Experimental testing of a resistive sensor for monitoring frost formation in refrigeration systems

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Abstract

An experimental study of a resistive sensor is developed. Its performance is evaluated in function of the temperature and relative humidity of air, the temperature of the refrigerant and the relative position of the sensor on the evaporator's surface. A resistive sensor that include two electrodes measures the electrical resistance of the medium. The experimental study was developed in an experimental facility where different air and refrigerant conditions were set up. The results of the experimental study allowed analyzing the propagation of the frost layer and determining the existence of ice on the evaporator's surface. The results agreement is satisfactory for water detection and high for the detection of the frost layer. The ice behavioral characteristics plays a key role in frost detection using resistive sensors.

Keywords: *Frost Formation, Resistive Sensor, Differential Power, Refrigeration Systems, Evaporator.*

1. INTRODUCTION

Frost formation represents a huge problem to refrigeration systems once it reduces the performance of the process. Typically, these systems operate with temperature below zero and the air mixture has a certain amount of water vapor in it. So, when the air mixture reaches the surface of heat exchanger, the water vapor content starts to change its phase and small droplets of water accumulate on the surface. Subsequently, the water droplets freeze and a fin layer of ice is formed. During the process, this layer keeps growing and eventually blocks the air passage, increasing the air pressure drop. Simultaneously, the increase of the frost layer represents an additional thermal resistance. The blockage and the additional thermal resistance reduce the evaporator performance.

Many researchers have been working to develop tools that mitigate or eliminate the consequences of frost formation in refrigeration systems. Several experimental and simulation studies have been reported. Tassou *et al.* [1] developed an extensive experimental work studying the influence of certain parameters of air in frost deposition. An experimental study is performed by Ozkan *et al.* [2] to evaluate the impact of air velocity in the rate of frost deposition. Xia *et al.* [3] analysed the thermohydraulic performance under frosting conditions on distinct types of evaporators. Aljuwayhel *et al.* [4] investigated the influence of air temperature, humidity and flow rate in the growth rate of frost layer. Seker *et al.* [5] developed a mathematical model that predicts the effect of air temperature, relative humidity and flow rate and the refrigerant temperature in the evaporator's pressure drop and its heat transfer coefficient. The results obtained in the mathematical model were validated with the results obtained with an experimental study [6]. Simultaneously, detection methods have been proposed. Buick *et al.* [7] developed a sensor that measures the capacitance of water and ice. Byun *et al.* [8] and Xiao *et al*. [9] described a sensor based on photoelectric technology to detect frost formation. Lawrence and Evans [10] presented an algorithm to predict the defrost needs based on the fluid refrigerant's instability.

There are a number of experimental and mathematical modeling research, as well as a large number of ice formation monitoring devices described and applied industrially. However, ice monitoring devices do not have consensual use due to some factors such as complexity, cost or efficacy of ice detection.
This work aims to detect the presence of frost accurately. As air mixture with a certain water vapor content, liquid water and ice have different values of electrical conductivity, a resistive sensor is developed to distinguish the medium, i.e., in particular the water phase between two electrodes.

2. EXPERIMENTAL APPARATUS

The sensor used in the experimental works is an improved version of the sensor developed by Marcos *et al.* [11]. The sensor consists of two commercial copper electrodes separated by 10 mm with 1.5 mm^2 cross section and total length of 150 mm. The main dimension of the structure is equal to evaporator's fin pitch. These electrodes were inserted in a body developed in the Stratasys uPrint SE 3D printer. A total of eight sensors were developed for the experimental tests. The CAD representation and the prototype were shown in Figure 1.

(a) CAD representation. (b) Prototype.

Figure 1. Resistive sensor.

An experimental installation composed with an air conditioning unit, a chiller and a bank of evaporators was used to perform the frost detection tests [12].
The experimental work was performed in one the evaporators with a constant air velocity of 3.5 ms^{-1}.
The sensors are distributed, placed between fins, at the inlet and outlet surfaces of the evaporator, according the scheme shown in Figure 2.

