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The thermal performances of a refrigerator incorporating a Phase Change Material

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Abstract

In this paper, a Phase Change Material (PCM) has been incorporated within the cabinet of a refrigerator, attached to the bare tube evaporator placed below the racks, with the aim of analysing the variation of temperatures and compressor operation, among others. The effect of different control settings (hysteresis) on the performance of such a system, equipped with tap water as PCM, is investigated. Furthermore, the impact of the variation of the ambient temperature and the product mass is highlighted. Two novel parameters are introduced: the first one to estimate the utilisation of the PCM during the cyclic operations of the refrigerator, and the second one is used to evaluate the fluctuation of the product temperature within the cabinet. Experimental results show that the introduction of the PCM has led to a noticeable reduction of the temperature gradient within the cabinet and the fluctuations of product temperature ensuring better conservation conditions, and to extend the OFF time of the compressor. The tests also show that with PCM, hysteresis has lower impact on the fluctuation of the product temperature, ON-time ratio and energy consumption of the refrigerator than without it. On the contrary, the product temperature distribution is more affected by the hysteresis with PCM than without, leading to a better uniformity with higher hysteresis.

Keywords: Phase Change Material (PCM), Temperature control, Hydrocarbons, Cold storage, ON/OFF control

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HIGHLIGHTS

- Cyclic operations of an R-600a refrigerator equipped with PCM were investigated;
- The effects of different control settings were shown;
- The utilisation of PCM latent heat was estimated;
- Product temperature fluctuation was reduced using PCM;
- PCM ensured a better uniformity of the product temperature, increasing with hysteresis.

Nomenclature

Symbols

E: electric energy consumption	[W h]
LHUR: Latent Heat Utilisation Ratio	[%]
m: mass	[kg]
P: power absorbed	[W]
PCM: Phase Change Material	
T: temperature	[K]

Greek symbols

Δ: hysteresis	[K]
δ: ON-time ratio	[%]
τ: time	[s]

Subscripts

24h: along 1-day
air: of air
amb: ambient
ave: average
cycle: ON plus OFF phase of the compressor
down: below the rack
el: electric
ev,inlet: at the inlet of the evaporator
ev,outlet: at the outlet of the evaporator
max: maximum
melt: melting point
min: minimum
OFF: phase of the stop of the compressor
ON: phase of working of the compressor
PCM: of PCM
prod: of product
rack2: within the rack 2
rack5: within the rack 5
set: set-point
up: above the rack
wall: close to the cabinet wall

1. Introduction

The International Institute of Refrigeration estimated that the total number of domestic refrigerators and freezers in operation worldwide is around 1.5 billion [1], and considering an annual electricity consumption of 450 kWh each [2], they cause worldwide annual greenhouse gas emissions equivalent to more than 480 million tons of CO_2-eq. As a consequence, they consume almost 4% of global electricity [1]. Only in the United States, 164 million domestic refrigerators and freezers in operation were estimated in 2015, that is approximately 10.7 million new units produced and sold annually [3], and the quantity produced increases every year. Besides, the share of total household electricity demand in the European Union is so relevant that they have created energy labelling for domestic refrigerators and freezers [4]. Therefore, given the relevance of domestic refrigerators and freezers in the global energy consumption and greenhouse gas emissions, energy efficiency measures must be considered for these household appliances.

Among different new techniques, Belman et al. [5] included the employment of PCMs as an excellent option to achieve considerable energy savings in domestic refrigerators and highlighted their utilisation for internal temperature control. Veerakumar and Sreekumar [6] concluded that PCMs are becoming essential in cold storage, but there are some practical problems like low heat transfer, super-cooling, corrosion of the PCM container and stability. The term super-cooling refers to a metastable state of PCMs in which they remain in the liquid phase when cooled below its freezing temperature [7]. Besides, they stated that selecting a PCM for a specific cold storage application is an essential criterion. In the same way, Oró et al. [8] highlighted that the adjustment of the melting/freezing temperature could be achieved through additives, that can also minimise super-cooling and phase segregation in the case they act as nucleating and thickening agents. Du et al. [9] showed that the PCM-encapsulation and the heat transfer enhancement are the latest proposed solutions to reduce the drawbacks presented by the PCMs placed in domestic refrigerators (PCM leakage, super-cooling, and low thermal conductivity).

Hence, besides energy consumption, domestic refrigerators also present the problem of the conservation temperature. James et al. [10] evidenced that throughout the world, most of the refrigerators work above the recommended maximum temperature of 5 °C. The review of Mastani Joybari et al. [11], about the application of PCMs in domestic refrigerators and freezers, concluded that the introduction of PCM in different places and configurations shows promising results in terms of operating temperatures and energy efficiency, but they recommend additional study to find the most appropriate PCM type for such application. An additional review about utilisation of PCMs in domestic refrigerators was written by Bista et al. [12]. They remarked that the position of the PCM regarding the refrigerator, or the vapour compression system, has a significant influence on the electric energy consumption, energy performance, and temperature distribution.

PCMs can be placed on the inner surface of the refrigerator to smooth the temperatures. Akif Ezan et al. [13] developed and experimentally validated a 3D transient model in ANSYS-FLUENT for a vertical beverage cooler with water as PCM. The implementation of the PCM slab reduces the ON-time ratio (the ratio between the ON time, τ_{on}, and the cycle period, τ_{cycle}) and preserves the inside air temperature by limiting the unanticipated temperature variations. Liu et al. [14] placed PCM in the fresh and frozen food compartments of an air-cooled frost-free refrigerator in two operating modes (different peak time operation). PCM restrained the air temperature in the fresh food compartment and the temperature of the M-packs (standardised refrigeration test packs equipped with temperature measuring sensors) in the freezing compartment but did not exhibit advantages concerning power consumption compared with the original prototype. Marques et al. [15] simulated a new thermal storage household refrigerator to investigate the effect of PCM orientation, phase change temperature and compartment height on refrigerator temperatures. They highlight the convenience of a refrigerator with PCM to be integrated into the electricity supply grid with intermittent generation by renewable energies. Lakshaman et al. [16] confirmed that PCMs are an excellent strategy to integrate domestic refrigerators in smart grids. Then, Marques et al. [17] studied the combination of more efficient larger compressors with PCM to store the excess cooling capacity and hence the refrigerator autonomy. They employed 5 mm thin water PCM slabs that were supercooled between -1.5 and -2 °C before the ice formation process started. Bakhshipour et al. [18] studied the effects of refrigerant property, condenser length and tube diameter, PCM thickness and mass flow rate on refrigeration cycle when N-Octadecane as PCM is located at the shell side. The simulation results showed that this configuration can increase energy performance up to 9.58% and suggest that an optimum PCM thickness improves the energy performance of the system.

Another possibility is the integration of the PCM in the condenser surface. Cheng et al. [19] studied a new household refrigerator equipped with the heat storage condensers. The resulting benefits were lower condensation temperature, higher evaporation temperature, and much larger super-cooling degree at the condenser outlet. As a result, the energy efficiency increased approximately by 12%. Then, a dynamic model of this system led to conclude that the energy saving effect increases if the ambient temperature increases and the freezer temperature decreases [20]. Sonnerein et al. [21] studied different options of sensible and latent heat storage elements equipped in standard wire-and-tube condensers, and finally reduced the electric power consumption up to 10% with 0.5 kg of non-encapsulated copolymer compound.

