Control strategies for defrost and evaporator fans operation in walk-in freezers

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Abstract

Heat removal is the most extended method for food preservation in food manufacturing industry by lowering food temperatures to stop microorganisms growing, which might spoil the product and could cause toxicity. Therefore, walk-in freezers are used for that purpose consuming a relevant part of the energy on service sector. The compression refrigeration system of the walk-in freezers can be blocked by the frost accumulated on the evaporator. For that reason a defrost process, which requires an important part of the energy consumption, has to be launched from time to time. In this paper, the schedule which manages the defrost process is investigated to limit its activation only when it is necessary. Moreover, different fan operation strategies were tested regarding the energy efficiency of the whole refrigeration system. This study has provided a system control strategy both for defrost and fans operation, depending on the frost built up on the evaporator. The control improves the energy performance of the whole refrigeration system.

Keywords: Compression refrigeration system; defrost cycle; fans operation; cooling.

Nomenclature

$E_{compressor}$	Active electrical energy consumption of the compressor
$E_{defrost}$	Energy consumed by the defrost process
E_{fans}	Energy consumed per hour by fans
E_{total}	Total energy consumption by the refrigeration system and defrost
h	hour
kW	kilo Watt

kWhe	Electrical kilo Watt per hour
min	minute
P_{fans}	Fans power
$P_{heat\ resistance}$	Electrical heat resistance power
$RH_{cold\ room}$	Cold room air relative humidity
$T_{cold\ room}$	Indoor air (freezer) temperature
$t_{compressor,f}$	Compressor ending time
$t_{compressor,o}$	Compressor starting time
$t_{defrost,f}$	Defrost ending time
$t_{defrost,o}$	Defrost starting time
T_{evap}	Evaporator surface temperature
$t_{expansion\ valve,f}$	Expansion valve closing time
$t_{expansion\ valve,o}$	Expansion valve opening time
$t_{fans,f}$	Fans ending time
$t_{fans,o}$	Fans starting time
Wh	Watt per hour
ΔT	Temperature difference between cold room and the evaporator surface
ºC	Degrees centigrade
ºC/h	Frost built-up rate in terms of hourly temperature difference increase

1. Introduction

In the food manufacturing industry, the most extended method for food preservation is heat removal. To keep all nutrients, taste/flavour and texture from the product for as long as it is safe and healthy, food is frozen. From that moment, frozen product must remain at temperatures from -20ºC to -18ºC. Once the cold chain is broken the microorganisms awake from their lethargy and keep on damaging the perishable products [1]. To keep the cold chain, supermarkets spend from 40% to 60% of the total energy consumption on the refrigerated storage [2,3].

Freezing is the most energy consuming step in the food manufacture, for instance a ton of vegetables requires from 80 to 280 kWhe [1]. Moreover, the refrigerator systems efficiency can be lowered by frost formation on the evaporator coil, which incurs in higher energy consumption. As the frost layer grows, the thermal resistance between the evaporator and air increases. If the frost formation is not stopped, the evaporator can even stop running [4]. Frost is accumulated on coils because the evaporator works at very low temperatures, below dew and freezing point, and the air in cold storages has high relative humidity due to moisture from food as well as from door openings. To avoid a complete evaporator blockage, defrost process must be often performed [5,6].
There are several defrosting methods which are currently used. On chilled room "off-cycle" defrost is usually employed, the frost built-up on the evaporator is melted at ambient room temperature, without any additional heat supply when the refrigeration is off. Other methods, which require an energy source for removing the frost, are electric heaters on the coil, hot gas passed through the evaporator, hot water sprayed on the coil, and reverse cycle [7,8]. By optimizing the defrost process, the energy consumption of refrigeration systems can be lowered. For instance, a cold storage system with electric heater for defrosting purposes, consumes around 25% of its total energy demand for that purpose [9]. Moreover, it must be taken into account that during the defrost periods the refrigeration is not running, as a consequence, the temperature of the stored product raises up which may cause the food spoilage [10-13], also part of the heat used for defrosting can be transferred to the cold room.

Some studies are focused on predicting the behaviour of the refrigeration systems by numerical models, so that the energy performance of the system can be improved. Zsembinszki et al. [14] succeeded in developing a numerical model to predict the steady-state performance of a simple vapour compression refrigeration system. Ge and Tassou [15] achieved to simulate different control strategies; the simulation shows the benefits when using a variable-head-pressure control. Bendaoud et al. [16] developed a mathematical model which includes the effect of the built-up frost on heat exchangers. The study concludes that as frost grows the heat transfer between air and refrigerant decreases. Mastrullo et al. [17] developed a transient mathematical model which incorporates door openings, frost formation, and defrost process. Datta and Tassou [18] included artificial neural network on refrigeration systems for predicting the energy consumption.

Other than numerical investigations, important efforts have been done to experimentally study the performance of these systems. Within this context, Melo et al. [4] investigated the defrost efficiency of three distinct types of electric heaters (distributed, calrod and glass tube) combined with three different heating operating modes (integral power, power steps and pulsating power). The results showed approximately same efficiency results for all studied heaters, however the step mode, which lowers the heater power gradually along the defrost, presented the best efficiency. Hai-Jiao [8] tested an air bypass circulation and electric heater method, which isolate the cold storage while hot air passes through the electric resistance and the evaporator. Along the experimental study done by da Silva et al. [19], which tested the system with different evaporator geometries, it was noticed that increasing the time between successive defrosting processes improves the thermal performance of the system, so the pair fanevaporator must be designed as a coupled system. Moreover, Votsis et al. [20], reached similar conclusions demonstrating that defrost cycles should be kept to a minimum.

Defrost are usually scheduled at pre-set times, typically every 6 or 8 hours. This defrost launching method can result in unnecessary cycles with the consequent energy waste and temperature fluctuation. The indicators used for ending a defrost cycle are usually temperature or time, whichever comes first [7]. Many researches have designed accurate defrost control systems. By means of detecting the frost formation, defrost process can be launched just on demand, hence the energy consumption will be reduced no matter the defrost method used. Different parameters were measured and used to determine the amount of frost in the evaporator, such as air pressure difference across the evaporator [20], temperature difference between room air and evaporator [**¡Error! No se encuentra el origen de la referencia.**-24], fan power [25], frost thickness by measuring frost thermal conductivity with optic sensors [26,27] or with acoustic oscillators [28], refrigerant flow instability [7,29], air humidity [30,31], measuring the heat transfer rate on the air and refrigerant side of the evaporator [32], or use of photo-electrical sensor [33-37]. However, there is no method which can measure the frost formation accurately enough to avoid what Wang et al. [38] called mal-defrost phenomena.

