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Frost detection method on evaporator in vapour compression systems

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Abstract

To preserve food nutrients, texture, and taste, as well as to prevent its putrefaction, food is frozen and kept at around -20 ºC. Refrigerators and freezers are highly energy demand systems which can suffer a considerable decrease in operational efficiency due to frost growth on the evaporator. Defrost processes are launched periodically to avoid the frost built-up, consuming a relevant part of the total energy demand. To control the defrost launching and to improve the energy performance of the refrigeration system an accurate measurement of the frost level is required. Many frost detecting methods are expensive, not feasible due to their size, or simply they cannot measure the frost stacking precisely enough to swerve mal-defrost phenomena. This study provides an accurate parameter to indirectly estimate the frost layer built-up on the evaporator. The new parameter called thermal variation easiness (TVE) was experimentally tested and validated by comparison with another frost levelling method, ΔT method, on a walk-in freezer unit. Then the TVE was successfully tested on a multi-cold room refrigeration system, proving its applicability on both walk-in freezers run by remote condensing units and multiple cold rooms fed by a rack of compressors. The novelty of this parameter lays on its capacity to work on refrigeration facilities which are used to feed several walk-in fridges and refrigerated displays in big installations, such as supermarkets.

Keywords: Compression refrigeration system; defrost cycle; frost detection; cooling.

Nomenclature

A	Contact area for each fluid side in the evaporator
$C_{P.evap}$	Effective heat capacity of the evaporator and frost
Δt	Evaporator temperature increasing period time
ΔT_{evap}	Temperature difference between cold room and the evaporator
ΔT_{lm}	Logarithmic mean temperature difference
$E_{compressor}$	Energy consumption of the compressor
M_{evap}	Evaporator and frost total mass
n	Number of measurements collected when calculating TVE
SP	Set Point
$T_{air,cold\ room}$	Indoor air (freezer) temperature
$t_{compressor,o}$	Compressor starting time
$t_{compressor,f}$	Compressor ending time
$t_{defrost,o}$	Defrost starting time
$t_{defrost,f}$	Defrost ending time
T_{evap}	Evaporator surface temperature
$t_{evap,o}$	TVE calculation starting point
$t_{evap,f}$	TVE calculation ending point
$t_{expansion\ valve,o}$	Expansion valve opening time
$t_{expansion\ valve,f}$	Expansion valve closing time
$t_{fans,o}$	Fans starting time
$t_{fans,f}$	Fans ending time
TVE	Thermal Variation Easiness
TVE_{dry}	Thermal Variation Easiness in dry conditions
U	Overall heat transfer coefficient

1. Introduction

Heat removal is the most common method for food preservation. Food is frozen to keep all the product nutrients, flavour, and texture as well as ensure safety and health considerations. Once the product is frozen, it has to be kept at temperatures from -20ºC to -18ºC, otherwise, the microorganisms will start damaging the perishable products (European Commission, 2006). However, freezing is a very energy demanding process. For instance, supermarkets spend from 40% to 60% of their total energy requirements on refrigeration, to ensure the cold chain (Axell and Fahlen, 2002; Howell RH, Rosario L, Riiska D, 1999).

Moreover, the efficiency of refrigeration systems can decrease by frost stacking on the evaporator coil, meaning higher energy consumption. The frost stacked on the evaporator reduces the heat transfer between the evaporator and the air flow. The evaporator could even stop working if the frost growing is not cut (Melo et al., 2013), hence, defrost processes are required to be periodically launched (Ghadiri Modarres et al., 2016; Waldron, 2007).

Nowadays there is a wide range of defrosting methods. Some of them use the ambient room temperature for defrosting when the refrigeration system is off, while some others require a heat intake such as electrical heaters, hot gasses or hot sprayed water to achieve the frost removal (Lawrence and Evans, 2008; Yin et al., 2012). It has to be taken into account that defrost process can consume 25% of the total energy demand of a refrigerator with an electric heater as defrost system (Kazachi, 2001). For that reason, improving the defrost process can significantly lower the refrigeration energy consumption. Moreover, food spoilage may occur throughout defrost, due to the temperature increase of the frozen product (Bansal et al., 2010; Ndoye and Alvarez, 2015; Tsironi et al., 2009).

