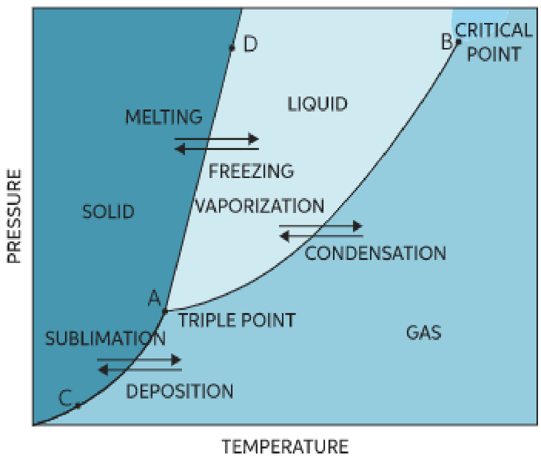


Figure 14. Phase diagram of water as a function of temperature and pressure [42], where A—triple point, B—critical point, C—sublimation/deposition, D—melting/freezing.

When the flow of moist, warm air passes over a cold surface, it can either transfer to liquid (condensing) or solidify (freezing). In the case where the cold surface has a lower temperature than the value of the dew point (point B) for the air but is still above the freezing temperature (triple point), condensation will occur.

On the other hand, if the surface temperature is lower than both the dew point and the freezing point, the moisture contained in the air will condense and solidify. Furthermore, if both the surface and dew point temperatures are below freezing, the air vapour can instantly sublimate into ice. This is the most common way for frost to form and occurs at the boundary between solid and vapour below the triple point, as shown in Figure 14.

If none of the above conditions are fulfilled, the area should remain free of frost or any condensation. In [51], it was reported that frost had been observed in two different types of fridges with a warmer compartment on the top. Another classification, based on the thickness of the frost, is presented in Figure 15.

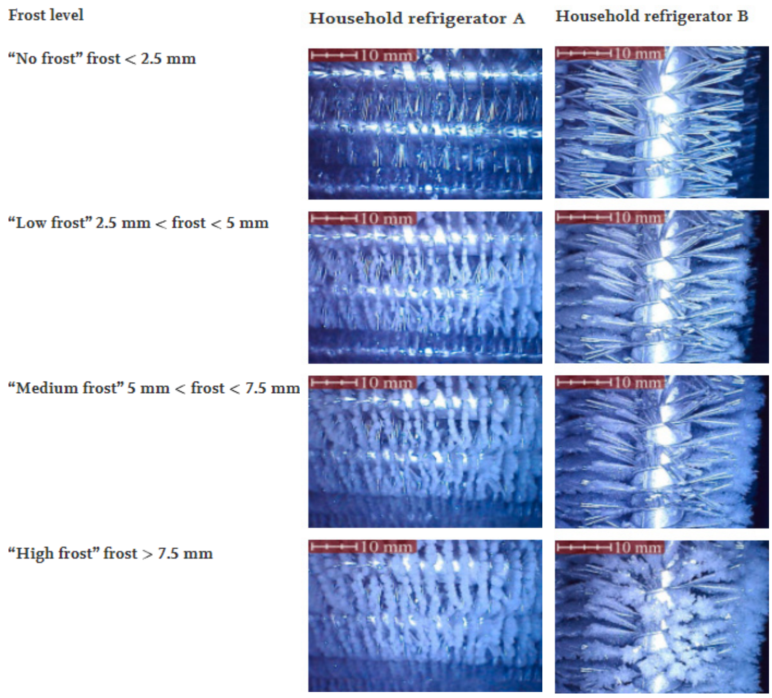


Figure 15. Frost layer growth on the evaporator of the domestic refrigerator. Visualization and thickness measurements. Reproduced with permission from [48], Elsevier, 2022.

2.2. The Early Research on Frost Formation Phenomena

The topic of frost formation on evaporators has been gaining attention in the scientific world for more than 100 years, starting with the first published articles dedicated to understanding the phenomena of ice generation and accumulation on different types of evaporators. Stoecker (1957) [52], Gatchilov and Ivanova (1979) [53], and Gates, Sepsy, and Huffman (1967) [54] were researching the frosting of fins on tube evaporators with different fin pitches, while studies by Lotz (1967) [55], Kondepudi and O'Neal (1989, 1990) [56,57] were dedicated to more sophisticated shapes such as rectangularly ribbed finned-tube coils, louvred and wavy fin configurations, and many other types. Some studies were concentrated in separate parts. For example, Barrow (1975) [58] was researching frosting phenomena only on the surface of flat fins, and Sami (1989) [59] was investigating standalone tubes in his research. A number of master's and PhD theses were dedicated to the topic of frost growth in such appliances as domestic refrigerators [60,61].

With time, technological progress allows for more detailed research with higher-resolution cameras and new types of sensors. Furthermore, this article is focused on the most novel studies conducted by different groups of scientists in the period from 2000 to 2023.

2.3. Most Recent Studies

All of the previously described investigations create a great base of knowledge about the driving mechanism and a basic understanding of the frost formation process and frost morphology, as well as the occurrence of heat transfer and thermodynamic processes.

The experiments related to frost formation that have been conducted to date have different conditions that are crucial to the process, such as, the inlet mass flow rate, temperature distribution, and humidity level. A wide range of articles have been dedicated to filling this knowledge gap. Hence, more recent articles can be grouped into 3 categories:

- Category 1: articles focused on the experimental investigation of frost formation phenomena. In such articles, the test stand and experimental conditions, measuring devices, experimental methodology, and output variables are described;
- Category 2: articles focused on the numerical description of the process. These types of articles describe the process of heat transfer analytically and present different mathematical modeling approaches, from the simplest algebraic equations to more sophisticated integral forms;
- Category 3: articles aimed at the simulation way of problem solving. In this category of articles are included papers in which CFD techniques are applied with the use of software such as Open FOAM/Ansys Fluent/Ansys CFX. These papers are usually describing boundary conditions, the chosen model, and the way of doing phase change modeling.