However, the most commonly studied PCM configuration is the integration into the evaporator. Shikalgar Niyaj and Sapali [22] located the PCM (mixture of ethylene glycol and water) in the evaporator (free convection, roll bond, back wall positioned with a cavity). The average compressor ON-time ratio per cycle and the temperature variation inside the cabin was reduced. Yusufoglu et al. [23] used two substantially different refrigerators to study four PCM types (including distilled water with and without additives) wrapped around the evaporator. The compressor ON/OFF period was optimised, and the energy efficiency increased between 8.8% and 9.4%. For further improvement of the energy efficiency, the authors recommend to consider the heat gain of the refrigerator at selected ambient temperature when the amount and the location of PCM is selected. Azzouz et al. [24] placed PCM on the back side of the evaporator of a single-door single compartment refrigerator. The cold storage capacity of the system was slightly reduced with a eutectic aqueous solution (freezing point -3 °C) than with water as a PCM, but the eutectic solution kept the air at proper temperature values recommended for the refrigerator. The coefficient of performance increased between 10 and 30%, and the PCM allowed between 5 and 9 hours of continuous operation without electrical supply. These results confirmed the benefits predicted by a previous numerical simulation [25]. Visek et al. [26] implemented several technologies in a bottom-mount built-in refrigerator/freezer (4.5 and -18 °C compartment air temperatures respectively), such as block valve, check valve, P/O phase, condenser fan and PCM in contact with the refrigerator compartment evaporator. The evaporation temperature increased by a maximum of 8.4 K and the overall energy saving was 5.6%. They suggested improving the thermal conductivity and heat transfer area between PCM and evaporator external surface. Cofré-Toledo et al. [27] also found an increase in the evaporator temperature, but the average temperature of the fresh food and fast cooling compartments was reduced. Berdja et al. [28] demonstrated that the PCM has a significant impact on evaporator heat transfer during the ON time, comparable to frost.

Oró et al. [29] studied the PCM (freezing temperature of -18 °C) effect in a commercial freezer under power failure and door openings. The PCM allowed the M-pack temperature to stay about 2 °C lower during 3 h of electrical power failure. Besides, for door opening tests, -19°C storage temperature provided the highest benefit. Using the same system with two commercial PCMs, Oró et al. [30] simulated food storage and transportation in non-refrigerated trucks or vans subjected to refrigeration system failure. The E-21 PCM maintained lower temperatures (between -16 and -12 °C) than C-18 (between -12 and -7 °C). Wang et al. [31] used chilled food multi-deck display cabinet equipped with water gel PCM (deionised water, 1.2% silver iodide, 0.9% guar and 0.15% sodium tetraborate, with a freezing temperature of -2 °C) at heat exchangers. The addition of silver iodide reduced the super-cooling of water the energy saving around 5% at the set-point of -1.8 °C. Sonnenrein et al. [32] continued their previous work and integrated the copolymer-bound PCMs in evaporators as well as condensers. In a roll-bond evaporator and a wire-and-tube condenser, the power consumption can be reduced up to 17%, and temperature amplitudes in the fresh-food compartment, from 4 to less than 0.5 °C. They also highlighted that future work on designing control algorithms and evaluating their effects on the power grid is necessary.

The state of art analysis shed light on the benefits of PCMs in domestic refrigerators and freezers on product temperature control, longer off periods and lower energy consumption, among others. Previous studies considered different ambient temperatures, extreme situations as a power outage or repetitive door openings, PCM type, position and size. However, any work focuses on temperature control settings. According to Siddhartha Batth [33], one of the best options to reduce energy consumption in an immediate time frame is to use an ON/OFF control strategy that can match the output of the refrigerator with the load. Therefore, and considering the problems to keep the temperature control inside the refrigerator within appropriate limits, and the priority that is given to the energy efficient appliances, this paper studies different control settings applied to a eutectic plate refrigerator with water as PCM under different ambient temperature and product mass conditions. The effect of hysteresis variation on the OFF time and ON-time ratio of the refrigerator, as well as the energy consumption, are analysed. Furthermore, two new parameters are introduced to indicate both the utilisation of PCM latent heat and the fluctuation of product temperature.

2. Experimental setup

2.1. Refrigerator system characteristics

A 520 litres single door refrigerator is used for the experimental validation of the PCM effects. The external and the internal dimensions are 750x695x1695 mm^3 and 650x545x1500 mm^3, respectively. The cabinet is built with seven aluminium racks where the products are arranged.

The evaporator is placed below these racks, in direct contact with them. The external diameter of the evaporator tube is 8.9 mm, whereas its total length is equal to 23.5 m. Therefore, the total heat transfer area is 0.66 m^2. The air circulation within the cabinet is obtained by free convection. The vapour compression system is composed by a hermetic fixed-speed compressor, with a nominal power of 180 W, a rear statically cooled condenser and a non-adiabatic capillary tube. The system uses 70 g of R-600a (isobutane) as a refrigerant. The main characteristics of the refrigerator system are summarised in Tab.1.

This refrigerator also includes twelve boxes with a capacity of 0.03 m^3 and two of 0.02 m^3 in which the products are placed. The system targets typical food conservation conditions that according to James et al. [10] are between 0 and 5 °C.

2.2. PCM configuration and characteristics

Sonnenrein et al. [32] proved that the melting temperature of the PCM affects the temperature distribution inside the refrigerator but also in the evaporator. For the operation at the selected temperatures, tap water has been selected as PCM. Water is a popular PCM for conservation temperatures above 0 °C for many reasons: it is cheap, has the best thermal properties, and also presents good long-term stability [8]. The utilisation of tap water instead of distilled water favours crystallisation (it presents nucleating agents) and hence reduces the super-cooling effect.

Elarem et al. [34] noticed that when the PCM is placed in direct contact with the evaporator, and also in racks, it produces an enhancement on system energy efficiency. Moreover, the stabilisation and homogenization of the temperature are optimised if the PCM covers 75% of the racks. Therefore, PCM has been placed both above and below the rack-evaporator set. According to Azzouz et al. [24], an excessive increase of the PCM thickness does not produce substantial benefits on the refrigerator. Therefore, the thickness of the PCM container was chosen as the minimum value to cover entirely the rack surface, exploiting the dead volume of the refrigerator. The dead volume is referred to the volume of the refrigerator cabinet that is not used to store the products.

Water has been contained in 24x24 cm low-density polyethylene (LDPE) plastic boxes with a density of 0.92 g cm^{-3} and a thermal conductivity equal to 0.33 W m^{-1} K^{-1}. Each container has been filled with 3.0 cm^3 of water, which corresponds to the minimum PCM volume necessary to ensure proper coverage of the rack with a PCM thickness of 4.0 mm. Hence, each rack has been covered with 2.4 kg tap water, excluding the upper rack where only a layer of PCM has been used below it due to construction limitations (1.2 kg). Therefore, 15.6 kg of PCM has been used in the overall refrigerator.