Some researchers invested their efforts to experimentally study the efficiency of refrigerating systems. For example, da Silva et al. (Da Silva et al., 2011) tested a refrigeration system by installing different fin-shaped evaporators. The study showed that the cooling capacity, fin density, and air flow rate, among other parameters, were related to the frost stacking rate. Moreover, it was pointed out that the time between two consecutive defrost processes affects the overall system efficiency as the system thermal efficiency improves when this time increases. Same conclusion, that defrost processes should be the lesser as possible, was achieved by Votsis et al. (Votsis et al., 1989). Melo et al. (Melo et al., 2013) tested three different electric heaters used for defrosting purposes, focusing on improving the defrost efficiency. Similar goal was targeted by Hai-Jiao et al. (Yin et al., 2012) who developed a novel cold storage defrost method, which bypasses the airflow through an electric resistance and the evaporator.

Many researchers carried out studies to control accurately the defrost cycles, because they are commonly launched at pre-set times, resulting in unnecessary defrost processes and/or possible evaporator blockage situations. Allard and Heinzen designed a loop system for launching the defrost based on the defrost time (Allard and Heinzen, 1988). Also, Mastrullo et al. developed a transient model, which can be used as a tool for setting the parameters for defrost processes (Mastrullo et al., 2014). Energy consumption can be lowered by launching defrost process on demand, only when frost is accumulated on the evaporator. Thus, some studies are focussed on frost detection and estimation of frost level. Several different parameters were gauged to evaluate the thickness of the frost layer built-up on the evaporator such as, for instance, temperature difference between the evaporator and the indoor air (Buick et al., 1978; Ciricillo, 1985; Kim and Lee, 2015), air moisture (Tassou et al., 2001; Zhu et al., 2015), air pressure difference on the evaporator (Votsis et al., 1989), flow stability on the refrigerant flow (Lawrence and Evans, 2008; Lawrence and Parker, 2001) or fan energy demand (Muller, 1975). Other researchers developed optic (Paone and Rossi, 1991; Woodley, 1989) and acoustic (Llewelyn, 1984) sensors to measure heat transfer on frost, linking it with frost thickness. Recently, measuring the frost layer thickness through direct methods was on fashion, using microscopic imaging systems (Liu et al., 2006) or photoelectric devices (Byun et al., 2006; Ge et al., 2016; Wang et al., 2013; Xiao et al., 2010, 2009). However, these methods are expensive, not feasible due to their size or simply they cannot measure the frost stacking precisely enough to avoid mal-defrost phenomena (Wang et al., 2011). The most extended frost detecting method is the ΔT method, which quantifies the frost level built up on the evaporator by the difference between the indoor air and evaporator temperature

(Kinoshita and Sasaki, 1983). This method proved its value on walk-in evaporators run by remote condensing units nevertheless the ΔT method fails when it is used to monitor the stacked frost on rack of compressors systems which are commonly used to feed several walk-in fridges and refrigerated displays in big installations such as supermarkets.

In this paper, a novel indirect frost detection method was developed and experimentally tested. The new methodology can be applied to both walk-in freezers run by remote condensing units and multiple cold rooms fed by a rack of compressors. By monitoring the evaporator and indoor air temperatures, the rate at which they ramp up along the refrigeration cycles can be evaluated, and this ramp is linked with the stacked frost on the evaporator. The method proposed in this study allows to accurately quantify the frost level regarding the initial dry state, with no frost stacked. As it was proved in previous studies (Maldonado et al., 2018), a proper frost detection method can increase the efficiency of the refrigeration unit.