Most of the papers are written in a combined way (for example, with both experimental and numerical investigation), therefore, in further analysis, they may repeat in a couple categories.

2.3.1. Experimental Studies

The experimental setup is usually designed and implemented in a way that meets a certain experimental aim. Therefore, depending on the experimental objective, the test stand components may be different. From the article review, it can be seen that in most cases, the experimental setup to research frost formation on the evaporator consists of the following components:

- wind tunnel (which is applied to create a stable and uniform air velocity profile);
- tested element (which can be the full evaporator or a selected part of this heat exchanger, i.e., the fin/tube/fin channel);
- fan (to represent forced convection as it is happening in some refrigerators);
- humidifier or climate control chamber (to maintain a constant operating humidity level since it is one of the most important impact factors for frost growth) [62];
- cooling system (to maintain constant and stable heat removal from the surface of the tested element).

The results of experimental and numerical analysis aimed at understanding the most important parameters and the morphology of frost formed on simple geometry (i.e., flat and cylindrical shapes) are summarized and presented in [63] based on 382 test data points. Compared to a simple flat or cylindrical geometry, frost formation on the evaporator will also have important parameters and conditions similar to those driving the process.

Moreover, with increasing geometric complexity, additional parameters (such as the number of rows, type, and orientation of the evaporator, distance between the fins, and others) will play a role. Experimental investigations have been done for the purpose of better understanding the frost formation on evaporator, and these experiments are usually conducted in one of the following two ways:

- The evaporator or its part is located inside a wind tunnel, and humid air is blown through the test section with the help of a fan (see Figure 16);
- The evaporator is adjusted inside the refrigerator (see Figure 17).

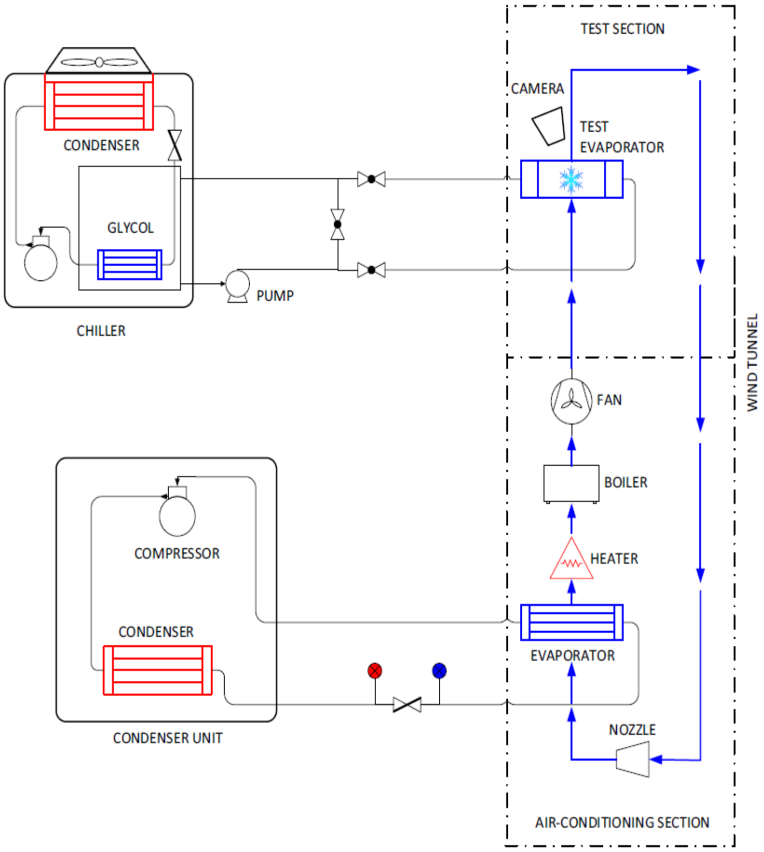


Figure 16. Schematic of the test setup. Where the blue color represents refrigerant (glycol) cycle and red—the air. Reproduced with permission from [64], Elsevier, 2021.

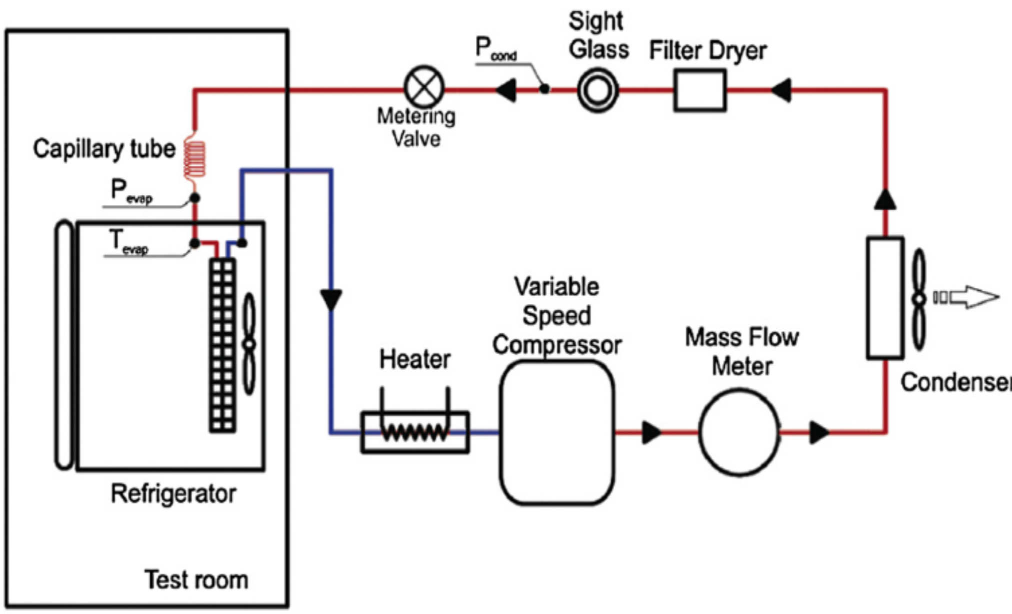


Figure 17. Schematic representation of the test setup. Reproduced with permission from [64], Elsevier, 2021.