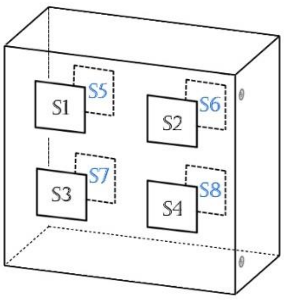


Figure 2. Resistive sensors location and distribution: S1 to S4 in the inlet surface and S5 to S8 in outlet surface.

Several measurement devices were used to control and monitoring the process variables:

- A digital hygrometer with two hygrometer probes, to measure air relative humidity;
- A hot wire anemometer, to measure the air velocity;
- A datalogger, recording air and refrigerant temperatures with thermocouples type T;
- A multimeter to evaluate the sensor's differential voltage.

Additionally, a camera was used to visualize the frost layer formed in the heat exchanger surfaces. The images were collected at time intervals of 6 minutes.
A total of six experimental tests were performed in order to evaluate the performance of the proposed resistive sensor and to describe the frost growth. Table 1 summarizes the air and refrigerant conditions used in the experimental tests.

Table 1. Air and refrigerant conditions.

Test n.[er]	Air temperature [ºC]	Relative humidity [%]	Refrigerant's temperature [ºC]
1	21	70	-12
2	23	50	-8
3	23	50	-10
4	21	50	-8
5	21	60	-8
6	21	50	-10

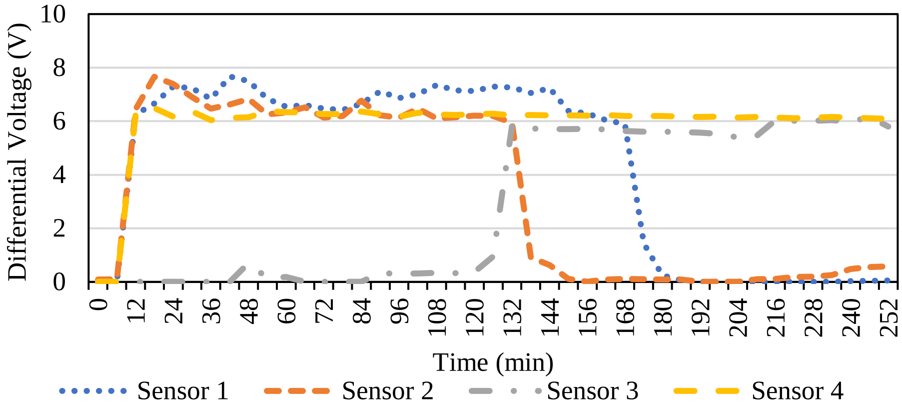
3. RESULTS ANALYSIS AND DISCUSSION

Each experimental test followed a procedure to ensure the same initial conditions. First, it is required to eliminate any remaining water droplets in evaporator surface and sensors structure from previous tests. So, warm and dry air is provided by the air conditioning unit to these elements. Afterwards, the differential voltage of sensor is measured to verify that electrodes are free of water. As soon as these assumptions and operating conditions are reached, the experimental tests begin.
The values of differential voltage measured for an air medium are comprised between 9 mV and 32 mV. When water starts to condense in the electrode terminals, the differential voltage measured between the electrodes increases to a plateau of 6 V to 7 V. When ice is detected, the differential voltage drops to value similar to that obtained with air medium.
After a brief analysis, the results of test number 3 and 4 are considered the most important ones, so discussion will be focused on them.