In this paper, the energy consumption of the cooling system depending on the frost level on the evaporator coil has been explored experimentally to determine the optimum level of frost to program defrost cycles. Moreover, different fan control strategies have been experimentally investigated when operating at different frost levels on the evaporator coil. This research will provide important guidelines for the operation and management of fans and defrost activations according the detected level of frost at evaporator.

2. Methodology

The main goal of this paper is to present a novel control strategy for defrost and evaporator fans to optimize the performance of a simple vapour compression system at different levels of frost in the evaporator. The schematic of the refrigeration cycle is shown in Figure 1, which consists of a condensing unit, an expansion valve, and an evaporator.

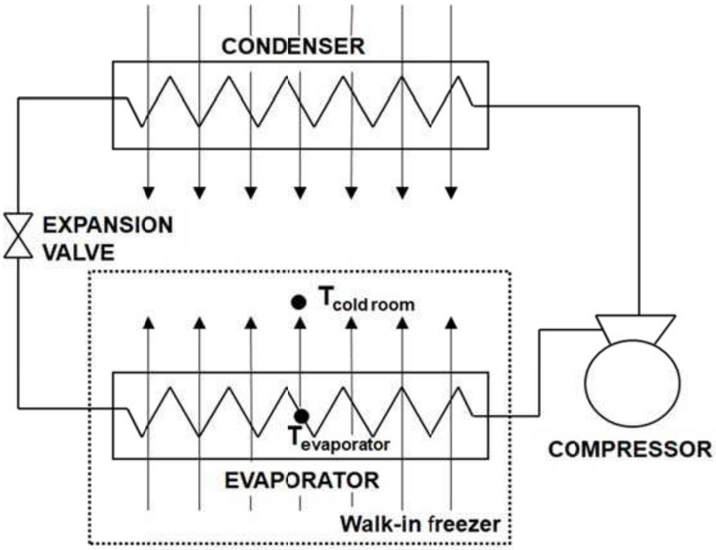

Figure 1. Refrigeration cycle scheme

2.1. Experimental set-up

The experimental set-up consists of a walk-in freezer unit located in the laboratory room of AKO ELECTROMECÀNICA, S.A.L. (Figure 2). The freezing unit employs R404A as refrigerant and is equipped with a Silensys condensing unit (SIL2464Z) from Tecumesh consisting of a three-phase hermetic reciprocating compressor, fin-and-tube air-cooled condenser with a variable speed fan. The system also contains a fin-and-tube evaporator with a constant speed fan that blows air over the evaporator. As expansion device the system uses an electronic expansion valve with AKO controller that sets the superheating to a constant value. The system has an electrical heater as defrosting method.

The test facility was comprehensively monitored to measure:

- the indoor air (freezer) temperature ($T_{\text{cold room}}$);
- the evaporator surface temperature (T_{evap});
- the cold room air relative humidity ($RH_{cold\ room}$);
- the compressor starting/ending time ($t_{\text{compressor,o}}/t_{\text{compressor,f}}$);
- the expansion valve opening/closing point ($t_{\text{expansion valve,o}}/t_{\text{expansion valve,f}}$);
- the fans starting/ending point ($t_{\text{fans,o}}/t_{\text{fans,f}}$);
- the active electrical energy consumption of the compressor using a CVM Mini power analyser ($E_{\text{compressor}}$). It has to be pointed out that the condensing

temperature remains constant along all the experiments, because that temperature affects the compressor energy consumption.

- the defrost starting/ending time ($t_{defrost,o}$/$t_{defrost,f}$).

The temperature measurements were performed using PT-100 temperature sensors with an accuracy of ± (0.3+0.005·|T|) ºC (DIN EN 60751 F 0.3 class B), and all the data was registered every 5 seconds through IPC-CON modules (ET-7015 and ET-7019Z), while the accuracy of the electrical power measurements was 1%.

Figure 2. Walk-in freezer in the laboratory of AKO ELECTROMECÁNICA S.A.L.

2.2. Set of experiments for fans operation strategy

Three different fan control strategies have been experimentally tested and monitored to analyse how the energy consumption varies depending on the management of the fans of the evaporator. These three fan control strategies are defined as follows:

- Mode 1, fans with compressor: This control strategy activates the fans at the same time as the compressor (Figure 3). Thereby, once the set point and the dead band are fixed, compressor and fans will run until the cold room temperature reaches the set point. Then both of them stop, letting the room temperature rises until the dead band is passed, at that moment compressor and fans will turn on again.

- Mode 2, fans always on: This control strategy will keep the fans of the evaporator always running, no matter if the compressor is on or off, regardless of the room temperature (Figure 4). The compressor will work as described on mode 1. At first sight, this strategy means an increase on the energy consumption; however, it may have some benefits on the whole system operation such as reducing stratification inside the refrigerated space. Moreover, the use of this control strategy makes that less frost is accumulated on the evaporator because the heat transfer is higher due to convection between air flow and the evaporator, when compressor is off. Also, it allows the use of the "cold energy stored" to delay the temperature rising on the cold room, while the compressor is not working, which makes refrigeration cycles longer so that compressor suffers less start-stops sequences.
- Mode 3, fans frost discharging: This control strategy turns the fans on along certain temperature conditions, while the compressor is off. The idea is to keep the cold room at the set point temperature by discharging the stored cold on the build-up frost [39]. Thereby, the compressor turning on will be delayed and hence electrical energy consumption is reduced. Figure 3 shows how once achieved a temperature level out of set point plus dead band (-16ºC in case of Figure 5) compressor and fans work at the same time to lower the cold storage temperature to the set point (-18°C). Once the set point is reached both devices stop, and the temperature starts to rise. Before hitting the dead band (-16°C), at an intermediate temperature level (-17°C) the fans switch on to check if there is any chance of decreasing the room temperature by using the cold of the stuck frost on the evaporator.

