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Medium materials for improving frost detection on a resistive sensor

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Abstract

Reducing food waste demands improvements in refrigeration systems. Furthermore, the rise of temperatures worldwide demands more capable and efficient refrigeration equipment. One of the problems that affects refrigeration equipment is the accumulation of frost in the heat exchanger that reduces efficiency, and in extreme cases, blocks the air flow. Usually, defrosting is timed for the worst-case scenario, which results in many unnecessary defrosting operations that compromise the efficiency, and temperature stability in the refrigerated environment. This paper presents a low-cost resistive sensor's reliability case studies, using several materials and configurations.

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Keywords: Defrosting; Evaporator; Frost; Heat exchanger; Refrigeration; Sensor

1. Introduction

Frost formation on the fin-and-tube evaporators has been widely studied, and yet it is one of the main causes of inefficiency [1]. The fin-and-tube evaporators used in light commercial systems have a large area-to-volume ratio. Subfreezing operation temperatures cause the formation of a frost coating on the fin surface [2,3].

Frost layers are composed of ice crystals and pores filled with moist air, making them a porous medium. The accumulation of frost on the evaporators fin surface thermally insulates it, decreasing the overall efficiency of the heat exchanger. This accumulation of frost may ultimately, block the passage of air in between the fins [4]. To prevent this blockage, it is common to preform defrosting operations [5]. Several parameters may affect frost growth, but those with most impact are air relative humidity, supercooling degree and velocity [2], but other parameters will also have influence such as fin spacing and shape [3], type of flow [6] and air cleanliness [7].

The decrease in efficiency caused by the formation of a frost layer on the fins surfaces results increases the energy demand, and in extreme cases, might damage the system, increasing the conservation temperatures and decreasing food safety. Defrost methods are a solution to decrease the consequences of this problem, even though additional energy is usually needed for them to operate [8]. These methods are classified as seen in Fig. 1.

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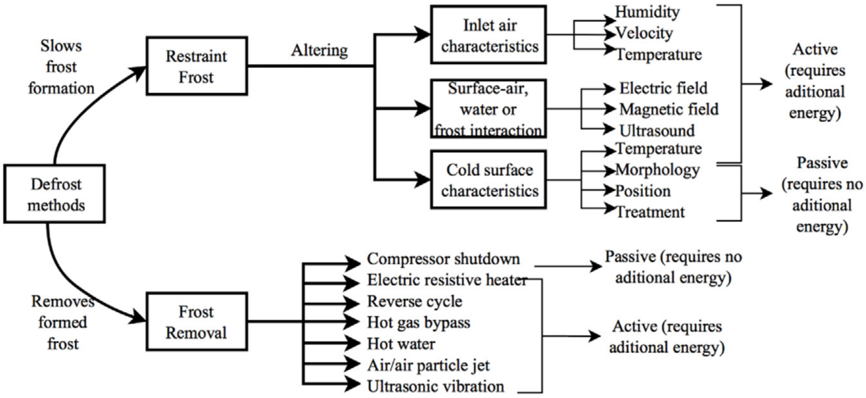

Fig. 1. Available defrost methods and their classifications [9].

On–off timed defrosting with an electric resistor or reverse cycle are still the most used defrosting methods. Apart from these, the abovementioned methods are yet to gain significant acceptance from the refrigeration industry, as they are complex, expensive, and not reliable, lacking sensing and prediction methods [10]. This causes a huge impact on energy consumption, because the timed defrost operations must be scheduled for the worst-case scenario (warm air and high relative humidity), properties that vary during the year, with the amount of necessary defrosting cycles. Tassou et al. [11] investigated frost formation and parameters of defrost control for vertical open refrigerated display cabinets. They found that the ideal time between defrosts changes considerably with air temperature and humidity. According to Tassou et al. [11] the ideal operation time between defrosts on these refrigerated displays can range from 4 to 9.5 h on different times of the year, according to the variation of parameters that affect frost growth.