2. Methodology

The new method allows to quantify the stuck frost on the evaporator not only of a simple vapour-compression refrigeration cycle system (Figure 1a) but also on multi-chamber refrigeration systems (Figure 1b), which are more difficult to evaluate using the current methods. The experimental tests were carried out on two different cold rooms, a walking freezer run by an isolated refrigeration system; and a cold room which is part of a multi-chamber system.

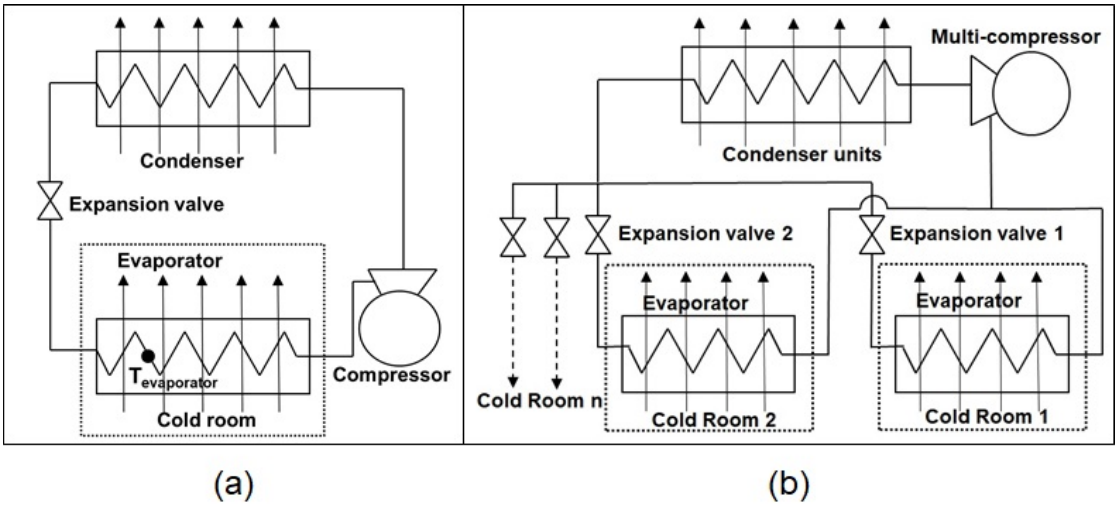

Figure 1. Refrigeration cycle Scheme of a walk-in run by a remote condensing unit (a) and a multi-evaporator system fed by compressor rack (b)

2.1. Experimental set-up

There are two set-ups which were used to carry out this study, both of them are located in the laboratory room of AKO ELECTROMECÀNICA, S.A.L. The first one consists of a walk-in freezer unit (Figure 2a) whose refrigerant fluid is R404A. The system is composed by a Silensys condensing unit supplied by Tecumseh (SIL2464Z) and a fin-and-tube evaporator unit with a constant speed fan. The condensing unit consist of a three-phase hermetic reciprocating compressor, fin-and-tube air-cooled condenser with a variable speed fan. An electronic expansion valve managed by an AKO controller is installed as expansion device. The controller sets a constant superheating value of the refrigerant at the evaporator exit. Finally, to carry out the defrost process, the system includes an electrical heater. This isolated cold chamber was used to test and validate the new method, by comparison with the ΔT frost detecting method (Kinoshita and Sasaki, 1983), which quantifies the built-up frost layer regarding the temperature difference between the cold room and the evaporator when the latter reaches its minimum.

The test facility was thoroughly instrumented to measure:

- the indoor air (freezer) temperature ($T_{cold\ room}$);
- the evaporator surface temperature (T_{evap});
- the compressor starting/ending time ($t_{compressor,o}$ / $t_{compressor,f}$);

- the expansion valve opening/closing point ($t_{expansion\ valve,o}$ / $t_{expansion\ valve,f}$);
- the fans starting/ending point ($t_{fans,o}$ / $t_{fans,f}$);
- the electrical energy consumption of the compressor using a CVM Mini power analyser when activated ($E_{compressor}$); and
- the defrost starting/ending time ($t_{defrost,o}$ / $t_{defrost,f}$).

