Frost Measurement Methods for Demand Defrost Control Systems: A Review

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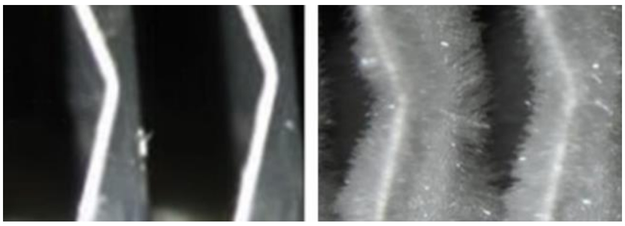
***Abstract*—It is widely known that defrosting operation on commercial refrigerators is one of the main causes of inefficiency on these systems. Several defrosting methods are used nowadays, but the most commonly used are still time-controlled defrosting, usually by either electric resistive heating or reverse cycle, as most demand defrost methods are usually complex, expensive or unreliable. Demand defrost can work by either predicting frost formation by processing measured conditions (fin surface temperature, air humidity and air velocity) and/or frost accumulation symptoms such as pressure drop and refrigerant properties. Other way of knowing when to defrost is to directly measure the frost formation using sensors such as photoelectric, capacitive or resistive. This review gathers some of the methods that can be used for directly measuring frost accumulation on the evaporator fin surface.**

***Index Terms*—Demand defrosting, frost measurement, controlling strategy, frost detection**

I. INTRODUCTION

THE issue of frost formation in air conditioning and refrigeration systems, more specifically on the fin-and-tube evaporators has been studied for several years, and yet it is the main cause of inefficiency [1], [2]. Because they are used in light commercial systems, these fin-and-tube evaporators have a large area-to-volume ratio. The demand for subfreezing operating temperatures cause the formation of a frost layer on the fin surface [3], [4] as shown on Fig. 1.



(a) (b)

Fig. 1 Visualization of the fins surface before (a) and after (b) the frost formation process (adapted from [3]).

Being a porous medium comprised of ice crystals and pores filled with moist air, the frost buildup on the evaporators fin surface increases its air-side thermal resistance, decreasing the overall efficiency of the system. If the frost is allowed to continue growing the efficiency keeps decreasing due to not only the increment of the heat transfer resistance, but also to the blockage of the air passage between the fins that can lead to a full blockage if no defrost method is applied [5]. Several parameters can influence frost growth, but those with most influence are air relative humidity, velocity and supercooling degree (difference between inlet air dew point and fin surface temperature) [4], [5], [6], [7], [8], but may also be influenced by other parameters such as fin shape and spacing [3], type of flow (laminar or turbulent) [9], or air cleanliness [10]. The lower system efficiency caused by the frost layer on fin surfaces result in a higher energy demand, and in extreme cases, system damage.

Defrost methods are used to reduce the problem, although additional energy is usually also consumed for them to function [11].

After reviewing the literature, it was found appropriate to divide the defrost methods in two different groups:

Restraint frost methods approach various methods for the retardation of the frost formation, by changing the characteristics of the inlet air (humidity, velocity and temperature) [12], [3], changing the features of the cold surface (temperature, morphology, position and treatment) [13], [14], [15], [16], [17], [18], changing the interaction between the air, condensed water or frost and the cold surface (electric field [19], magnetic field [20], ultrasound [21]), etc.

Frost removal methods act upon the formed frost to remove it and return the working conditions to normal, therefore, ideally, are only used after the frost is formed. These defrosting operations usually result in undesirable temperature fluctuations on the refrigeration cabinet [22]. There are several defrost methods, such as compressor shutdown [23], electric resistive heater [24], reverse cycle [25], [26], hot gas bypass [27], hot water [28], air jet or air particle jet [29], and ultrasonic vibration methods [30], [31], [32]. Both restraint frost and frost removal methods can be classified as passive or active: Passive if no additional energy is required for them to work and active if some additional power input is required to remove the accumulated frost [33]. This classification is summarized on Fig. 2.