The first group has an advantage due to its simplicity. In this design, the researcher can control more inputs, such as humidity level, flow velocity, and inlet temperature.

One of the earliest examples of such studies is presented in the work of Ogawa et al., 1993 [59]. It was dedicated to understanding frost patterns, and it led to the very important conclusion that frost should partly decrease at the leading edge of fins to reduce air pressure drop. Later, a few more authors studied the accumulation of frost in tube-fin evaporators designed for household appliances, among them Inan, Ozkan, Deng, and Zhang [65–70].

One of the latest publications was published by Silva [71] and is dedicated to the investigation of frost morphology. In turn, the works of Deng [69] and Zhang [70] concentrated on the efficiency of the evaporator under different frosting conditions. The experimental setups for all of the above-mentioned studies were very similar, with the main difference in operating conditions.

The second group of researchers uses the complete refrigerator. Surely, this type of research is much more complex in terms of the necessary equipment and requires more time for the process of thermal stabilization, nonetheless, it has its benefits. One of the benefits of this experimental approach is that the experiment is carried out using the real product under real operating conditions (for example, the air velocity profile in the chamber fully represents the operating conditions).

The importance of the velocity input has been verified by a couple experiments and mathematical models [63], and it has been shown to impact the frost growth rate and the frost profile. In refrigerators, the evaporator can be exposed to moist air that comes from the warmer compartment (in the worst-case scenario), which may be provided through the return duct or ducts (channels connecting the warmer and colder compartments). However, such ducts are usually located on the side walls, although they can be implemented on some models at the bottom of the warmer compartment.

Ducts may have different cross sections as well as a shape, which impacts the pressure drop distribution and hence the velocity of the air. The velocity profile may be impacted then and be not fully normally distributed, as is the case in a wind tunnel.

2.3.2. Mathematical and Numerical Models

Mathematical Models

As previously described in [58], most mathematical models of the fined evaporator are formed on the basis of a quasi-state regime. New models ([72–79]) have not yet proposed a different scheme.

Domains include two parts: air and frost, which are further divided into segments according to the geometry of the evaporator. The mass balance of the frost layer can be described by the following equation [65]:

$$m_f = \frac{d}{dt}\int_0^{x_f} \rho(x)dx \tag{1}$$

where

m_f—mass of frost
ρ—density of frost

The mass transfer from water vapour to frost is commonly estimated as the sum of two components: the mass transfer caused by the generation of new frost particles and the second one, the mass transfer forced by the growth of those crystals, which with time reduces the porosity of the frost layer as given by the equation [80]:

$$\varepsilon = \frac{\rho_f - \rho_i}{\rho_a - \rho_i} \tag{2}$$

where

ε—porocity
ρ—density of frost

On the other hand, mass flux can be described from the convective mass transfer coefficient using the Lewis analogy [65].

$$m_f = h_m(\omega_a - \omega_s) \tag{3}$$

where h_m—heat transfer coefficient between the air humidity and the frost.

In order to close the energy balance, such thermal properties as frost density and conductivity are taken mainly from studies in the past literature; however, in some articles (such as in [78]), different empirical coefficients are used for such purposes.

The analysis and comparison of mathematical models are presented and described in detail in [65].

Numerical Models

Numerical research and models, similarly to experimental research, can be divided into 2 categories:

- focused on the investigation of frost nucleus structure, composition, and growth rate.
  - on a flat, cold, horizontal [79] or vertical [80] surface;
  - on the surface of the coil [81], horizontal [82], or vertical [83], cylinder;
- The focus was on investigating frost formation that occurs on the surface of the heat exchanger or in the group of parallel fins [84,85].

A comprehensive review of the literature (based on more than 50 scientific publications published between the 1960s and 2010s) dedicated to different mathematical modeling approaches for frost formation occurring on simple geometric surfaces is presented in [86].

Refrigeration units, depending on the application, can be divided into 2 groups:

- Industrial cooling devices [87];
- Domestic appliances.

The first are designed for the storage and transportation of a large volume of meat, fruits, medicine, and other products that need to be preserved at a certain temperature level. Thus, such refrigerators are mostly those with larger capacity and/or higher volume (larger compartment design).

The second group meets the cooling needs of a family or a single person, and hence their sizes and power consumption are smaller. In this article, the focus is specifically on domestic refrigerators.

There are six main types of refrigerators that are mostly used for domestic purposes (see Table 2), depending on the door construction (1, 2, 3, and even 4 doors) and the location of the cooler compartment (freezer) (top/bottom). In each of the products, there is a cooling circle composed of the following main components: heat exchangers (evaporator and condenser), compressor, and expansion valve. In some models, there are two evaporators; in others, there is only one. Another difference is the presence or absence of the fan, which is used to generate the air flow passing through the evaporator unit and cooling the air (during the refrigerant phase change), which is then further distributed to reduce the temperature stratification.

The choice of model depends on the region (for example, in Europe it is the bottom/top freezer and the single-door fridge, according to [88], while in the USA it is most likely to find a French door or fridge in the kitchen).

In currently produced models, different types of evaporators are applied. Some of them are in direct contact with air, which is distributed further into the warmer compartment; others cover the liner (plastic part) externally and are not in direct contact with air. These evaporators are mostly covered with foam; therefore, the risk of frost formation on the surface of such an evaporator is rather remote. Therefore, in Table 3 are presented the evaporators of the domestic refrigerators that are in direct contact with humid air (thus having a risk of frost formation). Since the orientation of the evaporator and airflow inlets impact frost formation, they are separated in the table as different types.