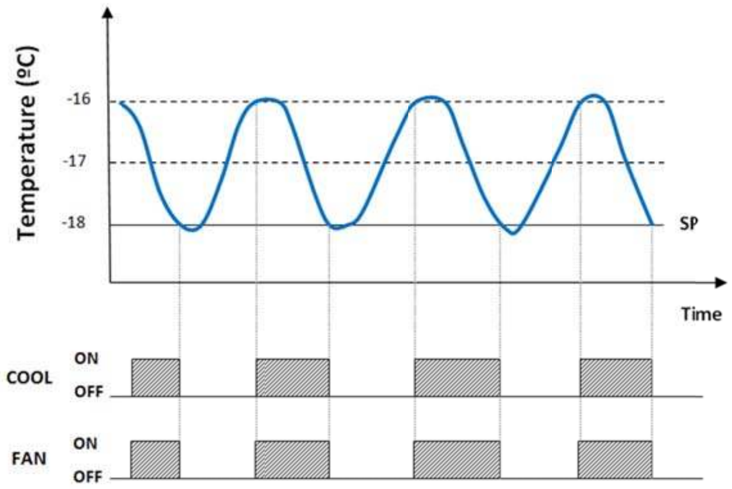

Figure 3. Running mode 1, fans defrost discharging

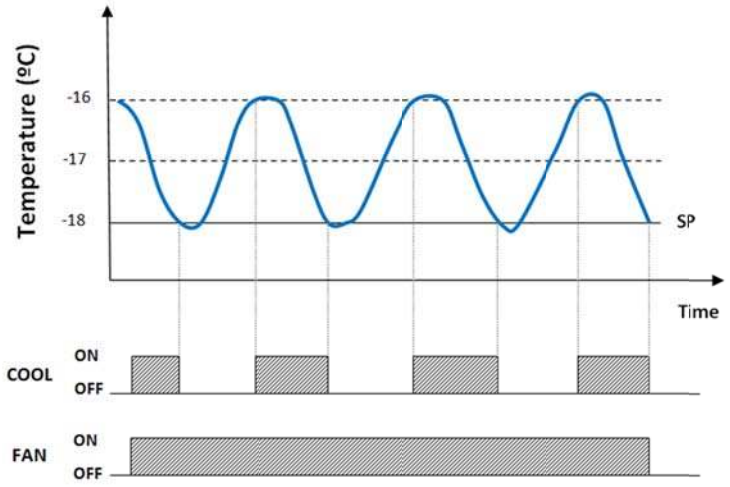

Figure 4. Running mode 2, fans defrost discharging

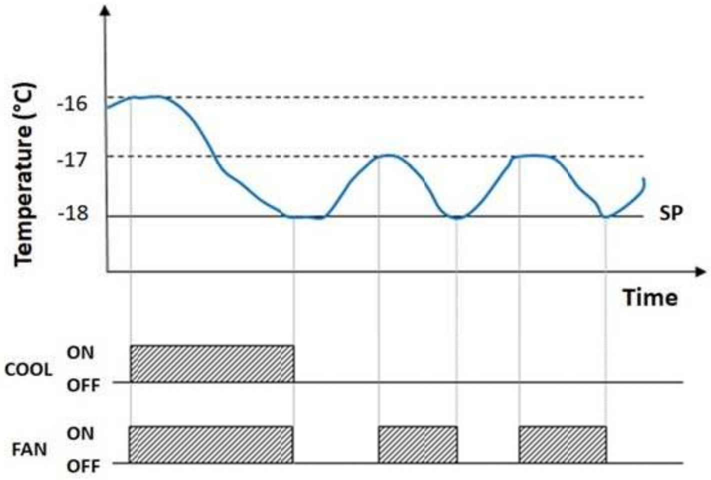

Figure 5. Running mode 3, fans defrost discharging

Each control strategy has a different behaviour depending on the level of accumulated frost on the evaporator. Therefore, different experiments are carried out: a first one with no frost stuck on the evaporator, and three of them with different frost levels. In this research, the frost level is quantified by the difference between temperatures at the refrigerated room and at the evaporator surface ($\Delta T = T_{\text{cold room}} - T_{\text{evap}}$) once the system achieves the set point, just before the compressor switches off and the expansion valve closes. This methodology was proposed by Buick et.al [22] and was patented by Minoru Kinoshita et.al [21].

2.3. Set of experiments for defrost cycle

Periodic evaporator defrost is necessary to avoid high level of stuck frost, which can produce a mal-functioning on the system or lead to higher energy consumption. The perfect timing for starting the defrost process as well as its periodicity depends on several parameters such as the humidity inside the cold room, the thermal load stored, the set point temperature, the frequency of door openings, etc. Launching the defrost when there is no frost stuck or just a small frost layer, or the opposite situation, affects the time and energy required, besides the defrost cycle frequency. For that reason, the impact of the defrost launching on the daily energy consumption of the system is studied. Two parameters are monitored for that purpose: the energy consumption of the system operating with different levels of accumulated frost in the evaporator, and the time required in the defrost process to melt these different frost quantities. As previously stated, the stuck frost is calculated through the temperature difference between the evaporator and the cold storage. In the different experiments performed, the frost was built up by leaving the cold storage door open. The system is running normally for 2 hours before carrying out the defrost tests, that way the system works under steady state conditions. For developing the tests, deep-freeze rooms with set points lower than zero (-10°C and -15°C) were selected, instead of positive cold rooms, because the frosting effect is higher. The tests include four different frost levels (starting at dry conditions) and the three fans running modes per each frost level and set point.

From latter experiments, the energy consumed by the system is related with the built-up frost through a regression. Three parameters are calculated, all of them regarding the built-up frost on the evaporator:

- Energy consumed per hour by the compressor and the condenser fans at usual running ($E_{compressor}$).
- Energy consumed per hour by fans at usual running ($E_{fans} = P_{fans} \cdot (t_{fans,f} - t_{fans,o})$).
- Energy consumed by the defrost process, which includes the heat required for melting the frost accumulated on the evaporator, and energy consumed by the compressor and fans for lowering the room temperature to the set point. ($E_{defrost} = P_{heat\ resistance} \cdot (t_{defrost,f} - t_{defrost,o}) + E_{compressor} + E_{fans}$).
- Defrost required time.

The results allow to calculate the daily energy consumption of the whole system depending on the defrost launching strategy (ΔT at which the defrost is launched) for each fan control strategy.