Demand defrost solves this problem by only defrosting when needed, by measuring or predicting frost formation. The prediction can be done by computing measured parameters that influence frost formation, as the temperature of the heat exchanger surface; Inlet air characteristics such as relative humidity, temperature and velocity [12]; Computing the measured system changes and symptoms of frost accumulation on the evaporator such as temperature difference between the air and evaporator surface (as frost accumulates it creates an insulating layer that decreases thermal conductivity, and therefore less heat is absorbed by the air, making the surface temperature lower, with an increase in the air temperature), pressure drop (frost blockage decreases the pressure after the evaporator), fan power sensing (airflow blockage results in increased power usage by the fan); or both [13]; Using algorithms [14] or methods of artificial intelligence [15]. On the other hand, demand defrost can be controlled by direct measurement of the frost accumulated on the evaporator surface. In this scenario the prediction is not necessary, as the sensors positioned on the heat exchanger measure the frost accumulation, and their data is processed so that the defrost operation only occurs when needed.

In the next sections, a resistive sensor is presented. Results obtained using various mediums in between the sensor electrodes are shown and discussed.

2. Resistive sensor

The electrical resistance of an object varies according to its length, section, and material, temperature, and physical state. Air, ice and water have very different electrical resistance values, therefore if two electrodes positioned in the evaporator close enough for a voltage drop to be measured are fed with voltage, a characteristic voltage drop will be measured when water condensates on their surface, and this voltage drop will increase when this water freezes, indicating frost formation. A device based on this principle was developed by Gaspar et al. [16] and Caetano et al. [17]. This sensor is based on the principle of the Eq. (1):

$$R = \rho . L / A \tag{1}$$

where R [Ω] is the measured resistance, ρ [Ω m] the resistivity of the substance between the electrodes which is the variable that changes its value for water, ice or air, L [m] the length of the substance (affected by the

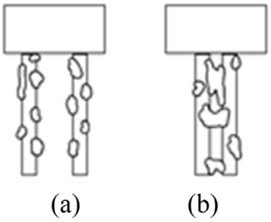

Fig. 2. Water droplets (a) and bridges (b) on the electrodes [18].

distance between electrodes), and A [m^2] the section area of this material. If the electrodes are close enough, a bridge between the electrodes is formed, as seen on Fig. 2. This accumulated water will decrease of the resistance between the sensor terminals, that will again increase as the water freezes.

2.1. Air gap resistive sensor

The simplistic approach to a resistive sensor for frost detection is to place two electrodes separated by a small distance with nothing but an air gap in between, so that water condensates between them and therefore water deposition is detected by the analog to digital converter (ADC). In [19,20], different resistive sensors with variable electrode configurations were tested, and promising results were obtained. The most promising results were obtained with the sensor shown in Fig. 3:

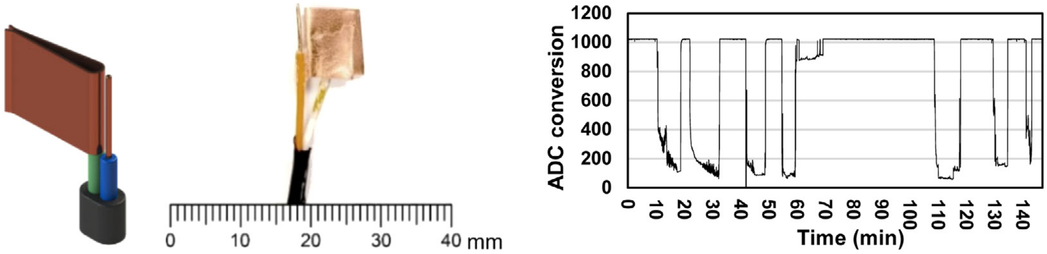

Fig. 3. CAD model (left), picture (center) and values obtained with the most reliable air gap sensor [19,20].

This sensor has two different electrodes. The first electrode acts as a clamp to fix the sensor on a fin of the heat exchanger, allowing for a lower thermal resistance between the sensor and fin surfaces, ensuring frost formation on the sensor. The second electrode is a wire with a diameter of 0.5 mm and a length of 6 mm, parallel to the first electrode, and facing the air intake vertically. The electrodes are separated by an air gap of approximately 0.6 mm. This sensor was able to detect 3 out of 4 frost–defrost cycles, as shown in Fig. 3.

Although the ADC used is unable to distinguish between air and ice, it still can detect frost, as there is no frost without water accumulating first, and there is no defrosting without water resulting from the molten ice. A sensor to be implemented for frost detection with the objective of controlling defrosting operations, must be reliable, in order to avoid malfunctioning of the refrigeration systems, so the possibilities that may lead to inefficiency have to be tackled. Some of the problems with the air gap resistive sensor are the precipitation of the droplet that connects the sensor electrodes with vibrations, and the accidental touching between sensor electrodes, and/or sensor electrodes and a heat exchanger surface that is not electrically insulated. Both these problems can be solved by insulating the terminals with a material that is not electrically conductive and permeable to water. Thus, the smallest amount of water is transported between the electrodes, creating a humid medium that becomes electrically conductive, and does not precipitate with vibrations. This also maintains the distance between electrodes constant and allows contact between the sensor and heat exchanger surface without causing interference.