Table 2. Most common types of the domestic refrigerators [89].

4 Doors	French Door	Side-by-Side	Single Door	Bottom Freezer	Top Freezer
					

Table 3. Types of evaporators used in the domestic refrigerators.

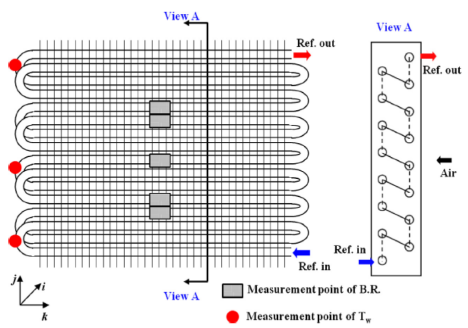
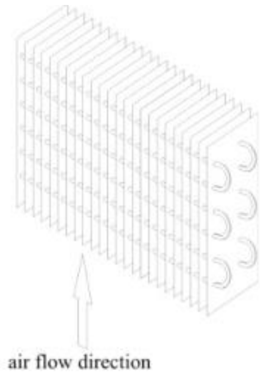
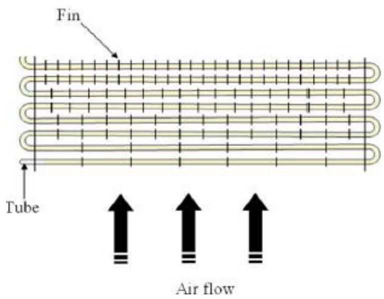
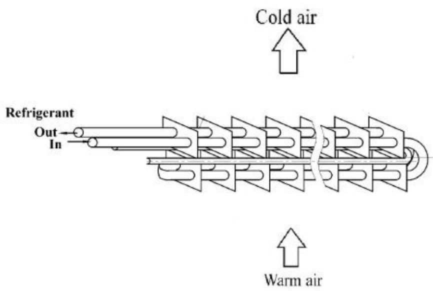
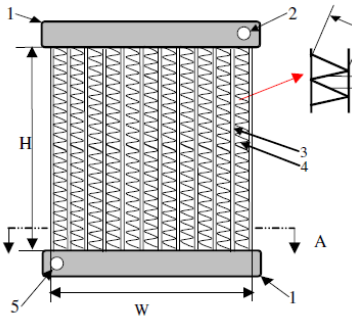
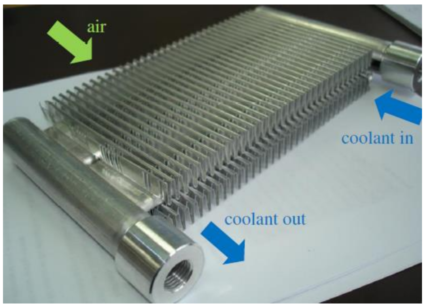
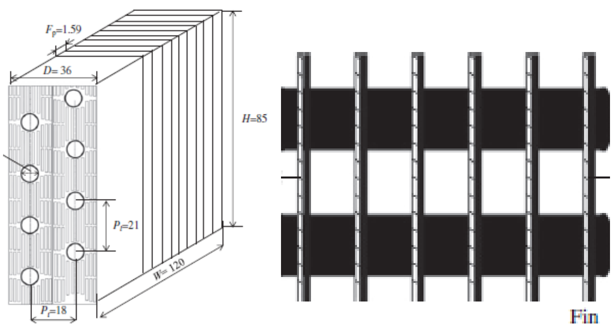
Schematic Drawing/Photo		Type of the Evaporator
 1 Reproduced with permission from [90], Elsevier, 2014	 2 Reproduced with permission from [36], Elsevier, 2015	1. Vertical FoT evaporator (air is blown through the larger surface) [90] 2. Vertical FoT evaporator with the flow coming from the bottom [91]
 3 Reproduced with permission from [92], Elsevier, 2006	 4 Reproduced with permission from [93], Elsevier	3. Horizontal FoT evaporator (air is blown through the smaller surface) [92] 4. Horizontal FoT evaporator (air is blown through the larger surface) [93]

Table 3. *Cont.*

Schematic Drawing/Photo		Type of the Evaporator
 5 Reproduced with permission from [94], Elsevier, 2010	 6 Reproduced with permission from [16], Elsevier, 2022	5. Wavy fin evaporator vertical (air flows through the larger surface) [94] 6. Wavy fin evaporator horizontal (air flows through the smaller surface) [16]
 7		7. Plate fin evaporator [95]
 8 Reproduced with permission from [96], Elsevier, 2012		8. Louvered Fin evaporator [96]

In Table 4, a classification of mathematical models that scientists used for their investigations of different types of evaporators that can be applied in domestic refrigerators is presented below. To give a better overview of this classification, Table 3 summarizes schematics and photographs of different types of heat exchangers that are referred to further in the classification. Furthermore, the most recent articles are discussed in which numerical studies are validated either by the experiment conducted by the same group of scientists or by the available experimental data from other scientific sources. Some of the models are also validated by CFD modeling (i.e., models in [76,91,97–106]).

Table 4. Input parameters of the articles dedicated to the numerical simulation of frost formation on the heat exchanger surface.