The temperature sensors used were PT 100 type whose accuracy is ± (0.3+0.005·|T|) ºC (DIN EN 60751 F 0.3 class B), the monitor system collects all the data every 5 seconds through IPC-CON modules (ET-7015 and ET-7019Z). The electrical power measurement has 1% accuracy.

The second part of the study was developed on a refrigerated multi-chamber set-up, run by a multi-compressor rack (Figure 2b). The refrigeration system is an R134A-CO_2 cascade system. The CO_2 refrigeration cycle keeps a cold chamber and a cabinet at -18ºC by means of two compressors. The R134 cycle, on one hand, uses two dedicated compressors to supply a HVAC system on the roof, and on the other hand a freezer island and a cold chamber, which temperature goes from 0 to 5ºC. The last described chamber was selected to carry out the test with two dedicated compressors. The compressors are from Bitzer, semi-hermitic ones of 3.2 kW (with capacity reduction) and 2.2 kW (frequency-controlled) power.

(a) (b)

Figure 2. (a) Walk-in freezer and (b) multi-compressor rack (b), both in the laboratory at AKO Electromecánica S.A.L.

2.2. Thermal Variation Easiness Parameter

The developed procedure to accurately detect and quantify the frost accumulation on the evaporator requires a new parameter called Thermal Variation Easiness (TVE). TVE parameter quantify the easiness of the heat flux through the stuck frost on the evaporator. That easiness is lowered as the frost layer grows due to the thermal inertia of the frozen evaporator and the conductivity of the frost itself. The thermal resistance of the accumulated frost grows as it sticks on the evaporator, hampering the conductive heat flux because of an increase of the conductive thermal resistance caused by an increase of the frost layer thickness. Moreover, as it was said before, the frost detection method must work on individual cold rooms fed by remote condensing units as well as on multiple cold room storages run by compressor rack.

Once the liquid solenoid valve is closed after the cold room air temperature reaches the set point, the evaporator temperature starts to rise because of heat transfer from the cold room air to the evaporator. During that situation, the energy balance (1) can be applied to the evaporator, being the starting point the moment when the evaporator temperature begins to raise, and the ending point when the compressor starts working again or the evaporator reaches 0ºC, whichever comes first (Δt). It has to be pointed out that if the compressor were always running in continuous operation, i.e. there were no refrigeration cycles during which the compressor is turned on and off successively, the TVE parameter could not be calculated.

$$M_{evap} \cdot C_{P,evap} \cdot \Delta T_{evap} = U \cdot A \cdot \Delta T_{lm} \cdot \Delta t \qquad \textbf{(1)}$$

It has to be taken into account that M_{evap} is the evaporator and frost mass. Also, in the same way, $C_{P,evap}$ is the effective heat capacity of the evaporator and frost. The evaporator and frost temperature are assumed to be the same, being T_{evap}.

Rearranging Equation (1), TVE is defined as:

$$TVE = \frac{\Delta T_{evap}}{\Delta T_{lm} \cdot \Delta t} = \frac{U \cdot A}{M_{evap} \cdot C_{p,evap}} \quad \textbf{(2)}$$

By discretizing ΔT_{lm} term in Equation (2) we get:

$$\Delta T_{lm} = \sum_{i=0}^{n} \frac{(T_{air,cold\,room} - T_{evap})_i}{n} = \sum_{i=0}^{n} \frac{\Delta T_i}{n} \quad \textbf{(3)}$$

Finally, the starting and ending measuring time are defined as *o* and *f* respectively, and combining Equation (2) and (3), the TVE is calculated using Equation (4):

$$TVE = \frac{(T_{evap,f} - T_{evap,o})/(t_{evap,f} - t_{evap,o})}{\sum_{i=0}^{n} \Delta T_i/n} \quad \textbf{(4)}$$

As the frost layer grows on the evaporator, the total mass (M_{evap}) increases and the overall heat transfer coefficient (U) decreases. Hence, according to Equation (2), TVE value will decrease with the frost formation both because of an increase of M_{evap} and because a decrease of U.