3. Results and discussion

With the developed tests, the energy consumption of the refrigeration system is related with the temperature difference between the cold storage and the evaporator. The energy consumed by the compressor and fans, and the defrost process are studied separately. From the experimental results, the relation between the energy usage by both compressor and fans, and the accumulated frost is obtained, as well as the relation between the energy consumption of the whole defrost process, the required time, and the built-up frost. This calculus process is made for each fan control strategy and set point temperature.

3.1. Control strategy for fan operation

The first approach to determine the ideal control strategy is to analyse each fan control mode. To that purpose the refrigeration system energy consumption is isolated from the energy that the defrost process requires. Hence, the energy consumed by the compressor, the fans, and the condenser is studied when working at the three different modes separately from the energy required to carry out the defrost process.

Figure 6 and Figure 7 show that in case the evaporator has no frost on it, the most efficient fan control strategy is Mode 1, in which fans work simultaneously with the compressor. This tendency changes when the frost layer is considerably increased (ΔT is over 9) in both studied cases. At the mentioned situation, fan control strategy of Mode 3 steps forward to become the most energy efficient option. It has to be noticed that Mode 2 fan strategy reduces the energy consumed by the compressor when the evaporator has some frost stuck on it, but it does not provide overall savings due to excessive use of fans. Hence, if more efficient fans were used, the selection of the most appropriate fan control strategy according to frost level might have varied.

It also has to be taken into account that the set point can affect the control strategy efficiency, as it can be seen on Figure 6 and Figure 7, which show the hourly energy usage of the refrigeration system at set point temperatures of -10°C and -15°C respectively. For instance, at -15°C set point temperatures, Mode 2 becomes more efficient than Mode 1 when the frost layer grows (when ΔT is over 12ºC). However, it is required a frost level over 18ºC for Mode 2 to become a better option than Mode 1 at -10ºC set point temperature. Although at those built-up frost levels Mode 3 is still the most efficient in both situations.

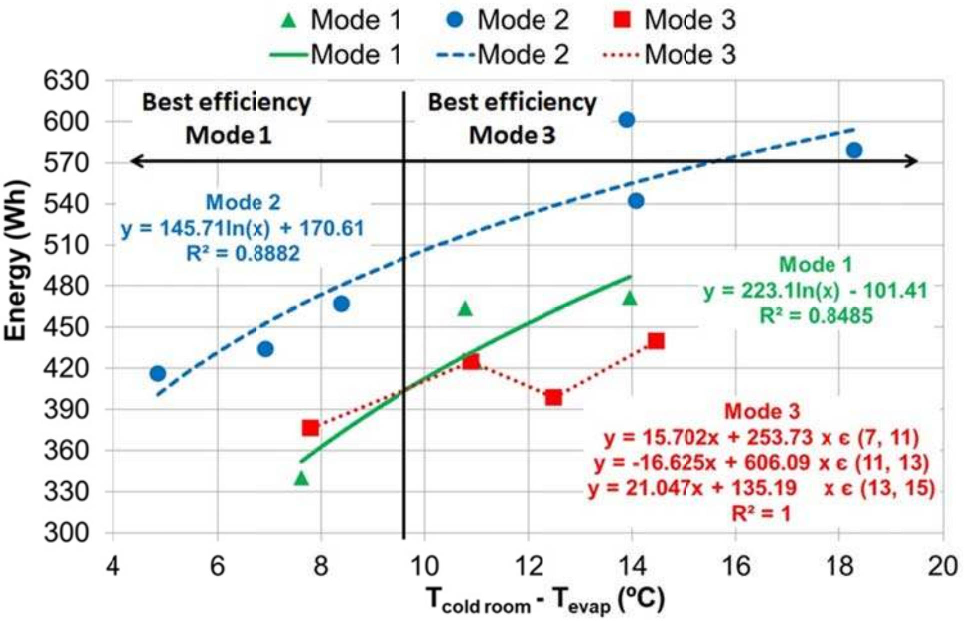

Figure 6. Refrigeration system hourly energy consumption at different levels of built-up frost on the evaporator (set point -10°C)

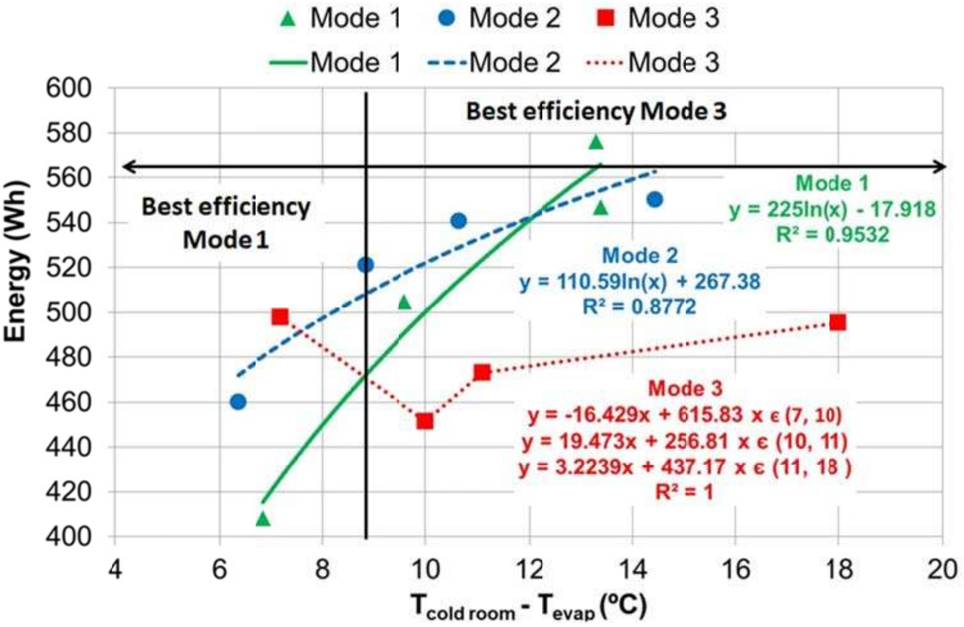

Figure 7. Hourly refrigeration system energy consumption at different levels of built-up frost on the evaporator (set point -15°C)

The latter data are used to develop correlations between the hourly energy consumption of the refrigeration system, and the frost built-up (ΔT) by logarithmic regressions. It has to be taken into account that the total energy required by the whole system includes the defrost process, which is added on the next section.