Reference	Year of Publication	t_{amb}	vel_{in}	φ	t_{cold}	Geometry
[100]	2005	0.0	0.8	80	−15 *	Evaporator type 2
[92]	2005	+5.0; +10.0; +15.0	1.0; 1.8; 2.5	75; 80; 85; 90; 95	−15; −25; −35	Evaporator type 3
[101]	2006	+5.0	flowrate 0.1 [m^3/s]	60	−12 *	Evaporator type 4
[94]	2007	−1.0	1.0; 2.0	80; 70	−10; −15 *	Evaporator type 5
[102]	2010	+1.7	1.0	72; 82; 92	−22	Evaporator type 1
[97]	2010	+10.0	0.6; 1.0; 3.0; 5.0	70; 80; 90	−20; −30; −40	Evaporator type 1
[91]	2010	−24.0; −18.0; −12.0	0.1; 0.4; 0.7	**	−31	Evaporator type 5
[103]	2011	**	***	75; 85	−5; −10	Evaporator type 5
[96]	2012	+3.0	flowrate 3.5 [m^3/s]	78	−10	Evaporator type 8
[104]	2013	+3.0; +5.0; +7.0; +11.0	1.5; 2.0; 2.5	75; 85; 95	−7; −11; −15	Evaporator type 1
[90]	2014	+2.5	***	90	−10	Evaporator type 1
[106]	2014	+2.0; +0.5	flowrate 5.8; 7.8 [m^3/s]	84; 94	−10 *	Evaporator type 1
[78]	2015	−11.0; −18.0	0.0; 0.1	20; 25; 30	−36; −38	Evaporator type 2
[107]	2015	−4.0; −8.0; −12.0; −16.0	***	74; 85	−5; −10	Evaporator type 6
[98]	2018	+0.7	1.7	85	−8	Evaporator type 7
[75]	2021	+2.0	1.6	82	−10	Evaporator type 1
[16]	2022	+25.0	1.0; 1.5; 2	95 and above	−10 *	Evaporator type 6
[76]	2022	−5.0; 0.0; +2.0; +5.0	1.0; 1.5; 2	70; 80	−5; −10; −20	Evaporator type 5
[77]	2023	+2.0; +4.0	2.8	60; 84	−20 *	Evaporator type 1

* Temperature of the refrigerant at the inlet, for all the references except [77], where it is the temperature of the pipe. ** Not given. *** Based on the fan curve.

For each numerical model, the most important input parameters are noted, such as:

- vel_{in}, [m/s]—velocity of air blowing from the evaporator;
- t_{amb}, [°C]—temperature of the airflow blowing the evaporator;
- vel_{in}, [m/s]—velocity of air blowing from the evaporator;
- φ, [%]—relative humidity level of the air;
- t_{cold}, [°C]—temperature of the cold surface;
- geometry—type of evaporator (accordingly to Table 3)

When the analysis is done, it is possible to observe that most studies have been conducted on FoT-type evaporators with flat, long fins (see Figure 18).

Operating conditions vary for all models. For almost all articles (except [91]), the humidity level is quite high (above 70% relative humidity), which perfectly corresponds to the operating conditions of domestic refrigeration. The value can vary depending on the region of location (for example, a lower humidity level (60–75%) should be expected in West European countries, while for India and Brazil the value can easily reach even 90%). The surrounding temperature has a large range (almost 50 degrees)—from very low (the most extreme case, [97,107,108]) −24 °C up to +25 °C for [16]. The inlet air velocity variation was from almost 0 (natural convection, without fan or fan off condition) up to 3 m/s (except for the case described in [109], in which simulations were carried out for even more aggressive conditions, where the speed had reached 5 m/s).

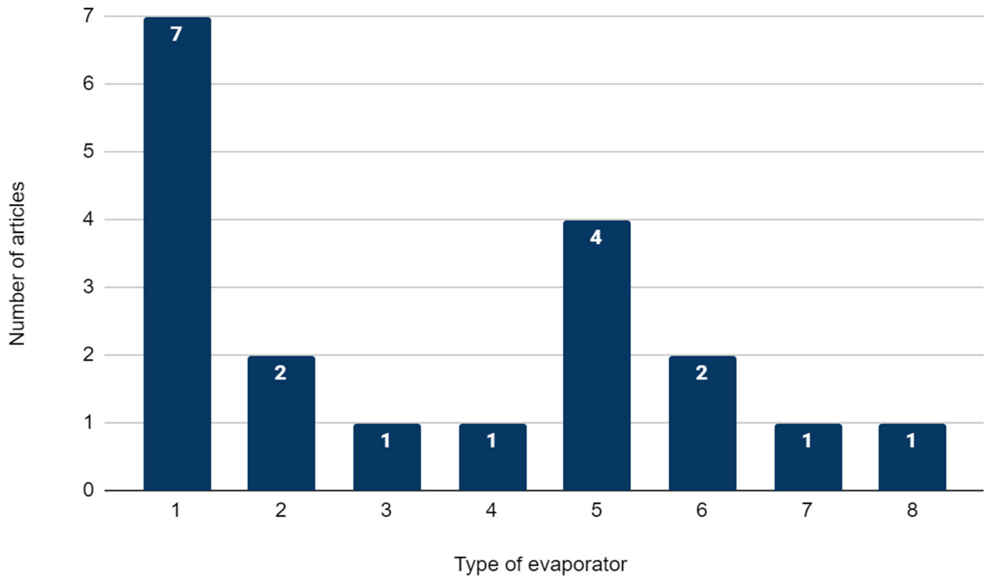


Figure 18. Number of articles dedicated to different numerical modes (for different types of evaporators). Where all the numbers represent the evaporator types described above in the Table 4: 1. Vertical FoT evaporator (air is blown through the larger surface) [90], 2. Vertical FoT evaporator with flow coming from the bottom [91], 3. Horizontal FoT evaporator(air is blown through the smaller surface) [92], 4. Horizontal FoT evaporator(air is blown through the larger surface) [93], 5. Wavy fin evaporator vertical (air through the bigger surface) [94], 6. Wavy fin evaporator vertical (air through the bigger surface [16], 7. Plate Fin evaporator [95], 8. Louvered Fin evaporator [96].