Figure 3 shows two refrigeration cycles in a cold room run by a remote condensing unit which set point is set at -15ºC. On this example it can be observed the evaporator and room temperature along time, as well as the corresponding TVE value. ΔT is measured between the points when the cold room temperature reaches the set-point and when the solenoid valve closes. However, the monitoring process starts when the evaporator temperature begins to rise, so avoiding the refrigerant inertia. As it can be observed, the slope drawn by the cold room and the evaporator temperature are quite different, so in order to consider the effect of cold chamber temperature in the thermal evolution of the evaporator, the ΔT mean value along the cycle works as TVE corrective factor.

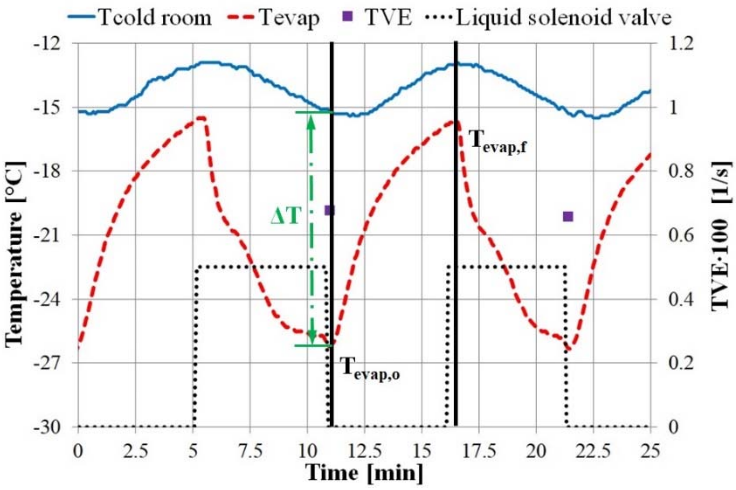

Figure 3. TVE value on individual walk-in freezer. Set point -15ºC

In order to check the accuracy of the TVE method, the first experiments were carried out on an isolated controlled walk-in freezer. Thus, the frost formation was artificially produced and known. Those tests were used to compare the TVE method and the ΔT method (Kinoshita and Sasaki, 1983) at determined frost levels. The set of experiments includes four different stuck frost levels, which were built up by leaving the walk-in freezer door open for zero, one, two or three hours respectively. Additionally, every single experiment at the different frost levels was tested at two different working modes. The first one is the most extended running mode, the compressor and the evaporator fans work at the same time (mode 1). The other method implies that the fans are running all the time except during the defrost process (mode 2). Also, the latter combination of experiments was carried out at two different set points, -10 and -15 ºC (**¡Error! No se encuentra el origen de la referencia.**).

Table 1. List of the performed experiments.

	Isolated controlled walk-in freezer		Multi cold room
	Compressor and fans work simultaneously (Mode 1)	Fans are always running (Mode 2)	Fans are always running (Mode 2)
Set point -10 ºC	Frost level 0	Frost level 0	Not applicable
	Frost level 1	Frost level 1	
	Frost level 2	Frost level 2	
	Frost level 3	Frost level 3	
Set point -15 ºC	Frost level 0	Frost level 0	
	Frost level 1	Frost level 1	
	Frost level 2	Frost level 2	
	Frost level 3	Frost level 3	
Set point -18 ºC	Not applicable		Frost level 0
			Frost level 1
			Frost level 2
			Frost level 3

Once the TVE value was tested regarding the already known ΔT method (Kinoshita and Sasaki, 1983), the next step is to check its performance on multiple cold rooms system, refrigerated all of them by a single rack of compressors. In order to accomplish that goal, several experiments were carried out on a refrigerated multi-chamber set-up run by a multi-compressor rack (Figure 2b). This cold chamber works on mode 1, as in real conditions, and it switches to mode 2 for four cycles to calculate the TVE. The multi cold chamber was tested at set point of -18º C (**¡Error! No se encuentra el origen de la referencia.**).