3.2. Defrost cycle operation

The next part of this study consists in finding the most proper defrost starting time. First of all it has to be pointed out that defrost energy usage takes into account the following aspects:

- Heat intake required by the heater to melt the frost.
- Compressor energy used to set the cold room back at the set point temperature.
- Energy consumed by fans.

Figure 8 and Figure 10 show the energy consumption by defrost process as the built-up frost on the evaporator grows. Alike, Figure 9 and Figure 11 show the time required by the defrost. As it can be observed by comparing Figure 8 and Figure 9, and Figure 10, and Figure 11, respectively, the energy use of the defrost process only depends on the time required to carry it out, which is related with the built-up frost layer on the evaporator. This is because while the heater is on, both compressor and fans are switched off no matter the running fan mode; also both of them turn on, when the defrost is finished, to reach the set point. Logically, the thicker the frost layer is the longer the defrost process takes, consuming more energy along the frost melting consequently.

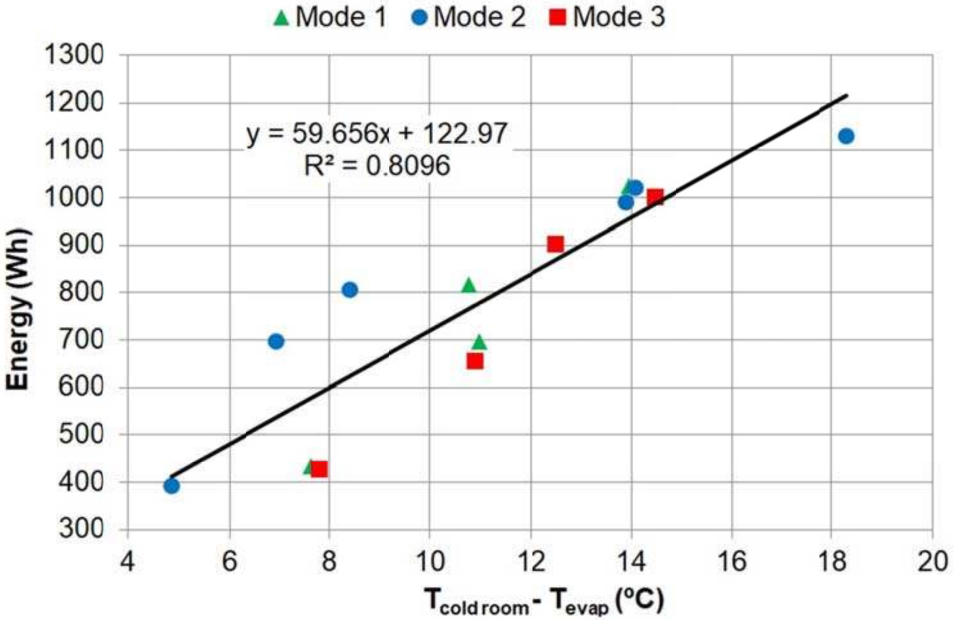

Figure 8. Energy consumption by defrost vs. the frost on the evaporator (set point -10°C)

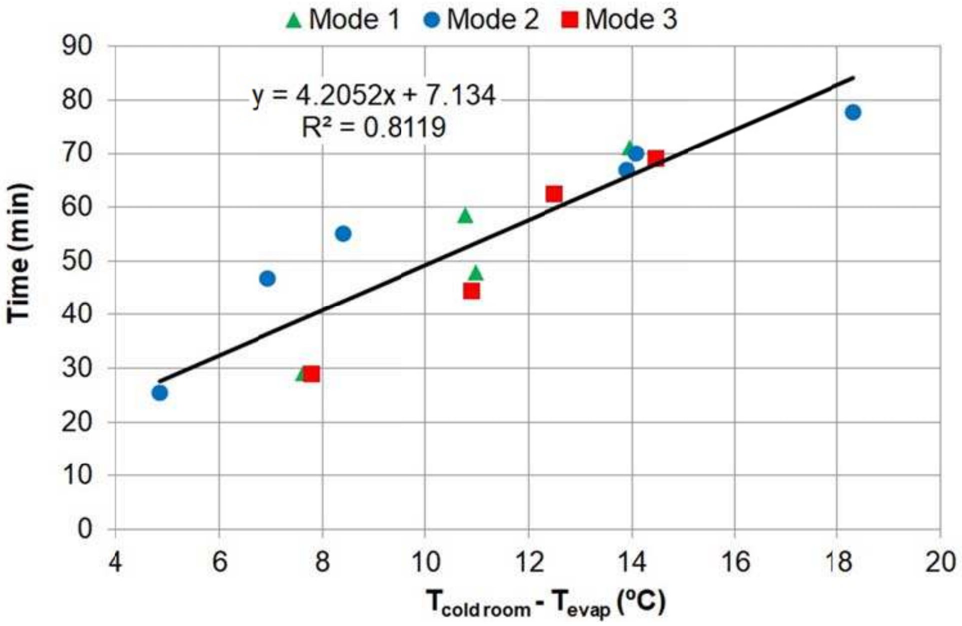

Figure 9. Time required for defrosting vs the frost on the evaporator (set point -10°C)