In domestic refrigerators, it is common to have a single or even a double fan system. The fan can operate with the constant rotational speed value switched on and off when the compressor starts working. However, there are also fans that operate at different rotational speeds at different times. To model such behavior properly, it is required to revisit the fan curve for each case. It will play a significant role in the frost growth rate and, hence, in the pressure drop decrease. The models that encountered the impact of the fan curve are [90,107].

The temperature of the cold surface (or, in some cases, the temperature of the refrigerant at the inlet) plays a major role in the frost formation process since it is one of the triggers of frost formation. Current models focus mainly on the similar range of values from −30 °C to −20 °C or from −20 °C to −10 °C.

Furthermore, the matrix of outputs (see Table 5) had been generated based on the models summarized in Table 4. For the cooling engineer, the most important parameters would be the thickness of the frost or the decrease of a pressure drop through the evaporator with the frost growth in order to understand how certain types of evaporators would perform under different operating conditions. Such data is accessible in most of the articles collected.

For the same models (gathered in Table 4), a matrix of the presence of the following most significant outputs was built (where the sign '+' means that the output is presented in the article, while '-' means that the output is not presented in the article; see Table 5):

- Frost surface temperature, °C;
- δ, [mm]—thickness of the frost layer in a particular segment;
- m, [g]—total mass of frost accumulated in the evaporator;
- ρ [kg/m^3]—density of the frost changing with time;
- dP [MPa]—pressure drop through the evaporator increasing with the frost occupying the space between the evaporator fins;
- q [W/m] or (the heat transfer coefficient [W/m^{2}K] or any other heat transfer parameter) describing the rate of heat transfer between the frost and the air.

Table 5. Output data of the articles dedicated to the numerical simulation of frost formation on the heat exchanger surface.

Reference	Frost t_{surf}	δ_{frost}	m_{frost}	ρ_{frost}	dP	Q
[100]	-	+	+	-	+	-
[92]	-	+	+	-	-	+
[101]	+	+	+	+	-	-
[94]	-	-	+	-	+	-
[102]	-	-	-	-	-	-
[97]	-	+	-	-	+	+
[91]	+	+	-	-	+	+
[103]	+	+	+	-	+	-
[96]	-	-	-	-	+	+
[104]	-	+	-	-	+	-
[90]	-	-	-	+	+	+
[106]	-	+	+	-	+	+
[78]	-	+	+	-	+	-
[107]	-	+	+	+	+	+
[98]	-	+	+	+	-	-
[75]	-	+	+	+	-	+
[16]	-	-	-	-	+	+
[76]	-	+	-	-	-	-
[77] *	-	+	-	-	-	+

* Temperature of the refrigerant at the inlet, for all the references except [77], where it is the temperature of the pipe.

2.3.3. CFD Modeling

Computational resources not only allow for a reduced capital investment but are also able to predict different physical processes with a high level of confidence as well as lift the veil and visualise processes that are difficult to observe.

With regard to the very rapid technological development, it still seems a challenging task to model the formation of frost on the evaporator due to the complexity of the multiphase phenomenon and its stiffness to the exact geometry, operating conditions, etc. [72]. In this part of the review, the current available models that calculate the mass transfer of the process will be analyzed.

Currently, there is a huge variety of paid and free software for the purpose of CFD modeling. Examples of this software are as follows:

- Simscale,
- Ansys Fluent,
- Flow-3D,
- Comsol Multiphysics,
- OpenFOAM,
- StarCCM+.

Additionally, during the review of the literature on the topic of frost formation in the evaporator, it was only observed that simulations had been conducted in Fluent software (mostly) or in OpenFOAM and STAR CCM+ (less than 5% of the studies).

Commonly, CFD modeling techniques predict multidimensional frost distribution using the mixture model. With that, often expensive computational resources are required. Therefore, most of the CFD models used to predict frost formation on the evaporator have a limited domain (not the full evaporator or at least half, but a segment of the fin or a couple fins) [72].

Furthermore, in Table 6, a short summary of current and existing models is presented. The main difference is in the simulating technique and the simulating domain, representing:

- Wavy fin,
- Flat fin,
- Parallel fins,
- Plate fin segment,
- Segment of the fin with cut-outs to represent the boundary conditions of the refrigerant tube.

In most cases, either the Eulerian model or the VOF (volume of fluid) model is used. The difference is that Eulerian analyses each phase using one equation for each transport phenomenon, while VOF analyses all phases using a unique equation for each transport phenomenon [110].

Of the 9 CFD models, 7 are three-dimensional (while the models presented in [69,100] are one-dimensional). Most simulations are based on the Eulerian multiphase model [72,74,78,98,100,102,106]. The refs. [105,109] are simulated based on VOF.

Mostly, all the models have as an output the thickness of frost; its mass increasing in time, and the visualisation of frost pattern on the cold surface.

While reviewing currently published articles dedicated to CFD modeling of frost formation on the heat exchanger surface, it is observed that not so many models are currently available; during the past 10 years, this topic has gained more scientific interest since existing mathematical models have matured, and the computational resources now allow one to calculate much more complex tasks. Nevertheless, there is a potential improvement area for different types of evaporator fins, as well as a larger computational domain and longer physical time.

Table 6. CFD models of frost formation on a heat exchanger surface.