Time controlled with on-off defrosting and electric resistive heater or reverse cycle are the most used defrost methods. Apart from these, none of the abovementioned methods has gained significant acceptance from the refrigeration industry, due to complex, expensive and unreliable sensing and prediction methods [34], [35].

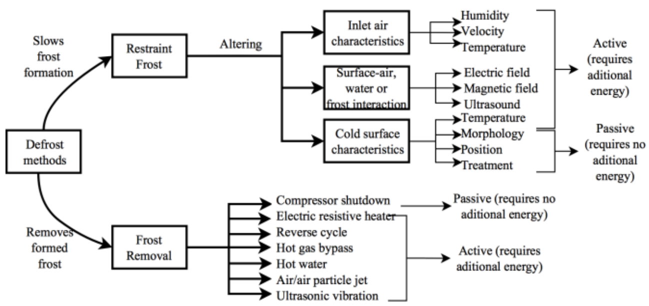


Fig. 2 Classification of available defrost methods.

This can cause a huge impact on energy consumption, as the timed defrost operations have to be timed for the worst-case scenario (warm and high air relative humidity) and thus, as these properties vary during the year, the amount of defrosting cycles could vary as well. Tassou *et al.* [36] studied frost formation and defrost control parameters for open multideck refrigerated display cabinets and concluded that the ideal time between defrosts varies greatly with air temperature and humidity. As shown in Fig. 3, the ideal operation time between defrosts on this food display cabinet can range from 4 hours to around 9.5 hours during different times of the year. A time-controlled defrosting must have in consideration the worst-case scenario on time between defrosting operations.

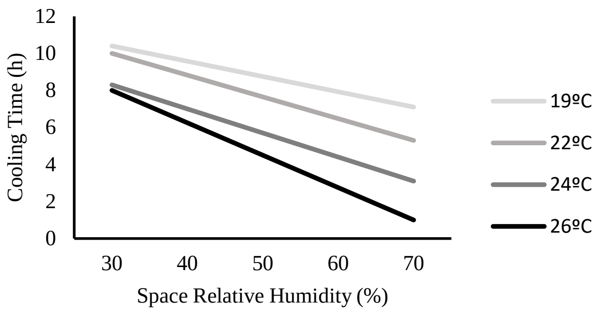


Fig. 3 Optimum time between defrosts in relation to air temperature and humidity (adapted from [35]).

Demand defrost tries to solve this problem by predicting frost formation. This prediction can be done by computing the measured factors that influence frost formation (such as surface temperature, and inlet air characteristics: relative humidity, temperature and velocity) [37], computing the measurable system changes caused by the frost accumulation on the evaporator (temperature difference between the air and evaporator surface [38], pressure drop [39], degree of refrigerant superheat [40], fan power sensing [41]) or both [42], using methods such as artificial intelligence [43] and other algorithms [44], [45].

Alternatively, demand defrost cycles can be controlled by directly measuring frost on the evaporator coils.

II. Frost measurement methods

Demand defrost can also work by directly measuring the frost accumulation. In this scenario no prediction is necessary, as sensors positioned on the evaporator directly evaluate the state of the frost accumulation and their data is processed so that the defrost operation occurs when best suited.

Direct methods that require human intervention such as using a cathetometer telescope [46], micrometer [6], vernier gauge movement [47], etc. will not be approached as they are not practical for incorporating in refrigeration systems.

A. *Laser displacement gauge sensors*

In [48] a laser displacement gauge was used for measurement of the frost layer thickness as shown on Fig. 4. Although the uncertainties are within 0.01 mm, this application's purpose is to measure frost thickness in a laboratory environment. Cheaper and less precise versions (still highly precise considering the application demands) should be researched for inclusion in refrigeration systems. Another concern should be the resistance of the sensor to the harsh conditions and consequent reliability.

Another difficulty found in [49] was when there were voids on the frost surface during frost formation, resulting in an ineffective laser reflection and consequent failed measurements. In order to diminish this problem, the laser beam must impinge the surface with an angle less than 90º rather than perpendicularly to the surface. An example of measured frost thickness is presented in Fig. 5. The short, smooth and level sections of the curves for cases 2, 3, and 4 just indicate the failure of the displacement gauge.