Along the first approach of the study, when working on multiple cold room storages run by rack of compressors, it was found out that measuring the TVE value shows more complications than on single cold rooms fed by a remote condensing unit. The studied system was isolated by closing the liquid solenoid valve and monitoring the evaporator temperature evolution. By doing so, the temperature data could be obtained considering every single room by itself. However, once the valve is closed there is refrigerant inside the evaporator which can evaporate there or move to the suction line of the compressor rack depending if the compressors are. The remained refrigerant flowing can affect the slope of the evaporator temperature. For that reason, if the evaporator temperature draws a peak downwards along the rise, that part of the slope is skipped. Moreover, due to the refrigerant inertia, once the system reaches the set point and the valve closes, room temperature keeps going down some degrees. Therefore, the evaporator minimum temperature at each cycle varies and so it does the studied slope. If the TVE calculation were launched when temperature started to rise, each TVE value would were obtained with a variable number of measures. To check if that phenomena affects the TVE parameter, the studied temperature ramp was narrowed down, resulting in three different TVE measures regarding the initial temperature of the calculation.

3. Results and discussion

3.1. Walk-in freezer run by a remote condensing unit

The TVE methodology was tested when working on mode 1 and mode 2. As mode 2 leads to a partial discharge of the cold stored in the evaporator, the cycles between two compressor starting points become longer (Figure 4). As a consequence, the evaporator temperature takes longer and its slope is easier to track. Also, mode 2 smooths the effect of the remained refrigerant suction after closing the valve. Despite that both running modes show the same tendency as frost accumulation grows, each one of them is ruled by different fluid dynamic phenomena. When working in mode 1, just natural convection plays a role on the heat transfer, unlike mode 2 whose main mechanism is forced convection. That makes mode 1 more sensitive to errors due to thermometer precision, because heat transfer through natural convection is weaker than forced convection. Therefore, the next experiments were carried out while running on mode 2.

As mentioned in Section 2.2, the TVE method is tested by comparing it with ΔT method (Kinoshita and Sasaki, 1983). Figure 5 shows ΔT and the TVE values for the chamber operating with a set point of -15ºC but at four different frost accumulation levels. It can be observed that, unlike ΔT, TVE shows a decreasing pattern as the frost layer grows, because the evaporator temperature ramps up faster in dry conditions, considering dry as a free frost situation (Figure 6). The frost increases the heat transfer resistance between the air room and the evaporator. Additionally, as it was said, the thermal inertia of the frost hampers the heat transfer. Hence the TVE value will decrease as frost is built up on the evaporator.

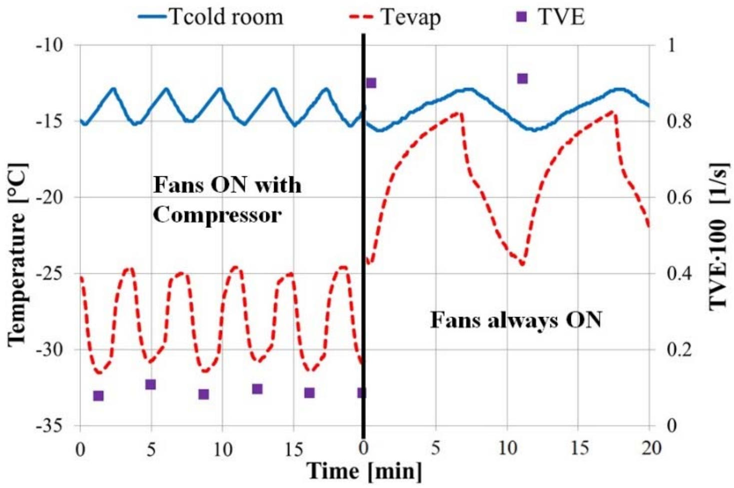

Figure 4. TVE value comparison between two different fans running modes. Set point -15ºC