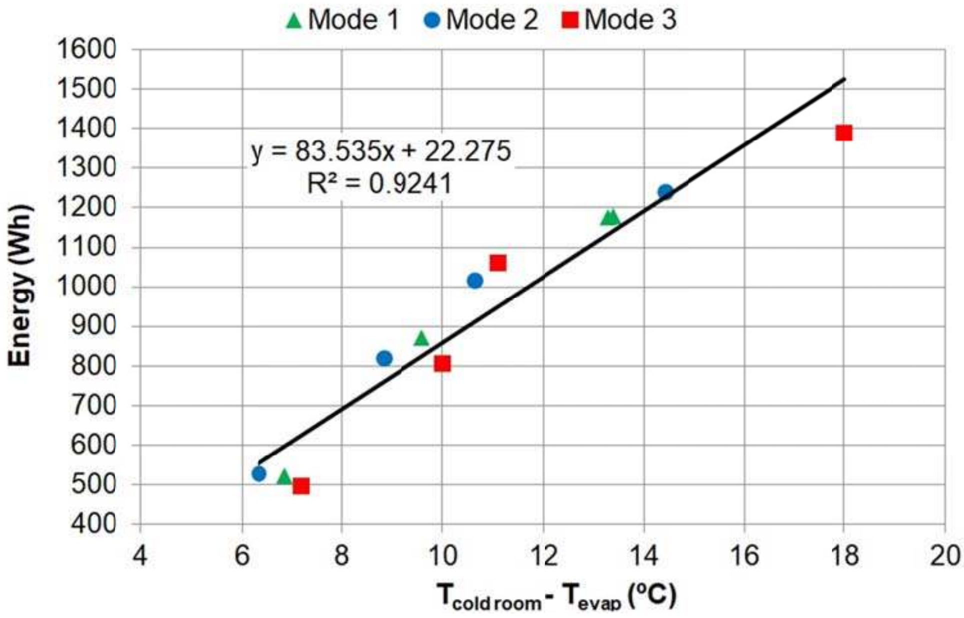

Figure 10. Energy consumption by defrost vs the frost on the evaporator (set point -15°C)

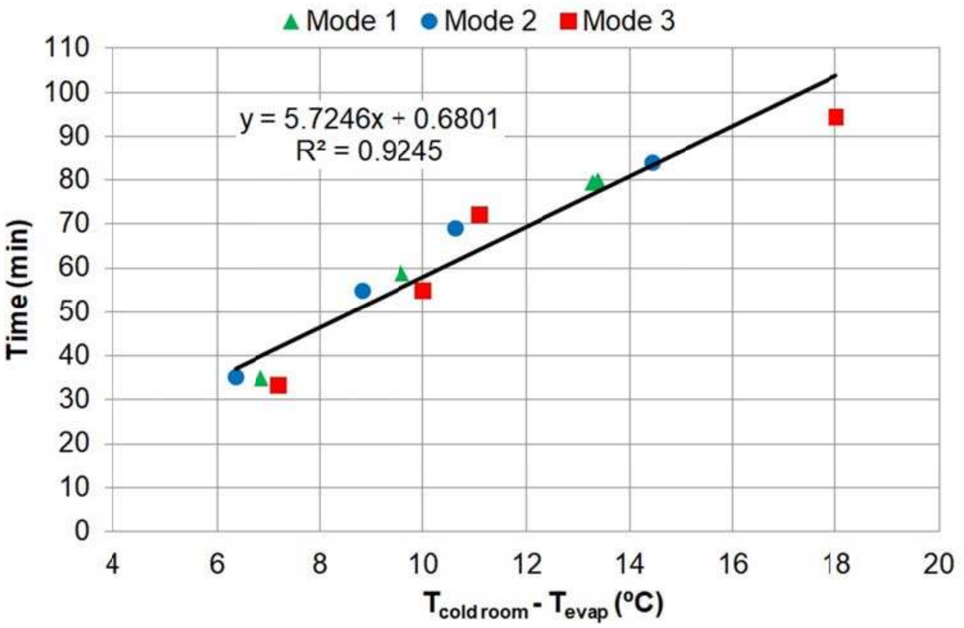

Figure 11. Time required for defrosting vs the frost on the evaporator (set point -15°C)

3.3. Optimization

The experimental data presented in Section 3.1 and Section 3.2 were used to develop empirical equations to calculate, depending on the frost level (ΔT between evaporator and cold room), the total energy consumption by compressors and fans during an hour of operation of the system (Figure 6 and Figure 7), as well as the energy (Figure 8 and Figure 10) and time (Figure 9 and Figure 11) required during the defrost process. From the experimental data shown in Figure 6 and Figure 7, the hourly energy consumption was estimated. Logarithmic regressions were used when estimating the energy consumed by modes 1 and 2. However, a function defined by parts was required to estimate the energy required for mode 3. These equations are used to optimize defrost launching strategy for each mode of fan operation. The overall daily energy consumption of the system is calculated regarding the different defrost strategies (ΔT at which defrost is launched). It combines the hourly energy consumed by compressor and fans, with the defrost process. This defrost process takes into account the heating energy, the cooling energy to get back to the set point, and the time needed for the process.

The study also shows the daily energy requirement at several scenarios; each one simulates the frost built-up rate in terms of hourly temperature difference increase (x °C/h). Along these scenarios the frost level ramp up was considered lineal. Situations from extremely fast frost growing (3 ºC/h) to a considerably lower one (0.1 ºC/h) were considered.

Total daily energy consumption (Etotal = Ecompressor + Efans + Edefrost) when the system is working in Mode1 fan strategy with a set point fixed to -15°C is shown in Figure 12. It is observed that when the frost built-up rate is 0.1 ºC/h, the optimal frost level for launching the defrost is ΔT = 8°C. It has to be specified that the frost level (ΔT) when there is frost on the evaporator, is compared with ΔT measured at dry conditions, so each refrigeration system has its own optimal ΔT. However, the general tendency, which the other scenarios follow, is to become more efficient in case defrost is launched when there is significant frost accumulated on the evaporator (values of ΔT above 11ºC). The performance of the refrigeration system working in Mode 2 and Mode 3 are similar, as shown in Figure 13 and Figure 14, respectively.

Figure 12, Figure 13 and Figure 14 also show the required time for the whole defrost process, considering time to melt the accumulated frost and time required to achieve set point conditions after defrost. It has to be noticed that during this defrost period, the refrigerated space is out of desired temperature range, which could lead to extra costs and reduce the product shelf-life. Within this context, the authors want to highlight that even though from an energy consumption point of view, the most appropriate strategy to launch the defrost is to allow frost accumulation as much as possible (before evaporator blockage), the duration of the defrost is a crucial parameter which has to be considered when deciding the strategy to launch defrost processes.