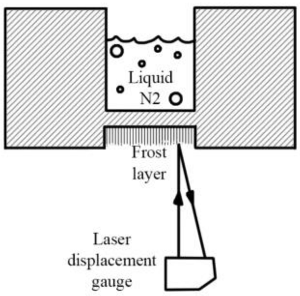


Fig. 4 Laser displacement gauge positioning (adapted from [47]).

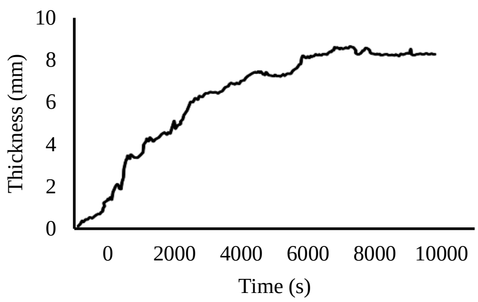


Fig. 5 Laser displacement gauge measurement results (adapted from [47]).

B. *Photoelectric sensors*

Photoelectric sensors work with an emitter (for example an infrared light) positioned towards a receiver (photoelectric sensor) and separated by a small passage as shown in Fig. 6.

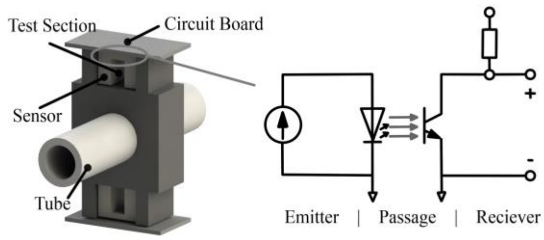


Fig. 6 Schematic of TEPS, the sensor installed on the refrigerant tube (left) is represented as a circuit (left) (adapted from [49]).

Once driven with current, the emitter emits constant light to the receiver through the passage. The receiver converts the received light into a voltage, that varies gradually from a value representative of air (open path) to a value representative of frost blockage (closed path), allowing a frost formation measurement with sufficient accuracy for defrosting control. In [49] and [50], a tube encircled photoelectric sensor (TEPS) for defrosting control is studied with promising results. When compared with timed defrost, the difference is clear. Fig. 7 shows a comparison between the two methods. The TEPS output is shown in the first row, while in the second row the temperatures of the suction and discharge zones of the compressor are shown varying as the result of frost-defrost cycles controlled using the TEPS. As a means of comparison, the last row shows the operation of a regular time-controlled defrost. Eight defrost cycles have been made on the TEPS controlled defrosting while 30 defrost cycles have been made on the time-controlled defrost.

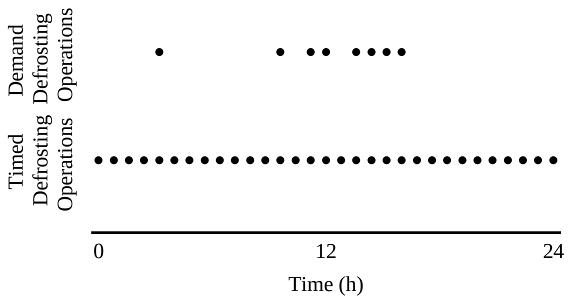


Fig. 7 Comparison between timed defrosting and demand defrosting using the TEPS (adapted from [48]).

Extensive testing should be done for long periods of time to ensure reliability, durability and performance when frosting conditions are more severe, but the results seem promising.

C. *Fiber-optic sensors*

Nowadays the most advanced ice sensing method in the world is fiber-optic method [51]. This sensor relies on the reflective properties of ice to work. An IR LED positioned as shown in Fig. 8(a) emits IR light trough the optic fiber bundle into the sensor tip represented in Fig. 8(b). When frost formation occurs, it reflects the light back into the system as shown in Fig. 8(c), going through the signal fiber bundle and finally received by the phototransistor.