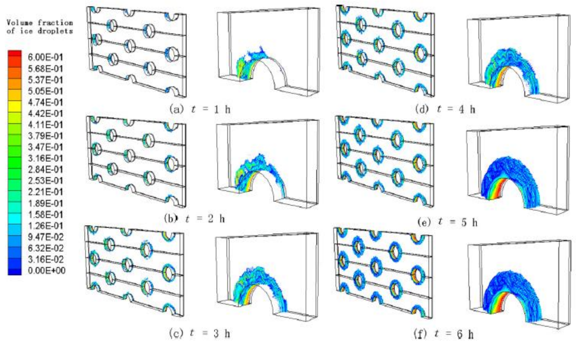
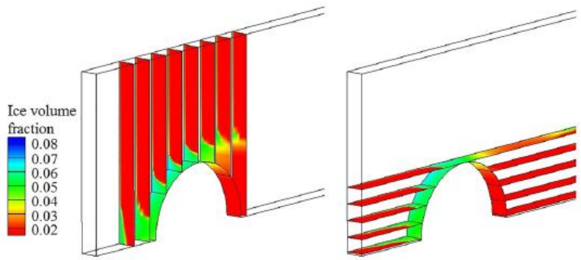
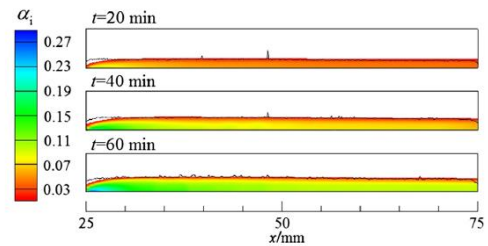
Reference	Visualization	Geometry	Model Used
[97]	 Reproduced with permission from [97], Elsevier, 2011	Fin with perforations for the refrigerant tubes	Transient 3D model, that can predict the frost formation in the initial period and represent the effect of surface structure.
[107]	 Reproduced with permission from [107], Elsevier, 2015	Part of the fin with perforations for the refrigerant tubes	The model of Hermes et al. (2009) [32] for the frost growth and densification is based on the fundamental principles of energy and mass conservation, with its derived set of equations invoking the assumptions typical for the given application: the processes of mass and heat diffusion within the frost layer are treated as quasi-steady and one-dimensional, the frost thickness was assumed uniform along the surface, and the Lewis analogy is applicable.
[72]	 Reproduced with permission from [72], Elsevier, 2017	Flat fin surface: Horizontal [72] Vertical [64]	Eulerian multiphase [90]

Table 6. *Cont.*

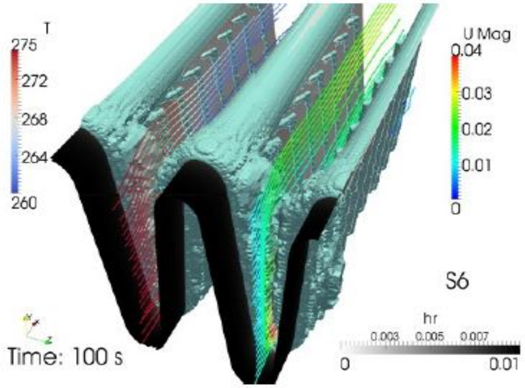
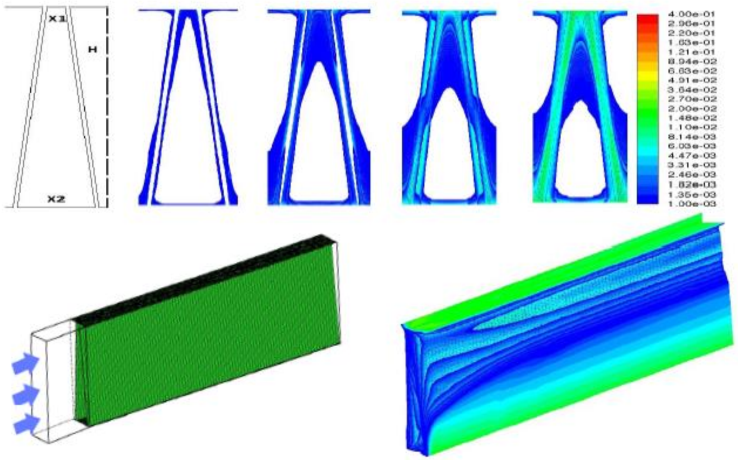
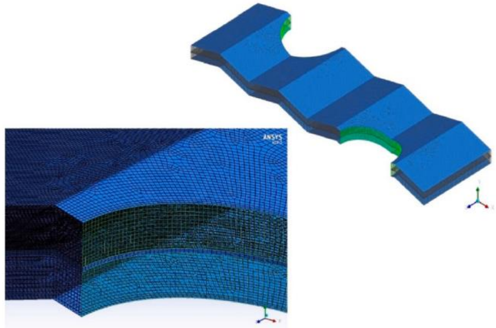
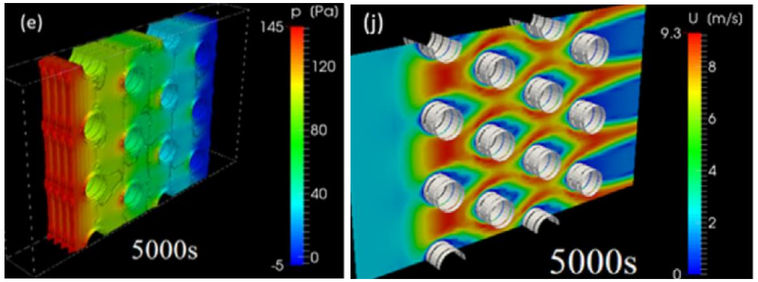
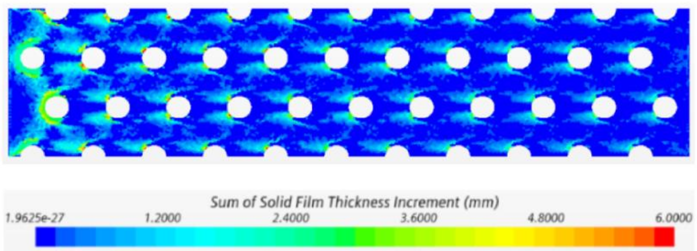
Reference	Visualization	Geometry	Model Used
[107]	 Reproduced with permission from Mirza Popovac, published in 24th IIR International Congresses of Refrigeration, Iif-iir, 2015	Wavy fin segment	The Eulerian multi-phase model was used to calculate the multi-phase flow and two phases were set in the model: the primary phase was humid air containing dry air and water vapor, the secondary phase was ice. In the frosting process, the water vapour in humid air conducted mass transfer to the ice, simultaneously the momentum transfer and energy transfer basing on the mass transfer generated.
[98]	 Reproduced with permission from Oleg Iliev, published in Proceedings of the 3rd World Congress on Momentum, Heat and Mass Transfer (MHMT'18), ICMFHT, 2018	Plate fin segment	Eulerian-granular model is adopted