3. Test Methodology

As has been identified in the literature review of the PCM effect on domestic refrigerators, the effect of temperature control hysteresis has not been studied. Therefore, three temperature hysteresis Δ, ±1, ±2, ±3 K, have been tested at the target temperature of 2 °C (set-point temperature T_{set}). The hysteresis refers to the amplitude of the fluctuations around the set-point temperature. It represents the temperature offset above (positive hysteresis) and below (negative hysteresis) the set-point temperature, and it defines the temperatures to which the refrigerator turns ON and OFF, respectively.

The apparatus has been placed inside a climate chamber. An electrical heater, controlled by an ON/OFF control logic, adjusts the ambient temperature within the desired limits. The experiments have been performed at two different ambient temperatures ($T_{air,amb}$), which are 25 $\pm$ 0.5 °C and 32 $\pm$ 0.5 °C, according to UNI-ISO 15502 [35] for sub-tropical and tropical areas conditions, respectively.

Furthermore, the product mass (m_{prod}) was simulated using chloride salt water (15/85 in mass percentage) with a freezing temperature of -5°C. The simulated charge has been equally distributed in every box. Considering the mass of PCM as a reference (Section 2), two different product mass values were used during the $T_{air,amb}$=25 °C tests: 18 and 12 kg, corresponding to approximately +20% and -20% in respect of the PCM charge.

Therefore, a baseline test has been performed fixing the hysteresis at ±2 °C, the ambient temperature at 25 °C, and charging 12 kg of product mass. Then, keeping constant m_{prod} and $T_{air,amb}$, the hysteresis was varied (±1, ±2, ±3 K) to evaluate the effect on temperatures, ON-time ratio and energy consumption. This operation has been repeated modifying only one condition to conclude about its single effect: first, $T_{air,amb}$=32 °C, and then, m_{prod}=18 kg. Hence, nine working conditions with the PCM, arranged as described in Section 2.2, have been measured (Tab. 2). The same tests have also been performed without PCM to compare between both configurations.

Fig.1 shows the arrangement of the temperature sensors and the PCM within the cabinet of the refrigerator. Two product containers have been monitored (rack 2 and rack 5), considering the temperatures of the PCM, above and below the boxes, the air within the box, and the product.

Furthermore, the temperature of the refrigerant at the inlet and the outlet of the evaporator has been measured, placing two sensors on the surface of the tube with a thin layer of silicone heat-conductive paste to ensure a proper thermal contact. Also, a temperature sensor has been placed in the air surrounding the apparatus, and another one on the rear wall of the cabinet, out of the product containers, at the middle of the third rack. Therefore, a total of 12 thermo-resistances, PT100 type (accuracy of ± 0.15 °C), have been used. Moreover, the energy consumption of the refrigerator was also measured using an energy meter of ± 1% (reading) uncertainty. Temperature and energy data have been recorded with a sample rate of 0.5 Hz and 0.2 Hz, respectively. An electronic balance (uncertainty of ±1 g) has been used to ensure the correct charge of both PCM and product.

The change of the hysteresis has been made possible by the addition of a switch relay connected in series with the electric motor of the compressor. Then, a programmable microcontroller, which is connected to a Personal Computer, actuates the relay. The average between the air temperatures inside the two boxes placed in the second and in the fifth rack (Fig. 1), which represents the coldest and the warmest controlled temperatures (James et al. [10]), is compared with the set-point temperature plus the hysteresis to command the switch of the relay. The measurements are gathered through a Data Acquisition System and monitored using a Personal Computer.

4. Results and discussion

This section presents and analyses the primary results of the experimental campaign regarding the refrigerator. The variation of the temperature of different parts of the refrigerator, ON-time ratio and energy consumption caused by the introduction of the PCM is deeply analysed considering different product mass, ambient temperature and hysteresis values. The temperatures have been recorded after the stabilisation of the system. The latter was identified when the differences in the cycle time between one cycle and the others were below 5%.

4.1. Effect on temperatures

Before analysing the influence of the different conditions imposed, the evolution of refrigerator temperatures during the baseline test (check Section 3 for conditions) is discussed. Fig. 2 reports the measured temperatures of a complete working cycle (ON and OFF period), 10h sample, of the refrigerator charged with PCM. The air temperature within racks 2 and 5 presents a similar evolution (Fig. 2a), although some differences are noticed between them, as well as between the product temperatures (Fig. 2c). The evolution of the PCM temperature reflects the latent heat accumulation period. The temperature profile of the PCM placed below the rack 5 (orange line in Fig. 2b) highlights the super-cooling phenomenon: the PCM cools down to -3.0 °C before starting the freezing process at -0.1 °C. For PCM placed below the rack 2 (light blue line in Fig. 2b), the temperature quickly descends during the ON period. However, for most of the OFF period, it is kept at the melting temperature and therefore the PCM does not completely melt. Furthermore, the latent heat of the other two instrumented PCMs (placed above the two racks) is not used since their temperatures differ from the melting point during the OFF period.

A detailed analysis for investigating the effect of the introduction of PCM on the product temperature is reported in Tab. 3.

It reflects the extreme and average temperatures of the products placed in rack 5 and rack 2 for the different tested conditions with and without PCM and specifying the distance to set-point (+2 °C).

In most of the cases tested, the addition of PCM helps to reduce the deviation from the set-point of the average product temperature, as shown in the third column. The deviation decreases at higher ambient temperature, and it is less pronounced using a higher hysteresis.

The behaviour of the average temperature can be analysed by observing the minimum and the maximum product temperature. In the first case, the introduction of the PCM has an adverse effect, leading to augment the distance from the set-point that increases with the hysteresis. On the contrary, the difference between the maximum product temperature and the set-point is lower with PCM, changing from being negative at lower hysteresis to positive at higher ones.

An additional benefit that can be highlighted by the introduction of the PCM is that the temperature difference between the rack 2 and 5 is significantly reduced (Tab. 4). The average absolute temperature difference with PCM between both racks at ±3 K hysteresis is 0.2 °C, whereas for the case without PCM, is 3.1 °C (considering Hyst3, Warm3 and PM3 tests). At ±1 K hysteresis, the average absolute temperature difference is reduced from 3.9 °C without PCM to 2.3 °C with it (considering Hyst1, Warm1 and PM1 tests). Consequently, the increase of hysteresis leads to a significant advantage, ensuring a better equalisation of the temperature along the vertical direction. Furthermore, the effect of the hysteresis changing is more pronounced with PCM.

To have a deeper understanding of the PCM effect, Fig. 3 presents a detailed representation of the air, product and PCMs temperatures during a 10h sample of the baseline test in the situations with and without PCM.

On the rack 2 (Fig.3a), the highest oscillation of the air temperature is highlighted. Without PCM, the temperature profile of the product is far below the set-point temperature (blue dotted line). The product temperature is between that of both PCMs (up and down) when they are used, and it gets closer to the set-point, although it reaches a lower minimum value than without this modification.