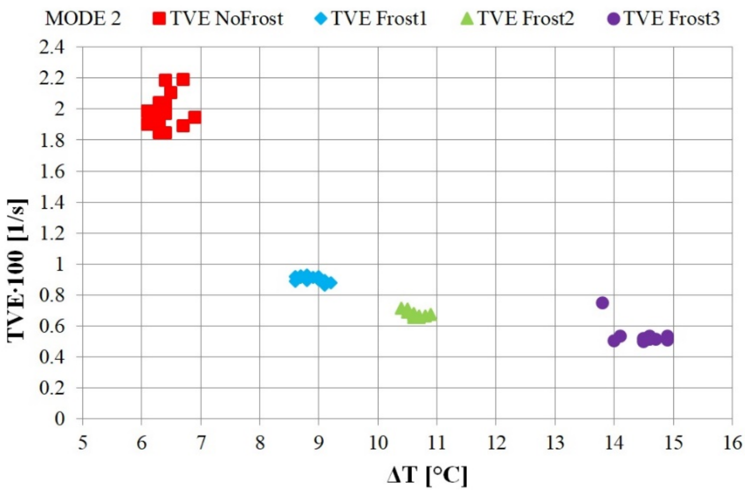

Figure 5. TVE and ΔT values on isolated walk-in freezer when working on Mode2. Set point -15ºC

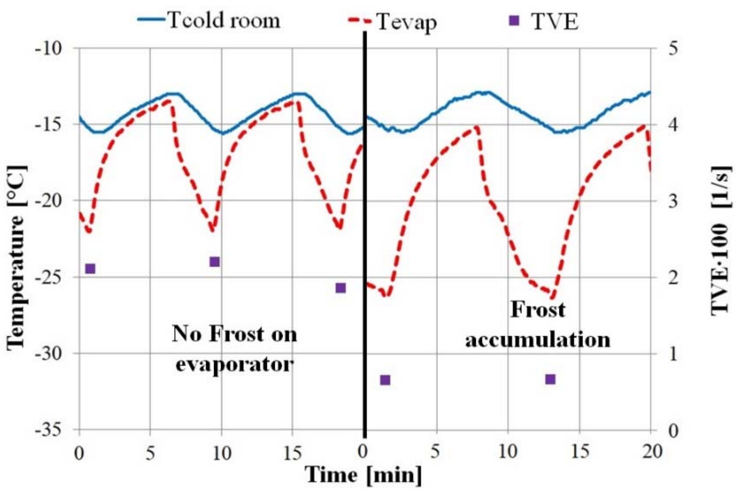

Figure 6. TVE value comparison between two different built-up frost levels on the individual walk-in freezer evaporator. Set point -15ºC

3.2. Multiple Cold Room Storages run by compressor rack

The results shown on Figure 7 were carried out on a cold room run by a rack of compressors which usually works on mode 1 and sequentially changes to mode 2 along four cycles to obtain the TVE value. Three different TVE values, each single one takes into account different slope ranges. TVE_1 measures the whole slope, while TVE_2 and TVE_3 start monitoring the slope when the evaporator temperature reaches -25ºC and -20ºC respectively. It can be seen that if the first part of the slope is neglected (TVE_2 and TVE_3), the TVE value shows more stable values.