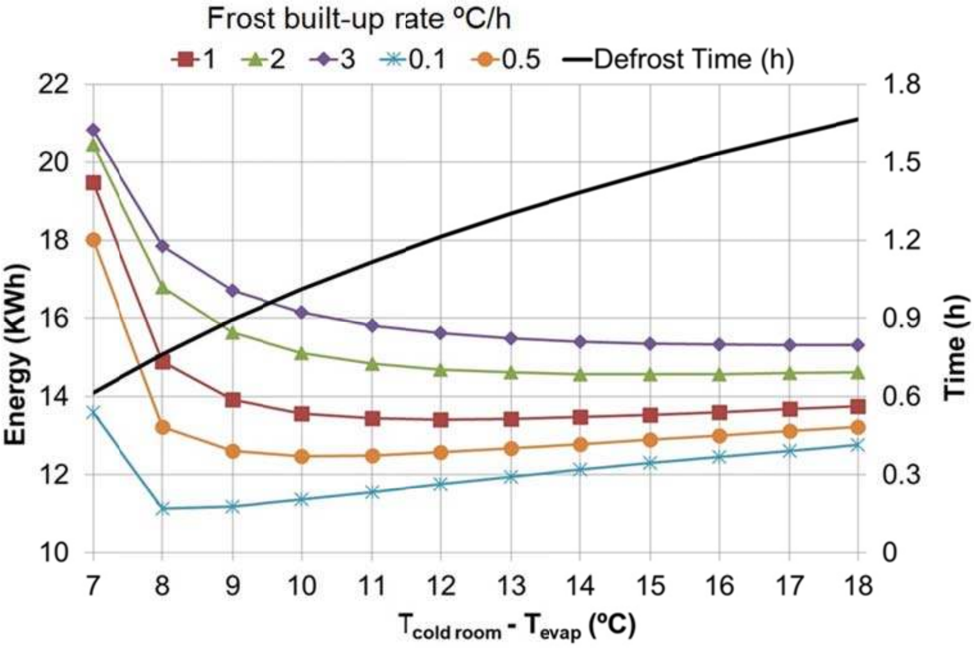

Figure 12. Refrigeration system and defrost daily energy consumption at different frost growth scenarios – Mode 1 (set point -15°C)

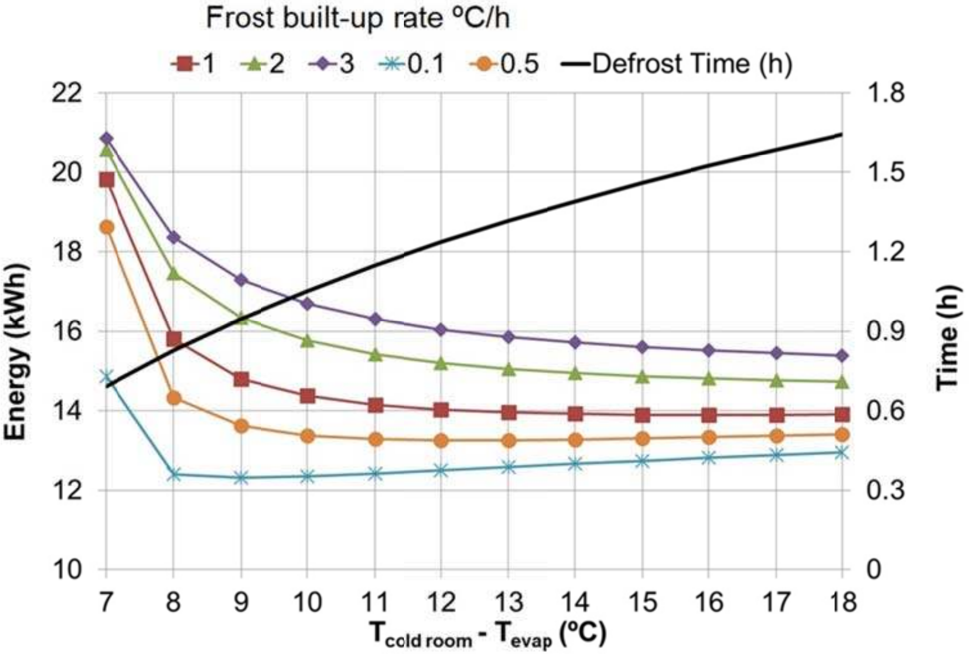

Figure 13. Refrigeration system and defrost daily energy consumption at different frost growth scenarios – Mode 2 (set point -15°C)

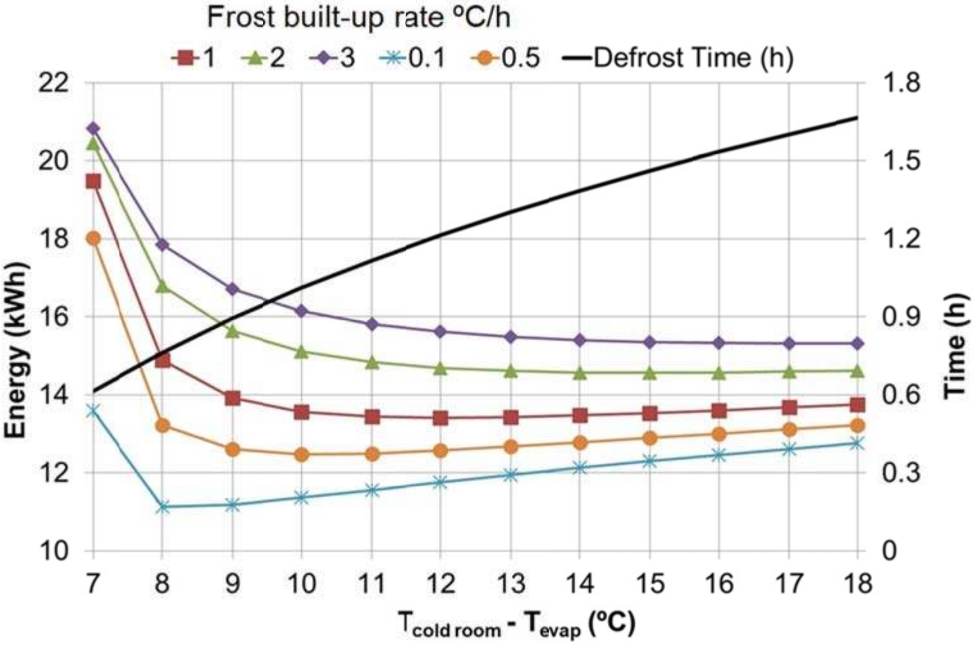

Figure 14. Refrigeration system and defrost daily energy consumption at different frost growth scenarios – Mode 3 (set point -15°C)

Once all results were collected, all modes were combined to develop the optimal control strategy. On the studied experiments, the optimal solution, for both set point temperatures, consists of setting Mode 1 when there is limited amount of frost accumulated in the evaporator, and Mode 3 for higher values of frost. As observed in Figure 15, the refrigeration system works at Mode 1 until ΔT = 9°C, when it changes to Mode 3 to always use the best energy performance running mode. The general tendency, for all scenarios is to become more efficient as the frost builds up on the evaporator. This efficiency improves slowly after frost levels over ΔT = 14°C. Meanwhile the time required to complete the defrost keeps increasing. Therefore a trade-off between efficiency and time out of the dead band has to be reached.