Then, on the rack 5 (Fig.3b), the product temperature without PCM is always above the set-point (it never reached values below 2 °C) whereas with PCM it results with an average temperature below the set-point. In the case with PCMs, the PCM below the rack (orange line) is not notably used, and its temperature quickly increases. The product temperature on the rack 5 (solid purple line) is kept between both PCM temperatures (orange and solid yellow lines). The latter leads the product temperature on the rack 5 to closer values to the set-point. While for rack 2 the air temperature (light blue solid line in Fig. 3a) shows a different behaviour to the product temperature (solid blue line in Fig. 3a), in this rack, air and product temperature profiles are quite similar (green and purple solid lines in Fig. 3b, respectively).

4.2. Effect on the ON-time ratio

The previous section has shown the critical influence of the ON/OFF period on the evolution of the temperatures, besides the own PCM melting and the refrigerator heat gain.

In Tab. 5, the values of the OFF time, cycle time and ON-time ratio during the tests without PCM are reported. It is worth mentioning that the ON-time ratio decreases as hysteresis increases in all the experiments whereas τ_{cycle}, as well as τ_{OFF}, augment with the hysteresis.

Therefore, Fig.4 is added to analyse the introduction of PCM further, making a comparison with the values reported in Tab. 5, and different hysteresis on the ON/OFF periods and ON-time ratio of the refrigerator. The differences between the cases with and without PCM are reported above the bars in Fig. 4. These are calculated according to Eq. 1, where x represents the investigated variable. Note that the ON period duration can be directly calculated using Fig. 4a-4b (see Section 3).

$$\%x_{diff} = \frac{x_{PCM} - x_{No-PCM}}{x_{No-PCM}} * 100 \qquad (1)$$

The lowest cycle times take place at higher ambient temperatures (Fig.4b), when the heat gain is higher. Hence, the refrigerator spends more time compensating it, both with and without PCM, and the PCM holds worse the temperatures inside the system. Then, as expected, higher temperature hysteresis leads to higher cycle times in the three cases considered. From ± 1 to ± 2 K hysteresis the difference in OFF period with the system without PCM is significantly increased (Fig.4a), and from this value, the modified refrigerator can be considered in common shut down situations, product transportation, or PCM charge/discharge cycles optimisation.

Moreover, the ambient temperature has a significant influence on the ON-time ratio and increases it to about 5% (Fig.4c). As the increment of both OFF and cycle periods with the augment of temperature hysteresis is comparable, the ON-time ratio is similar for all the hysteresis studied. However, when compared to the system without PCM, the ON-time ratio varies depending on the situations. The ON-time ratio of the system with PCM is only lower at the lowest hysteresis and ambient temperatures considered. Then, the difference is increased, being more significant for the situation of higher product mass.

Ghahramani Zarajabad and Ahmadi [36] prioritised the maximisation of PCM melting in their research to maintain the racks temperature in a proper level for a more extended period. A novel parameter proposed to provide a utilisation index of PCM is the Latent Heat Utilization Ratio (LHUR). LHUR can give an idea of the fraction of PCM used (melted) during the OFF period. LHUR is calculated as the ratio between the time that the PCM is at its melting temperature (during the OFF time) and the OFF time itself (Eq. 1).

$$LHUR = \frac{\tau_{T_{PCM}=T_{melt}}}{\tau_{OFF}} \tag{2}$$

This parameter can be used to explain the behaviour observed in Fig.4. Furthermore,the quantity of PCM that is freezing/melting can be evaluated by the LHUR, and this quantity influences the energy efficiency of the refrigerator, as Yusufoglu et al. [23] highlighted. The results of the LHUR for the different tests performed are shown in Fig.5.

As expected, the LHUR increases with the hysteresis and this can explain the increase of the OFF time shown in Fig.4a. This increment is more remarkable for rack 5 than for rack 2. Besides, the LHUR increases more with a higher product mass in the rack 2 (PM test in Fig. 6), whereas it increases more with a higher ambient temperature in the rack 5 (Warm test in Fig. 6). In general, the PCM is more used in rack 2 than rack 5 at lower ambient temperatures and higher product mass (Hyst and PM tests in Fig. 6). The opposite occurs at higher ambient temperatures (Warm test in Fig. 6). Therefore, the higher heat gain at higher ambient temperature promotes a higher utilisation of the PCM placed in the bottom of the cabinet whereas it reduces the use of latent heat of the PCM placed at the top.

Bearing in mind the results shown in Tab. 3, another innovative ratio is proposed to calculate the product temperature fluctuation during the cyclic operations of the refrigerator and to conclude about the PCM benefit on the product conservation. The difference between the maximum and minimum product temperature (amplitude of the oscillation) is divided by the time spent during an entire compressor ON/OFF period (period of the oscillation). Thus, Fig.6 shows the material temperature fluctuations with and without PCM in the three proposed cases and the three hystereses.

There is a clear difference when the PCM is used: the ratio between the amplitude and the period of product temperature oscillations with PCM is lower than without it for all tests. In detail, when increasing the hysteresis, the reduction of product temperature fluctuation obtained by the introduction of the PCM becomes more pronounced. Furthermore, the hysteresis variation strongly affects the behaviour of product temperatures without PCM whereas this dependence is slightly noticeable with it. Attending to the results presented through this new parameter, the benefit from the introduction of PCM on the product conservation can be confirmed.

4.3. Effect on compressor energy consumption

Besides the previously discussed effect of the introduction of PCM on different refrigerator temperatures, the analysis of the variation of compressor energy consumption is also required. As this refrigerator is based on natural convection for evaporator and condenser (see Section 2), the compressor power consumption can be assumed as the total of the refrigerator. Fig.7 shows the primary results in columns for the three hysteresis values analysed and the different cases proposed when tested with PCM. The differences between the refrigerator with and without PCM are also reported above the columns. They were calculated according to Eq. 1.

According to that expected, the energy consumption per cycle increases as the ambient temperature increases. The daily energy consumption has been calculated (Fig.7) considering the cycle time and the average energy consumption measured during each cycle for each test. These values are used to check the PCM real positive or negative influence on energy consumption. It can be seen that the hysteresis has no significant effect in the case with PCM. However, with the increase of it, the energy consumption increase becomes more relevant and hence, this modification less beneficial.

Contrary to that observed with the temperatures smoothing and the cycle duration increase, it seems that the introduction of PCM has no benefit from the energetic point of view. However, this is only a comparison one-to-one between the refrigerator with and without PCM, and some operating strategies can be selected to improve the seasonal energy efficiency since the introduction of PCM provides a high degree of flexibility. The latter could be performed adopting a variable control logic to maximise the utilisation of the PCM and reduce energy consumption over a certain period.

5. Conclusions

This paper shows and discusses the experimental results of a refrigerator retrofitted to be used in domestic applications by introducing PCM. The retrofit has been performed adding 15.6 kg of tap water PCM within the cabinet of the refrigerator, in direct contact below and above the bare tube evaporator arranged below the seven racks. Several conditions have been modified, and the influence of temperature hysteresis control has been highlighted.