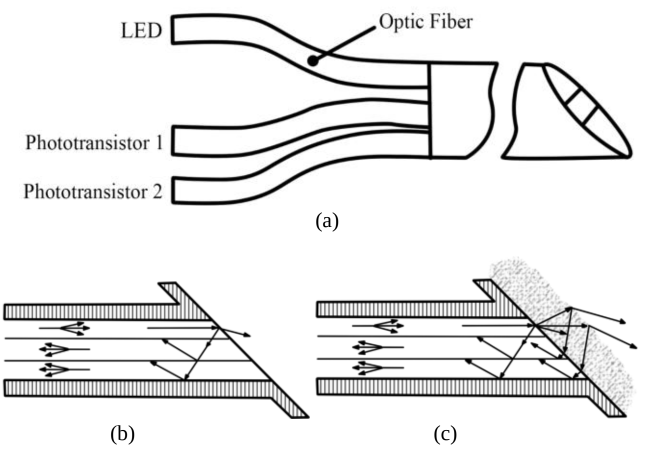


Fig. 8 Overall sensor scheme(a) and sensor tip operation without ice (b) and with ice (c) (adapted from [50]).

Because different frosting conditions generate different frost morphologies, the measured values differ not only depending on the frost thickness, but also on its morphology. Diverse morphologies have different reflective coefficients. This may be both a problem and an advantage: On the first hand it might cause measuring errors if not considered, but on the other hand, if properly implemented, will allow for not only the thickness to be measured, but also its morphology, as shown in Fig. 9.

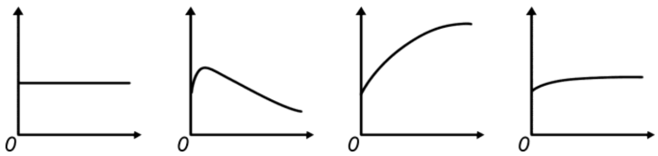


Fig. 9 Results for different measurements using the sensor studied in [50]. from left to right no ice, glazed ice, rime ice and mixed ice. The horizontal axis is the ice thickness and the vertical axis is the optical intensity. (adapted from [50]).

D. *Piezoelectric sensors*

Piezoelectric sensors work by applying a sinusoidal signal to a piezoceramic transducer, forcing it into resonance. This can be done by applying a voltage on the circuit shown in Fig. 10.

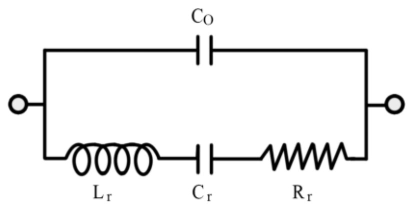


Fig. 10 Equivalent lumped electrical network of a piezoelectric resonator (adapted from [53]).

L_R, C_R, and R_R represent parameters associated with the piezoelectric transducer, and C_O represents the parasitic shunt capacitance of the resonator due to packaging.

The resonant frequency will tend to increase with greater net stiffness, while an increase in the resonating mass will tend to decrease the resonant frequency.

When water accumulates over the transducer it does not change the stiffness, but adds a weight, resulting in a decrease of the frequency. When frost forms, although its weight affects the frequency negatively, it is negligible when compared with the frequency increment due to the stiffness escalation, and thus frost can be detected and measured. The more frost forms on the transducer surface, the more its frequency will increase. In [52] some promising measurements were achieved as shown in Fig. 11.