2.2. Ceramics as a medium between electrodes

The usage of a porous medium that eases the formation of a wet connection between electrodes should increase the sensor accuracy and reliability, as a connection between the two electrodes can be achieved with less water deposition, and this water will not precipitate with vibrations as it will stick to the medium. The ideal medium is not electrically conductive, is porous and a good thermal conductor so that its surface gets cold and results in water condensation. Some ceramics can fulfill all the requirements with the advantage of an easily controlled porosity, and low-cost.

To test the usability of ceramics, Aluminum Oxide was the chosen material, as it is low-cost, widely available, is an electrical insulator and has a relatively high thermal conductivity. Three circular samples with 12,0 mm diameter and 2,6 mm thickness and with porosities of 33.15%, 26.74% and 19.93% were tested. The first test was the conductivity test, in which the sample was clamped between two terminals, as shown in Fig. 4 and gradually, distilled water was slowly added to the sample for one minute to test the conductivity of the sample while dry and wet. The results for the 26.74% porosity sample are shown in Fig. 4 and are similar for all the porosities.

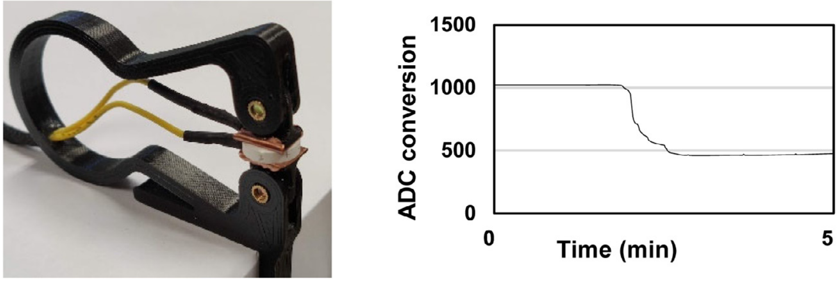

Fig. 4. The clamp (left) and the results obtained (right).

Another thing to consider is the impact that the rigidity of ceramics has in its resistance to frost–defrost cycles, as it might result in fractures due to the dilation of water as it freezes. To test this, the samples were cut in half with a diamond blade saw, and half was kept for control while the other half was saturated with water and went through 10 frost–defrost cycles. The results are shown in Fig. 5, being the bottom samples the control and the top samples those that went through the frost–thaw cycles. From right to left, are shown the samples decreasing porosity. The 33.15% porosity sample broke in two pieces after 4 cycles, and into 3 pieces at 6 cycles. The 26.74% porosity sample broke into 2 pieces after 6 cycles and the 19.93% porosity sample only lost small flakes during the 10 cycles. Microscopically, the porosity of the samples can also be observed in Fig. 5.

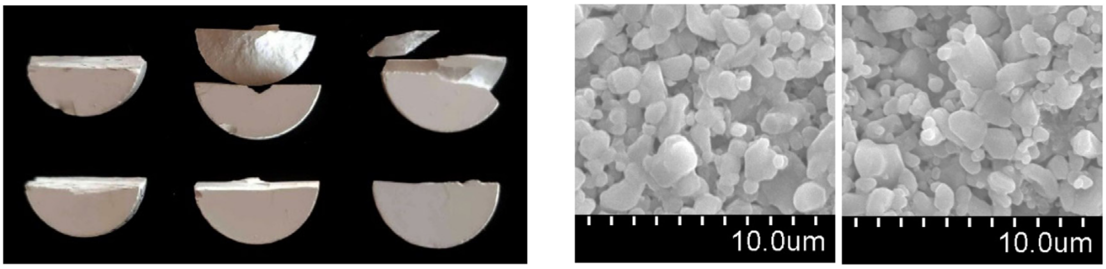

Fig. 5. The test samples (left) and the observation of porosity in the 19.93% (center) and 33.15% (right) samples with an ampliation of 3000x.

From these results, although ceramics like aluminum oxide fulfill most of the requirements, their fragility to frost–thaw cycles make them useless as medium for the sensor. Even though no big fractures were observed in the 19.93% porosity sample, the small flaking is enough indicator that it is not viable either, especially because 10 frost–defrost cycles is something that could be expected to happen daily on some heat exchangers.