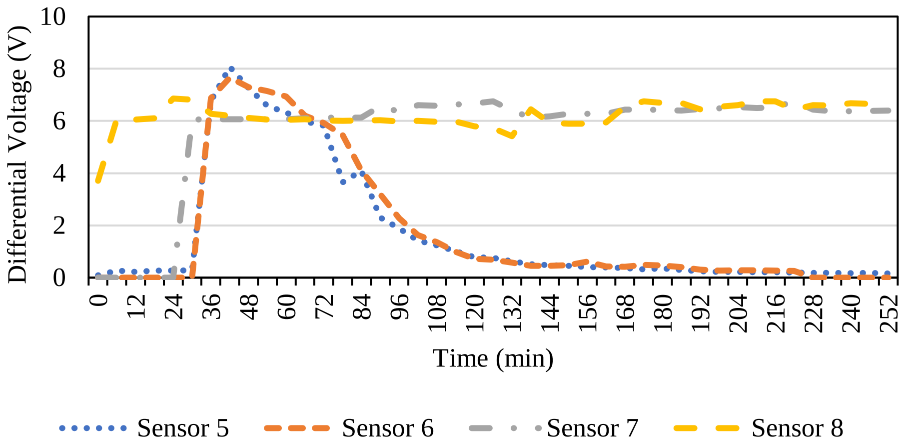
Figure 3 shows the results of the experimental test number 3. In Figure 3 is shown that condensate detection at the evaporator surface happens simultaneously for resistive sensors 1, 2 and 4. Sensor 3 remains at dry conditions for about 42 minutes. Then, a few drops of water accumulate on the sensor electrode, but the resistive sensor 3 detects water effectively only after 132 minutes from the beginning of the test.

According with Figure 3, the resistive sensor 2 was the first one to detect frost. This happen because this sensor is near to the refrigerant inlet in the evaporator. After that, sensor 1 was the next one to detect ice as frost formation occurs from location 2 to location 1 following the refrigerant flow. Until the end of experimental test, frost formation does nor occurs at sensor 3 and sensor 4.

In terms of outlet surface, it is important to note that the sensor 8 remains at wet conditions since the beginning of test, despite the initial procedures. During this experimental test, frost formation did not occur in the evaporator lower zone, so sensor 7 and sensor 8 detect water only. Sensor 5 and sensor 6 reveals the same behavior and detect water at the same time. However, the frost layer formed on outlet surface has a less dense structure and differential voltage decreases more slowly than at the inlet surface.



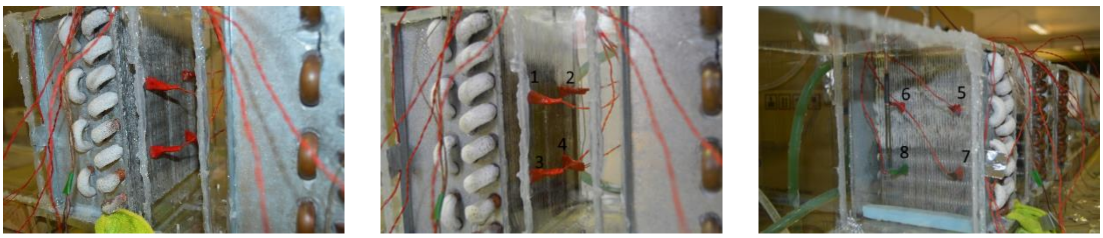
(a)



(b)

Figure 3. Results from data recorded in experimental test number 3: (a) differential voltage of the resistive sensors located on the inlet surface; (b) differential voltage of the resistive sensors located on the outlet surface.

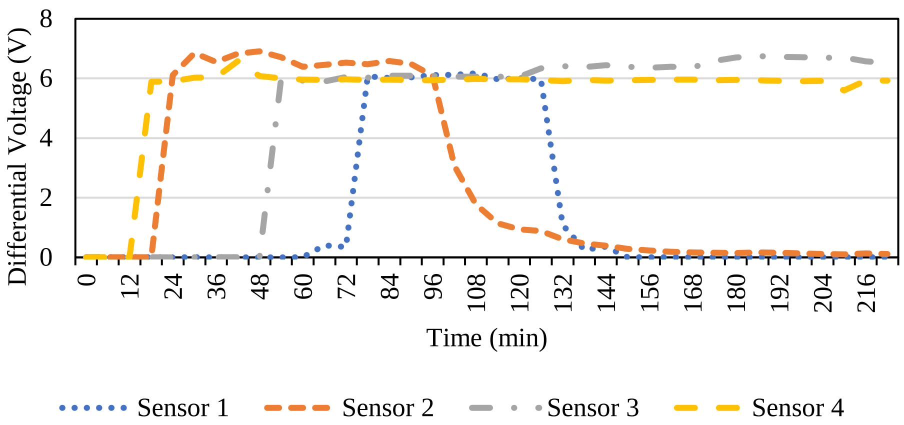
Figure 4 shows the images for the growth of the ice layer on the evaporator surfaces. Note that ice cannot be observed on the surface at the time that sensor 2 detects it, but a small amount of ice is visible upwards.