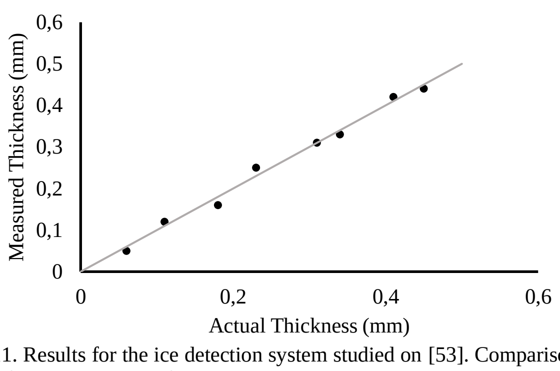
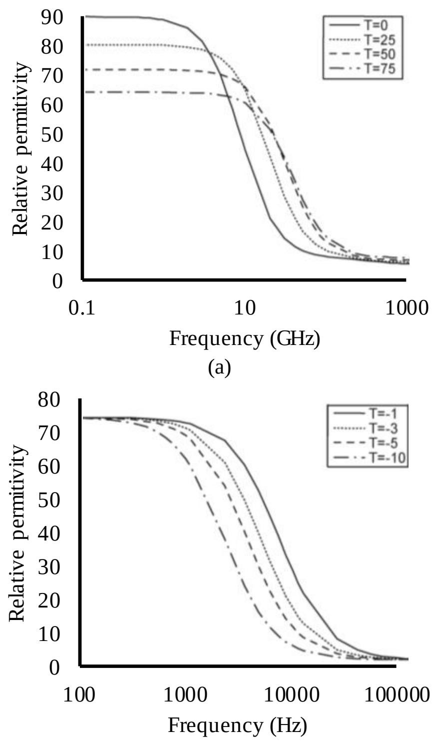


Fig. 11. Results for the ice detection system studied on [53]. Comparison in mm of the determined frost thickness (vertical axis) vs the actual film thickness (horizontal axis) (adapted from [53]).

E. Capacitive sensors

The capacitance of an electrode assembly generally depends on the shape and dimensions of the electrodes, distance between them and on the permittivity of the dielectric, which is the material placed between the electrodes.

This permittivity, varies with the temperature and measurement frequency. The relation between the relative permittivity of water or ice and the temperature and measurement frequency is shown in Fig. 12.



(b)

Fig. 12 Relative permittivity of water (a) and ice (b) (adapted from [52]).

Knowing that the air permittivity will be low and constant in all frequencies a sensor can be made by measuring the capacitance at different frequencies. An ice sensor was developed in [53] using this principle as shown in Fig. 13.

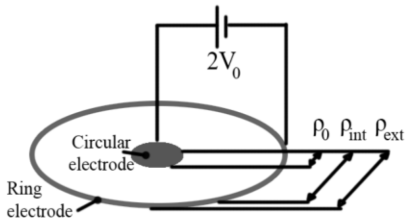


Fig. 13 Sensor scheme, as developed in [52] (adapted from [52]).

Theoretically this sensor could be used to detect water, ice, and measure its thickness although results show that the frost/water layer thickness affect very little the measured results. Probably, a different electrode configuration or data processing could show more promising results, as this study was developed to detect water or ice on roads, with little concern for its thickness.

F. Resistive sensor

The resistance of a given sample varies with its form and material. Air, ice and water have quite different electrical resistance values, meaning that if two electrodes are positioned in the evaporator (but close enough for a voltage drop to be measured on a highly resistive material such as ice) and a voltage is applied on the terminals, a characteristic voltage drop will be measured as water forms, and this voltage drop will decrease as this water freezes, giving accurate measures of the ice formation. A device based on this is presented in [54] and [55], as shown in Fig. 14.

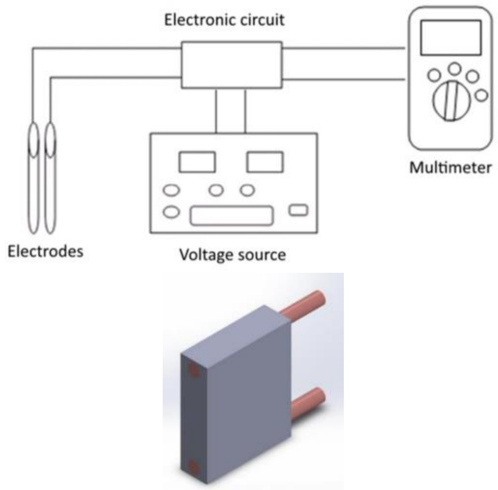


Fig. 14. Apparatus for water and ice detection using a resistive sensor (top) [54] and sensor prototype CAD model (bottom) [55].

Fig 15 clearly show the results for detection of water ccumulation at 45 min and then the ice detection at 95 min.