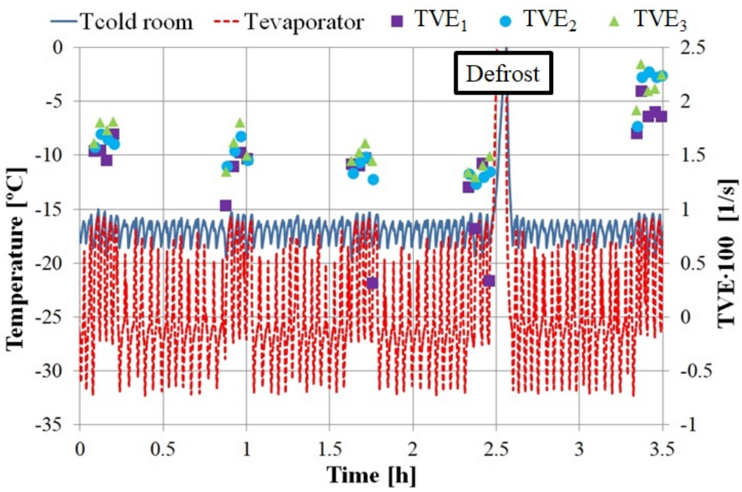

Figure 7. Multiple cold room refrigerated system at set point -18ºC

Figure 8 shows the descending tendency of the TVE_2 as frost is being stuck on the evaporator. Finally, after launching the defrost and the evaporator is dry, the next TVE value goes back to be as high as the original level. On Figure 8 it can spotted some TVE_2 measurements deviated from the tendency line, those points correspond to the first TVE calculated when switching from mode 1 to mode 2. This deviation is due to the evaporator mass inertia. As it can be observed on Figure 7, the evaporator temperature has different range when running on mode 1 and mode 2. Therefore, it cannot be compared the first TVE measurement with the others, which were calculated when the evaporator running dynamic is settled for mode 2. For that reason, the first TVE point following the running mode shift is discarded; the mean of the other three will set the final TVE level of the evaporator.

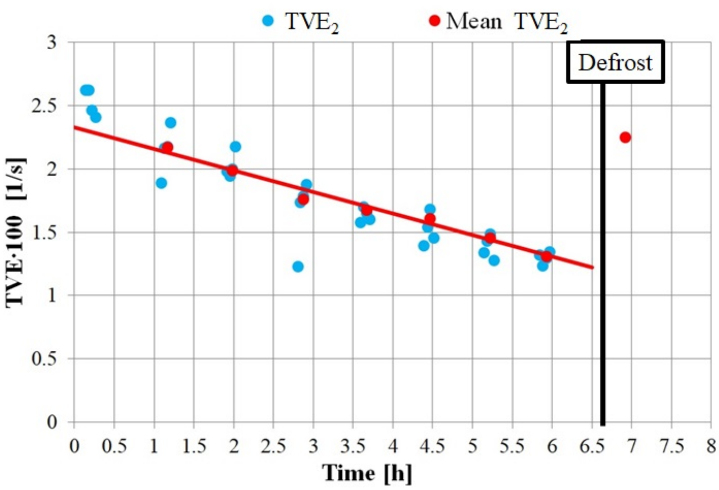

Figure 8. Variation of the TVE_2 and mean TVE_2

The results of this study provided evidence that the presented method works properly in a quantitative way to monitor the level of frost stuck on the evaporator when working on multiple cold rooms run by a rack of compressors. However, a reference value of TVE in no-frost conditions (TVE_{dry}) after a defrost process is needed to quantify the frost level, because this parameter is system dependent and it has different values for different refrigeration systems. The latter parameter will be used as reference along the system working life, but it will be restarted if the set point temperature changes.

4. Conclusions

In terms of energy efficiency, an accurate frost detection method allows to control the defrost process, providing direct energy savings by reducing the number of defrost launched and avoiding the extra energy required to cool down the cold room after each defrost (Maldonado et al., 2018), or avoiding possible evaporator blockage due to an excessive level of frost. With the aid of the developed tests, the TVE value shows its potential as indirect method for measuring the built-up frost on the evaporator, even on multiple cold room storages where a compressor rack is used. The experimental results, which were obtained from the tests using a walk-in freezer run by a remote condensing unit, confirmed the usability of the TVE method by validating it against the commonly used ΔT method (Kinoshita and Sasaki, 1983). The tests made on multiple cold room storages with a compressor rack showed the complexity of measuring the frost accumulated on those systems. Therefore, this new procedure was specially developed to work on systems with several evaporators and fed by a multi-compressor rack. Herein lies the novelty and innovation of the TVE parameter, where the ΔT method fails, the TVE parameters showed its potential as an indirect parameter to monitor the frost level stacked on the evaporator of a multi-chamber refrigeration system run by a rack of compressors.

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