The tests have been carried out fixing a set-point temperature of +2 °C and varying three values of hysteresis (±1, ±2 and ±3 K) and two values of ambient temperature (25 and 32 °C) according to UNI-ISO 15502:2005, as well as of product mass (12 and 18 kg). The products have been simulated using 15% chloride salt water equally distributed.

The analysis of temperature profiles pointed out an improvement of product conservation conditions since the introduction of PCM reduced the fluctuations of the product temperature during the refrigerator operation. Furthermore, better temperature distribution within the cabinet has been obtained (more pronounced with higher hysteresis value), being reduced the difference between the temperature at the top and the bottom of it.

The PCM extended the OFF time of the compressor and reduced its switching frequency, and it can also extend the lifespan of its mechanical components. However, the PCM has shown an adverse effect on the ON-time ratio when the hysteresis and the ambient temperature increase.

The percentage of utilisation of the PCM increased as the hysteresis and the ambient temperature augment, but the product mass had a negligible effect. Moreover, a significant difference between the utilisation of the PCM at the bottom and the top of the refrigerator is noticed. PCMs with different melting point according to their position could address this problem.

The adverse effect on the ON-time ratio is also reflected in the energy consumption, which increased for higher hysteresis in comparison with the standard configuration of the system. However, focusing on the behaviour of the refrigerator with PCM, negligible variations have emerged in respect to the hysteresis. Although the energy performance with PCM seemed to be worse, it is worth highlighting that such system ensured high flexibility. The latter could lead to reducing the energy consumption of the refrigerator. Hence, future works can be addressed to manage the system in such a way as to pursue an energy saving. Besides, future improvements can be addressed to identify different PCMs to test the refrigerator with a layered PCM structure, with the aim to increase the utilisation of the latent heat in every part of the system and improve its energy performance.

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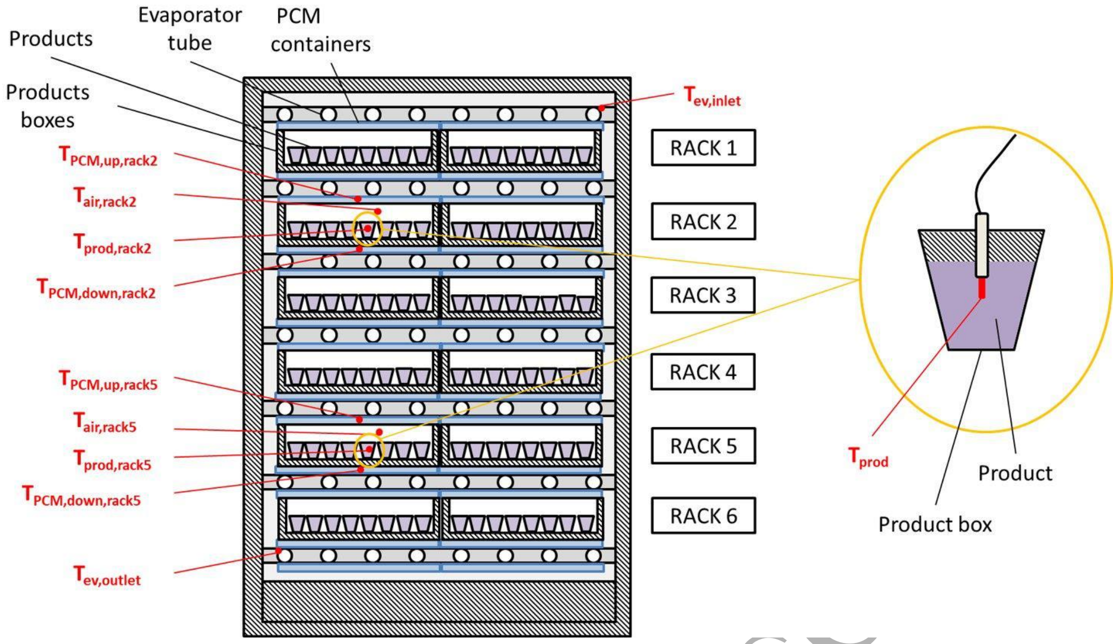
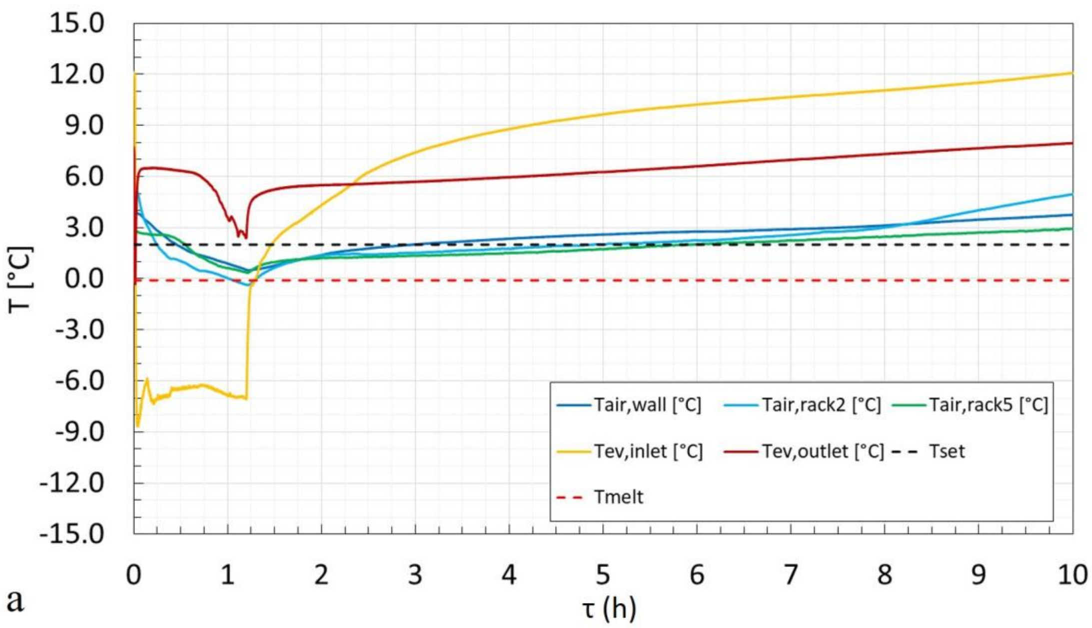


Figure 1. *Frontal schematic view of the refrigerator with temperature sensors and PCM arrangement. The upper rack is not considered since the products are not placed above it.*