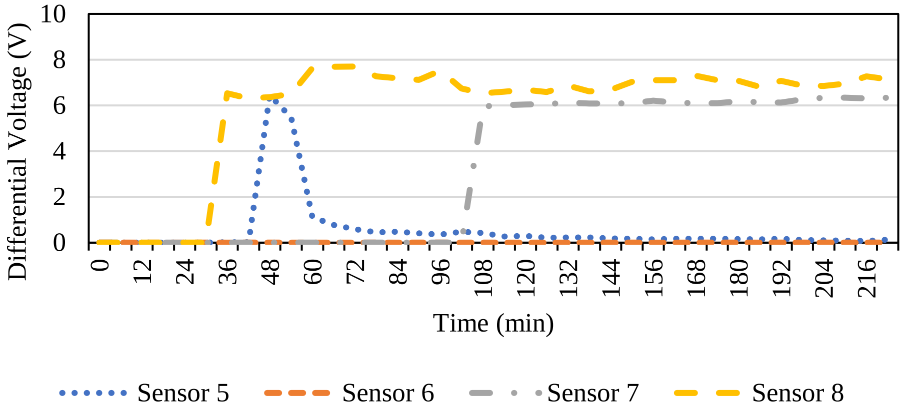
(a) *t* = 132 min. (b) *t* = 168 min. (c) *t* = 252 min.

Figure 4. Frost growth: (a) sensor 2 detects ice into its electrodes; (b) sensor 1 detects ice into its electrodes; and (c) frost developed at the end of the test on outlet surface.

Figure 5 shows the data obtained from the experimental study number 4. The analysis of these data is similar to the previous experimental test number 3.



(a)

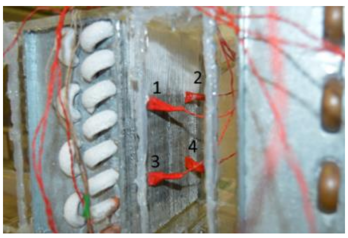


(b)

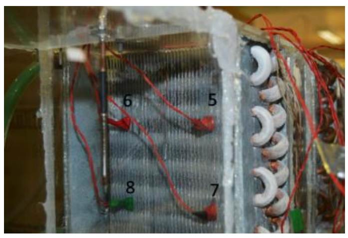
Figure 5. Graphics obtained from data recorded in experimental test number 3: (a) differential voltage of the sensors located on the inlet surface; (b) differential voltage of the sensors located on the outlet surface.

The resistive sensor 4 detects water after 12 minutes of test, and it is followed by resistive sensors 2, 3 and 1. Again, sensor 2 was the first one to detect frost formation and the resistive sensors 3 and 4 never detect ice during the test. At the outlet surface, sensor 5 reveals the start of the ice formation 54 minutes after the beginning of the test with the gradual decrease of the differential voltage. The resistive sensors 7 and 8 provide the information of water detection and remain in this situation until the end of the test, keeping a constant value of the differential voltage. Figure 6 shows the images collected related to the frost growth on the evaporator surfaces for this test.

(a) *t* = 96 min.



(b) *t* = 126 min.



(c) *t* = 216 min.

Figure 6. Frost growth images: (a) sensor 2 detects ice into its electrodes; (b) sensor 1 detects ice into its electrodes; and (c) frost developed at the end of the test on outlet surface.

4. CONCLUSIONS

The purpose of this work was evaluate the performance of a resistive sensor for ice detection on the evaporator's surfaces. The function of the tested sensor lays on the measurement of the electrical resistance in a medium placed between the two electrodes of the sensor. The results of the experimental study allowed the use of this sensor to detect and analyze the ice formation and its propagation over the evaporator's surfaces. Furthermore, in terms of measurement accuracy, it is concluded that the quality of the results is satisfactory for water detection and high for the detection of frost layer on the surface of the evaporator.

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