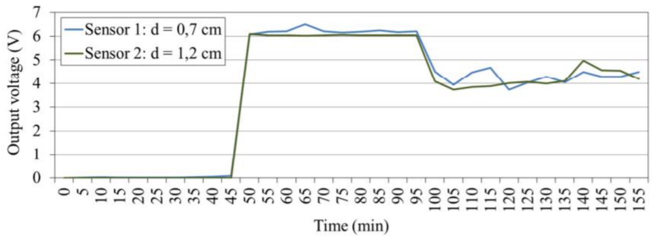


Fig. 15. Output voltage during operation [54].

Although this method does not allow for the measurement of the frost layer thickness, is it possible that different electrode configurations might allow for a layer height measurement.

III. COMPARISON BETWEEN METHODS

A sensor developed for monitoring the ice formation in refrigeration applications has cost as determining factor. Thus, any prototype to be developed must be inexpensive and have reasonable accuracy and reliability [54]. Complexity and size are also obvious factors of interest for refrigeration system manufacturers as these will drive the costs of implementing the sensors, and directly affect the final price. For ease of comparison, Table I was created so that the different methods can be evaluated:

TABLE I
COMPARISON BETWEEN FROST MEASUREMENT METHODS

Device	Cost	Accuracy	Reliability	Complexity	Size
A	✓✓	✓✓✓	✓	✓	✓✓
B	✓✓✓	✓✓	✓✓	✓✓✓	✓✓✓
C	✓✓✓	✓✓✓	✓✓✓	✓✓	✓✓
D	✓✓✓	✓✓	✓✓✓	✓✓	✓✓✓
E	✓✓✓	✓	✓	✓✓✓	✓✓✓
F	✓✓✓	✓	✓✓✓	✓✓✓	✓✓✓

From the results of Table I, method A is not appealing for implementation in refrigeration systems, although it is perfect for testing in laboratory. Method B is good for implementation and has the advantage that can be conveniently placed on the refrigerant tube, with no need for large design changes and operations. Another advantage is that it has also been already tested on refrigeration systems and preformed greatly. Method C is very accurate and has the advantage that it has been proven to distinguish between different frost morphologies, although it has the disadvantage of being slightly more complex and large than the average method approached. The method D also has the advantage of measuring not only the presence but also the thickness of the frost layer. Although, it must be tested with frost layers over 0.5 mm and in refrigeration systems setups to evaluate if vibrations do not interfere with the measurements. The method E also seems promising but should be redesigned for implementation in refrigeration systems, perhaps allowing it to measure frost thickness. Method F has the great advantage of being very cheap and very sturdy, although further studies should be developed to attempt the measurement of frost thickness and the study of a simple implementation on a refrigeration system, perhaps by adopting a new design.

IV. CONCLUSION

Different methods for demand defrosting have been developed so far, and although many solutions exist nowadays, defrosting operations in refrigeration systems are still mainly time controlled. Thus, they are characterized by high energy consumption and temperature fluctuations that affect the conservation state of foods.

Directly measuring frost on the evaporator may be one of the solutions to minimize the impact of this problem. Cheap, compact, simple, reliable, and still accurate enough to command defrost operations sensors can be easily developed. The necessity to measure the frost thickness is not one of high precision, but one precise enough to command the defrosting operations on the ideal time.

Future studies should be made for the development of a sensor (perhaps based on one approached on this study) that could easily be implemented on an existing system without requiring a lot of work, costs, and thus having minimal impact on the sale price of the refrigeration system, while resulting in huge energy savings in refrigeration and extended shell life of the refrigerated goods.

Additionally, it must be taken into consideration how outside factors during frost formation can impact the frost characteristics such as crystal morphology and consequent density, translucency, reflection coefficient, stiffness, capacitance, electrical resistance, etc. These variations could induce errors in measurements that should be studied to be minimized before implementation in commercial systems. Method C already has this issue in consideration, and not only corrects it as it also uses it in its advantage for frost morphology detection as well as frost thickness measurement. This conclusion does not mean that other promising methods such as B or F are not viable for development of a commercial application, but that they should be further studied and developed to achieve a better solution.

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