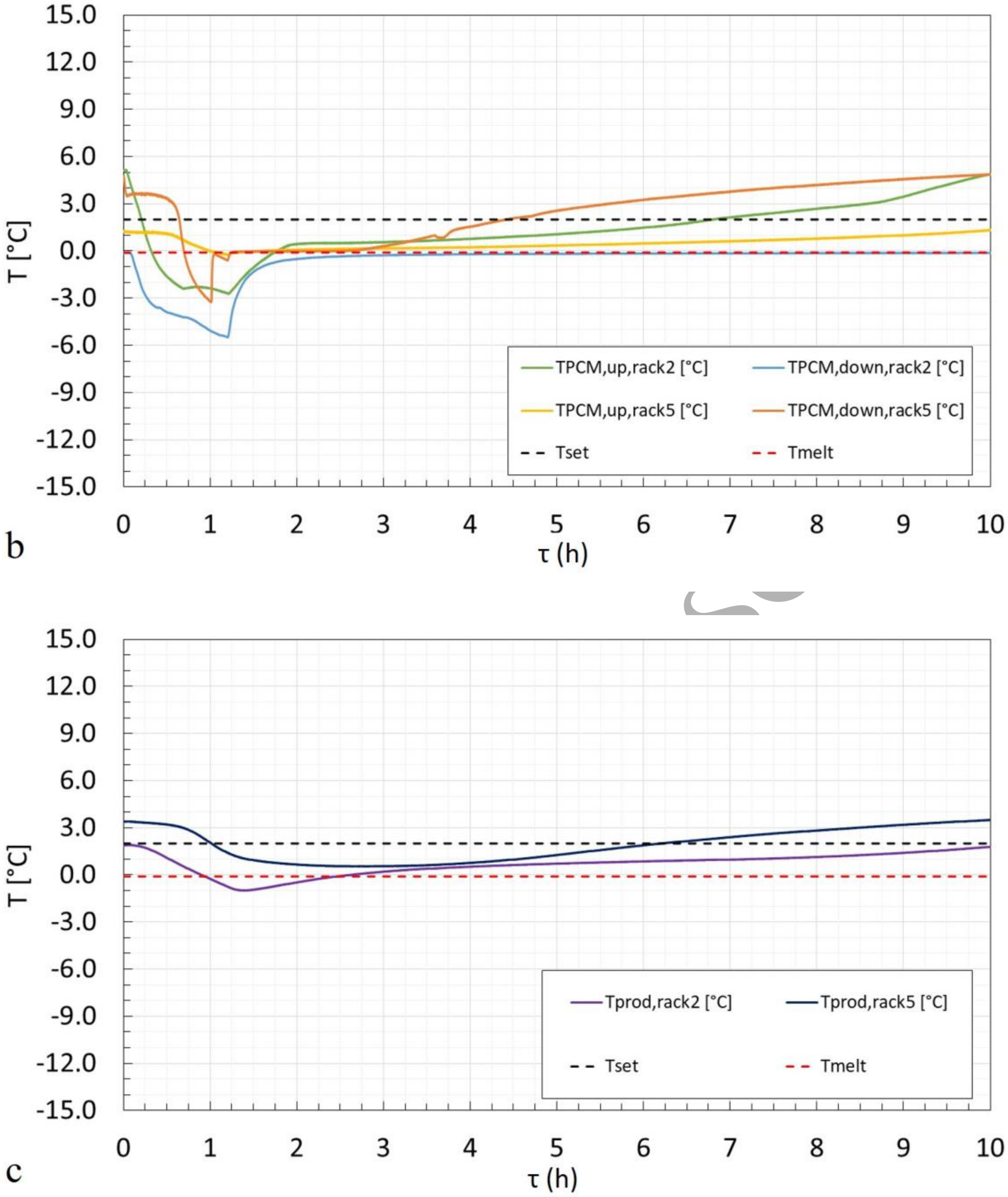


Figure 2. *Temperature profiles during the reference test with T_{set}=2 °C, Δ=±2 °C, $T_{air,amb}$=25 °C and m_{prod}=12.5 kg*