Finally, Figure 16 shows the three different running modes and the optimal combination of them, considering the same frost built-up rate (1ºC/h). Despite that mode 3 and the optimal one have the same development, after ΔT = 9ºC, the energy consumed is lower when working at optimal mode by the same level of stuck frost.

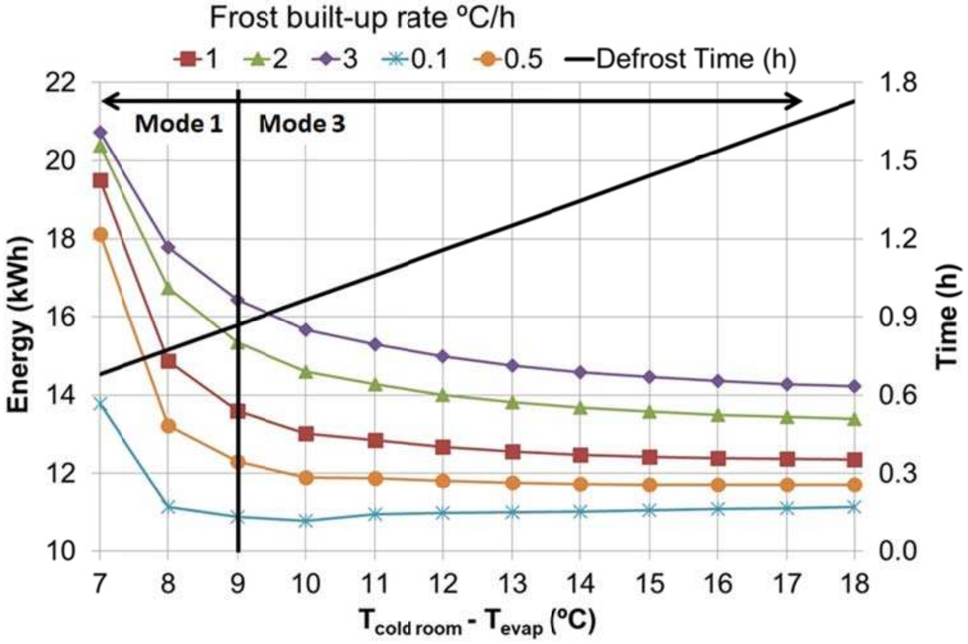

Figure 15. Refrigeration system and defrost daily energy consumption at different frost growth scenarios – Optimal Mode (set point -15°C)

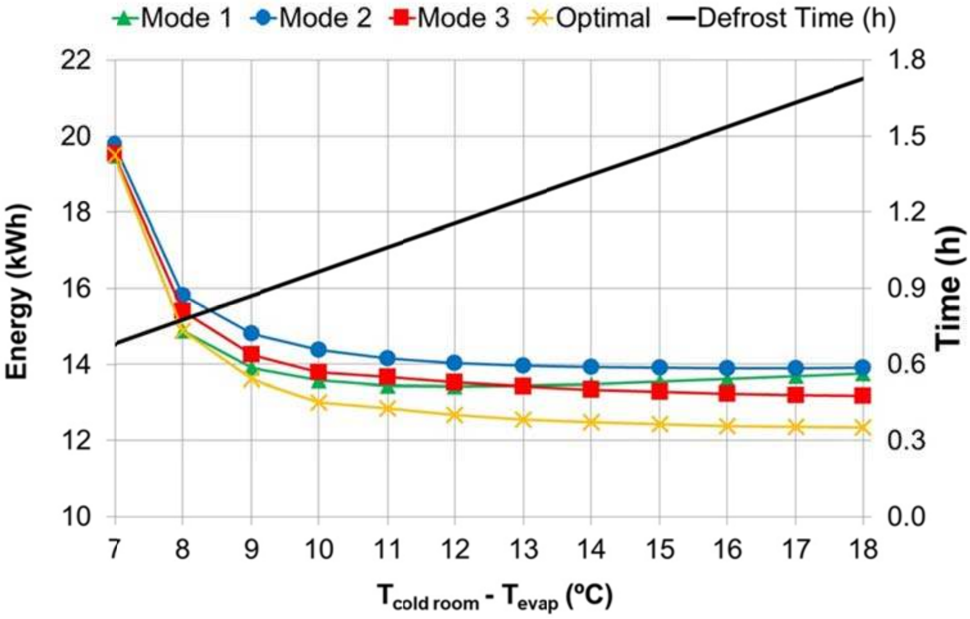

Figure 16. Refrigeration system and defrost daily energy consumption at 1ºC/h frost rate scenario – Mode1, Mode 2, Mode 3 and Optimal Mode (set point -15°C)

4. Conclusions

This paper experimentally investigates the performance of a refrigeration system when programmed using different control strategies for the evaporators fan operation, as well as optimizes the defrost operation based on experimental results. In conclusion, the research findings of this study have provided evidence that there are no unique fan control strategies which can assure the most energy efficient running way, as the performance of each strategy depends strongly on the amount of frost accumulated in the evaporator during the operation. Therefore the combination of several working strategies, regarding the frost built-up on the evaporator, can improve the performance of the refrigeration system. Moreover, the results revealed that the longer the defrost launching is delayed, the lesser energy is consumed by the system. However, despite the fact that some fan control strategies take the cold stored in the stuck frost [39], the frost layer keeps increasing along the refrigeration system is running. So, delaying the defrost increases the energy efficiency, but also the defrost time required is longer, as well as the time the cold space temperature is out of the dead band.

In terms of energy efficiency, refrigeration control strategy must combine Mode 1 and Mode 3 regarding the frost layer accumulated on the evaporator. For that reason, to manage any system, no matter its dimensions, an adaptive control, which combines the strategy tested, must be developed. As well as, an accurate frost detection method which can be used at any cold room, no matter the system installed.

Acknowledgements

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