Table 6. *Cont.*

Reference	Visualization	Geometry	Model Used
[74]	 Reproduced with permission from [74], Elsevier, 2021	Wavy fin segment	Eulerian multiphase [90]
[18]	 Reproduced with permission from [18], Elsevier, 2021	Couple parallel fins with perforations for the refrigerant tubes	VOF
[76]	 Reproduced with permission from [76], Elsevier, 2022	Fin with perforations for the refrigerant tubes	VOF

3. Conclusions and Recommendations

From the analysis of scientific articles published between 1999 and 2022, it can be observed that there has been an increase in interest in the topic of frost formation, which affects refrigeration, aviation, and HVAC systems, reduces performance, and may even lead to mechanical damage.

In this article, scientific literature that is dedicated to the topic of frost formation on the evaporator of domestic refrigerators have been reviewed, analyzed, and summarized. Additionally, this article reviewed the most common types of domestic refrigerators and the classification of applied evaporators. What is more, the most recent articles dedicated to the CFD tools solution for prediction of frost agglomeration on different fin surface types have been analyzed and grouped as well.

The nature of frost formation has been recognized, and frost morphology, layer classification, and growth on the surface of a heat exchanger over time have been presented for the two scenarios below: frosting on the clean surface of the evaporator and on the wet one.

The review results show that different shapes of frost flakes, when agglomerating in a more complex structure, will establish the porosity of the frost, which may further impact the thermal properties of the frost and the heat and mass transfer processes. The literature indicates that because of the very small distance between the fins (ca. 4 mm), frost layer formed on the surface of the fin can, in the worst case, easily block the entire air passage.

Due to the high complexity of the frosting phenomenon, the research was conducted with a very different method. Starting from the microscopic level, through analysis of the creation and properties of the smallest frost crystals, up to the level of frost formation on the whole evaporator of the refrigerator or one used in the HVAC system.

Some reviewed studies showed that in domestic refrigerators, frost can be observed on the liner. However, most of the reported results show that it is observed in the riskiest zone, very near or on the surface of the heat exchanger. In addition, the relatively large temperature difference between the warmer air (+4 °C) and the colder surface of the evaporator (−25 °C) leads to the point when the humidity of the air condenses (with further solidification) or even is sublimated to ice.

Present studies in the topic focus on:

- the experimental investigation of frost formation phenomena,
- numerical description of the process,
- simulation way of problem solving.

From the article's review, it can be seen that, in most of the cases, the experimental setup consists of the following components: a wind tunnel, a tested element (which can be a full evaporator or a selected part of this heat exchanger, i.e., fin/tube/fin channel), a fan, a humidifier or climate control chamber, and a cooling system.

Scientists are conducting their experiments in two different ways: either the evaporator, or the part that is located inside a wind tunnel and humid air is blown through the test section with the help of a fan, or the evaporator is adjusted inside the refrigerator.

Some of the authors indicated the importance of the inlet velocity of the air in the process of frosting. Therefore, when applying this to the evaporator, the location, shape, and cross-section of the ducts are also important.

Published numerical research and models, similarly to experimental research results, can be divided into 2 categories focused on the investigation of:

- frost nucleus structure, composition, and growth rate (such as a flat cold horizontal or vertical surface; or the surface of the coil or horizontal and vertical cylinder);
- frost formation that occurs on the surface of the heat exchanger or in the group of parallel fins.

A comprehensive review of the literature (based on more than 50 scientific publications published) had highlighted the importance of the following input parameters: temperature, velocity, and humidity level of the airflow; temperature of the cold surface; and type of evaporator.

For the cooling engineer, the most important parameters would be the thickness of the frost or the decrease of a pressure drop through the evaporator. Such data is accessible in most of the articles collected.

As described in the literature models, the study focuses mainly on the similar range of temperature values ranging from −30 °C to −20 °C or from −20 °C to −10 °C. In addition, the humidity level is commonly high, above 70% relative humidity.

Disregarding the availability of different software that can be applied for the CFD modeling, the researchers' preference was given to Ansys Fluent (in 7 out of 9 reviewed articles, the authors had conducted the studies using this software), and only in 2 of them had they conducted the research in OpenFOAM and StarCCM+. In most cases, either the Eulerian model or the VOF (volume of fluid) model was used. Most of the models have as an output the thickness of frost, its mass increase over time, and the visualization of the frost pattern on the cold surface.

Upon reviewing currently published articles dedicated to CFD modeling of frost formation on the heat exchanger surface, it was found that not so many models are currently available.

During the review, it has been observed that the following scientific issues may be potential recommendations for further research:

1. Experimental analysis of inclined FoT evaporator frosting. There is a lack of research on this type of evaporator and the impact of gravity on both the frosting and defrosting processes.
2. Predicting the frost pattern and frost mass growth rate for the longer simulated operating time of the evaporator using CFD tools.
3. Develop a way to predict critical frost potential areas on the evaporator surface based on currently available CFD tools. Such an analysis can give recommendations for the better location of the defrost heater and its capacity, which may be applied to different designs of a domestic refrigerator.

Author Contributions: Conceptualization, methodology, validation, formal analysis, investigation, visualization, writing—original draft preparation, writing—review and editing, D.K.; writing—original draft preparation, writing—review and editing, methodology, formal analysis, supervision, P.K. writing—review and editing, P.B. All authors have read and agreed to the published version of the manuscript.

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