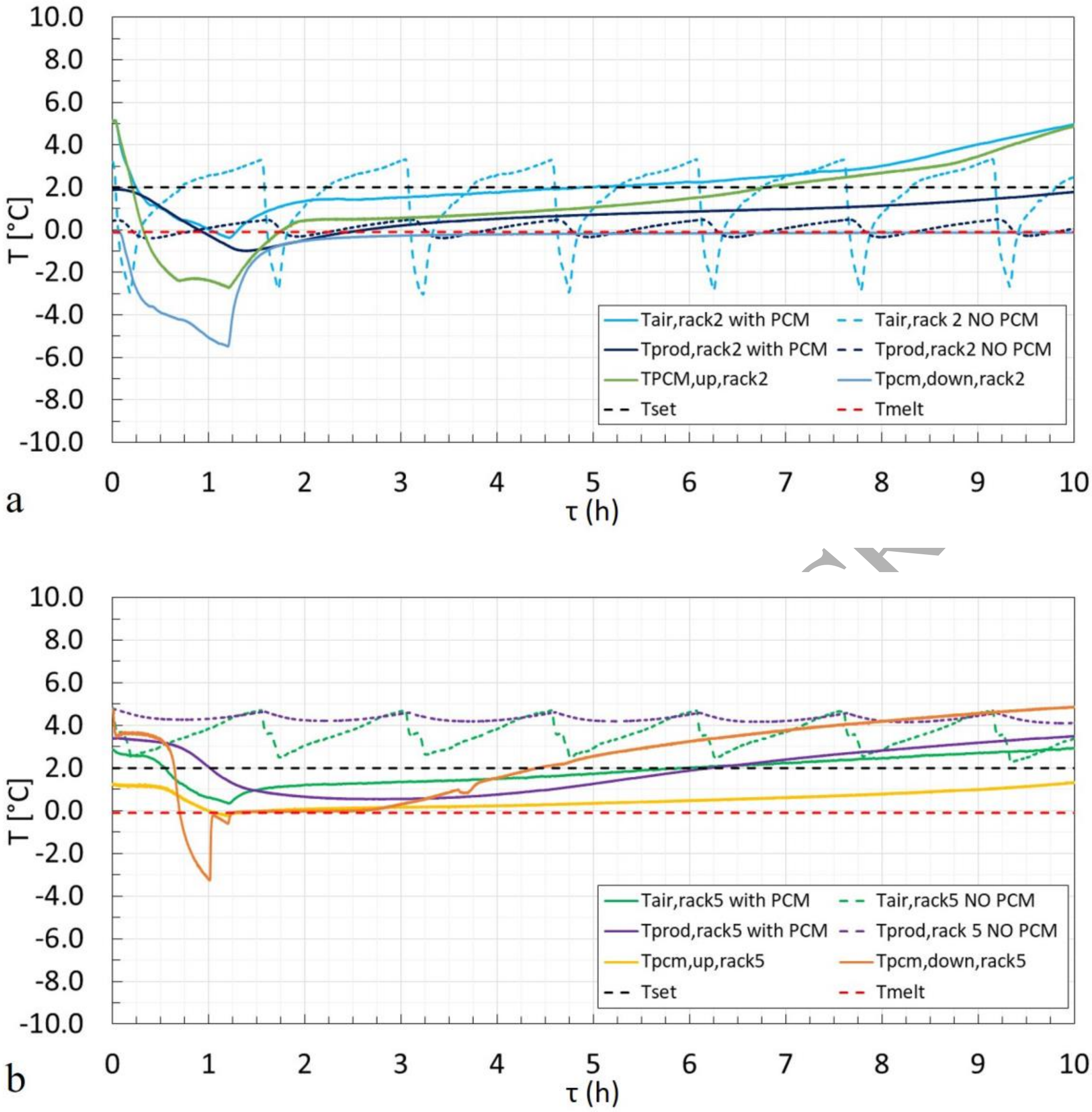
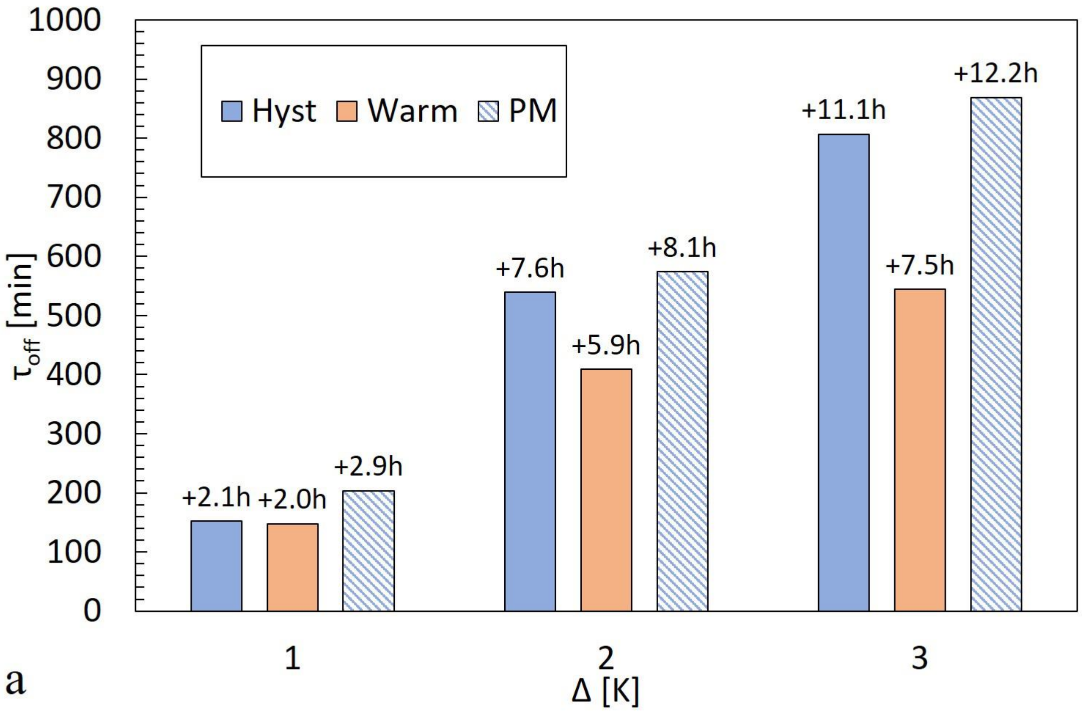
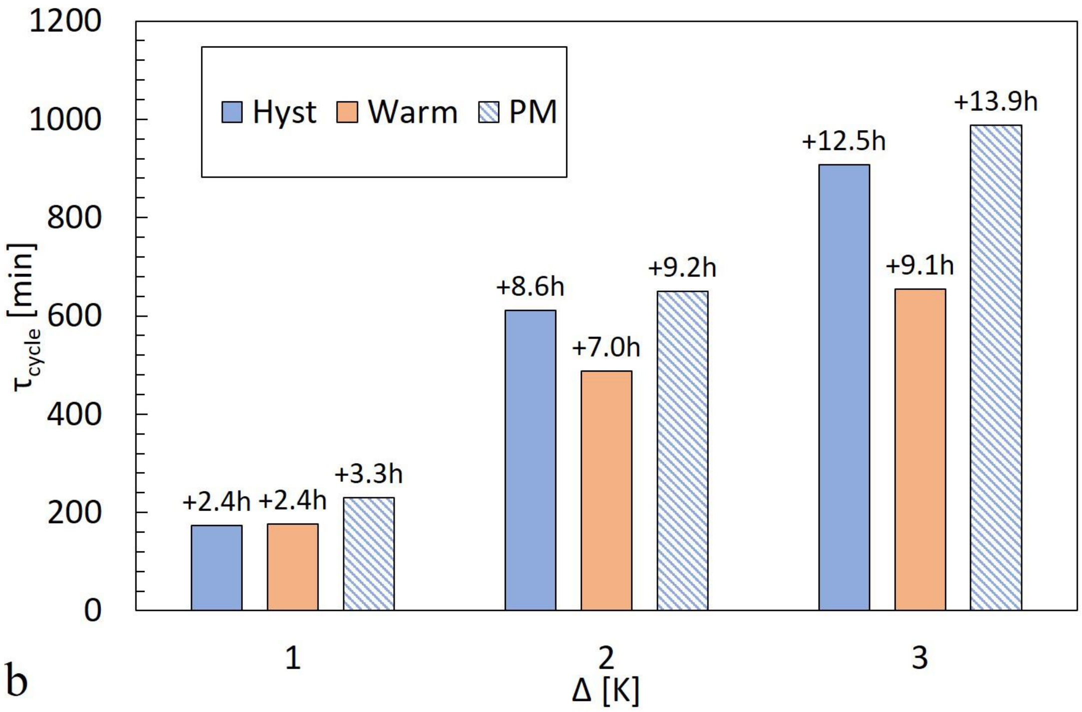


Figure 3. *Comparison between the temperature profiles during the reference test with and without PCM*


1000
900
800
700
600
500
400
300
200
100
0
τoff [min]
Hyst
Warm
PM
+2.1h
+2.0h
+2.9h
+7.6h
+5.9h
+8.1h
+11.1h
+7.5h
+12.2h
1
2
3
Δ [K]

a


1200
1000
800
600
400
200
0
τcycle [min]
Hyst
Warm
PM
+2.4h
+2.4h
+3.3h
+8.6h
+7.0h
+9.2h
+12.5h
+9.1h
+13.9h
1
2
3
Δ [K]