2.3. Fabric as a medium between electrodes

Most fabrics that are not electrically conductive are not good thermal insulants either and therefore their usage might affect the condensation of water on the electrode surface. Nonetheless, if this fabric is not tightly wrapped on all the sensor surface, it may allow for water to condensate on the electrode surface, and as most of these fabrics are great water absorbents, a small amount of water can be enough for the sensor do detect presence of water. In [19,20] a string of cotton wrapped around the sensor electrodes was tested and it was possible to improve the results achieved with an air gap resistive sensor. The best results were achieved with the sensor shown in Fig. 6.

This sensor is made from two cylindrical parallel copper electrodes with a diameter of 0.5 mm, separated by a cotton string, loosely tied in the shape of ∞ around both electrodes. This sensor is clamped on the fins, facing the intake front of the evaporator. This sensor was able to detect 5 out of 5 frost–defrost cycles, as shown in Fig. 6.

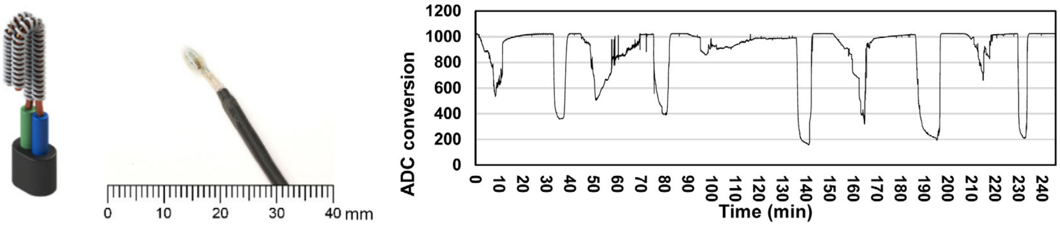

Fig. 6. CAD model (left), picture (center) and values obtained with the most reliable fabric medium sensor [19,20].

Besides the detection of all the frost–defrost cycles, one particularity observed in the resistive sensors with fabric medium is the difference in the shape of the curves in which water is accumulating before freezing, and the defrosting curves, being the latter a lot smoother than the former, unlike the curves in Fig. 3 that are quite homogeneous amongst each other throughout the different phases. This difference can be used to gather more information using the same input in a control system. Using fabric as a medium also greatly reduces the odds of the sensor terminals accidentally touching each other.

Table 1 points to the fabric medium as the best solution when considering the results obtained so far with the present work.

Table 1. Summary and comparison between sensor types in which ✓ means fair, ✓✓ good, ✓✓✓ very good and ✗ not suitable.

Features sensor	Electrically insulant	Thermally conductive	frost–defrost cycles resistance	Cost	Reliability
Air gap	✓	✓✓	✓✓✓	✓✓✓	✓
Ceramics medium	✓✓✓	✓✓✓	✗	✓✓	✓✓✓
Fabric medium	✓✓✓	✓	✓✓✓	✓✓✓	✓✓✓

3. Conclusion

The usage of a low-cost resistive sensor can enhance the efficiency of a refrigeration system by measuring frost and accurately control defrosting operations and avoiding unnecessary interruptions for defrosting operations.

More than the materials used in the sensor electrodes, the medium in between them has a great impact in the sensor accuracy and reliability.

Even if a resistive sensor does not distinguish between air and ice, it is possible to determine the values that the sensor is reading as there is no transition from ice to air or vice versa without passing through a water phase, and therefore, if a reliable enough sensor is developed, it might be a viable and low-cost solution for industrial application, even if using a basic ADC for control. Additionally, a resistive sensor with fabric medium might distinguish between frosting and defrosting operations, while adding further electrical insulation to the resistive sensor, reducing or eliminating the errors caused by the electrodes touching each other or the metallic surface of the heat exchanger.

Being fabric medium, low cost, electrically insulant, resistant to frost–defrost cycles and reliable, it can be seen as the best solution for a low-cost frost formation resistive-type sensor.

CRediT authorship contribution statement

M.L. Aguiar: Investigation, Formal analysis, Validation, Writing - original draft. **P.D. Gaspar:** Writing - review & editing. **P.D. Silva:** Review & editing. **A.P. Silva:** Supervision, Data curation. **A.M. Martinez:** Supervision, Data curation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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