b

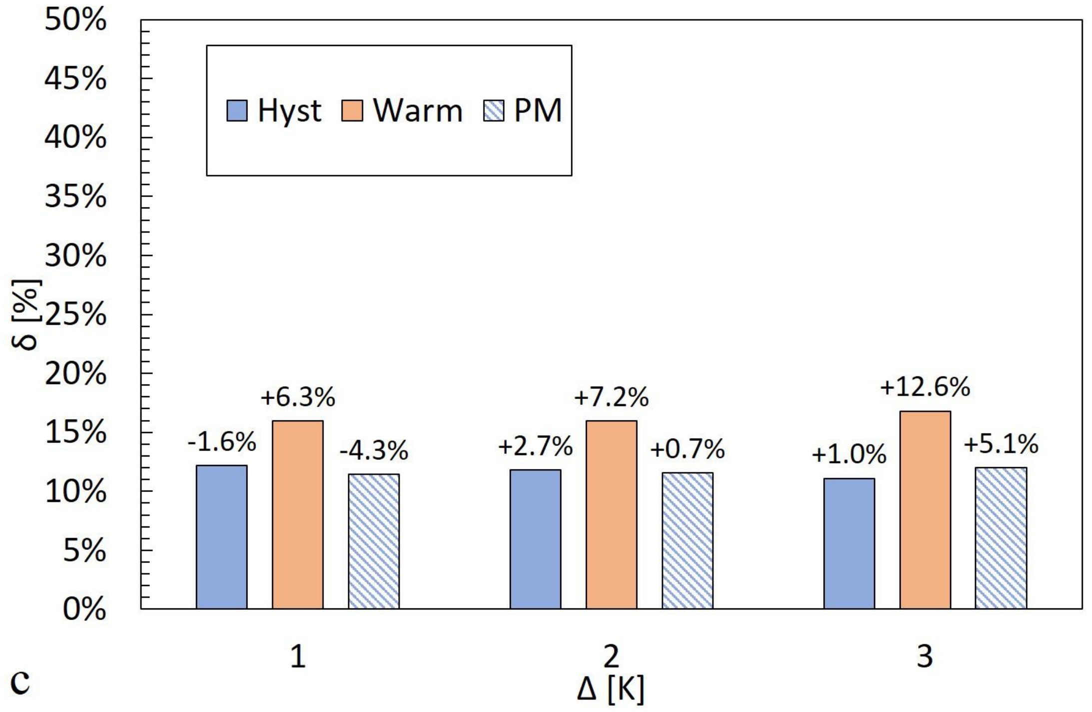


Figure 4. Hysteresis changing impact on cycle parameters with PCM: a) OFF period, b) cycle time, c) duty cycle. The labels report the difference between the test with and without PCM

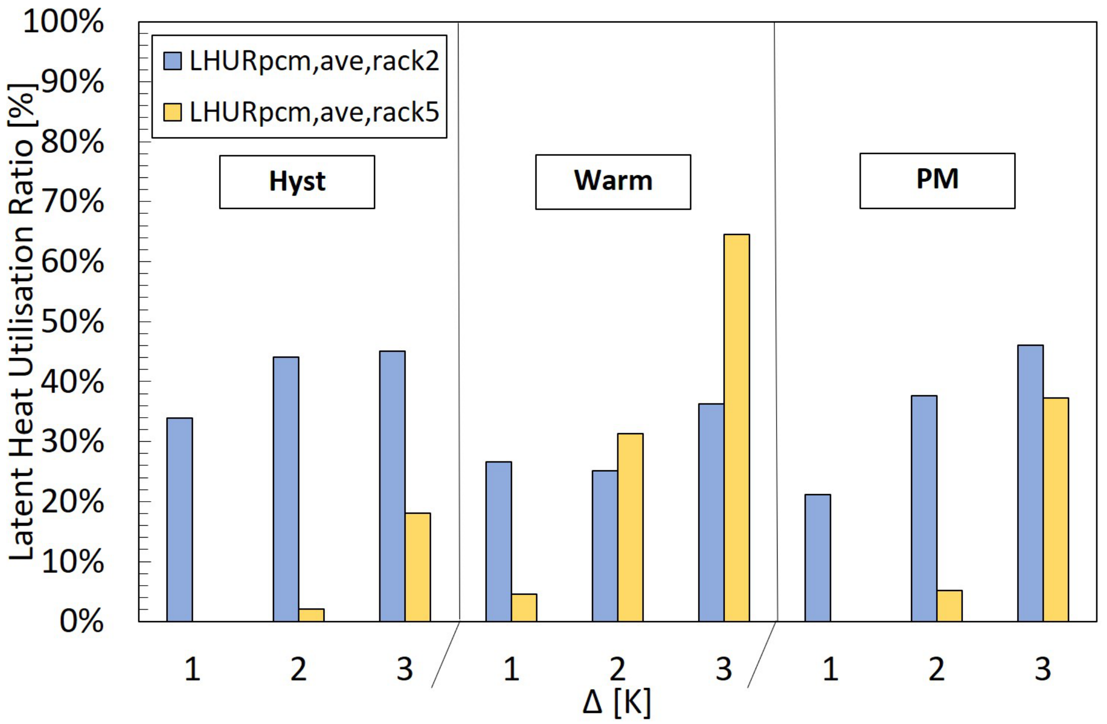


Figure 5. Latent heat utilisation ratio (LHUR) values of the PCMs placed in the rack 2 and the rack 5 during the different test conditions

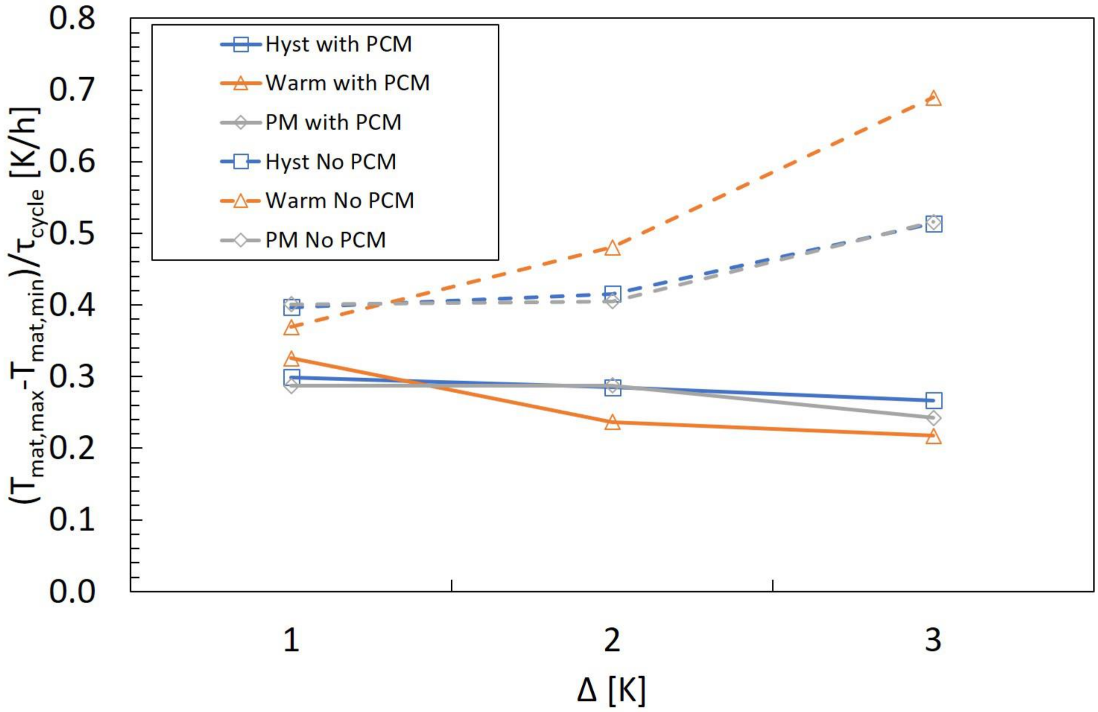


Figure 6. *Product temperature fluctuations with and without PCM*

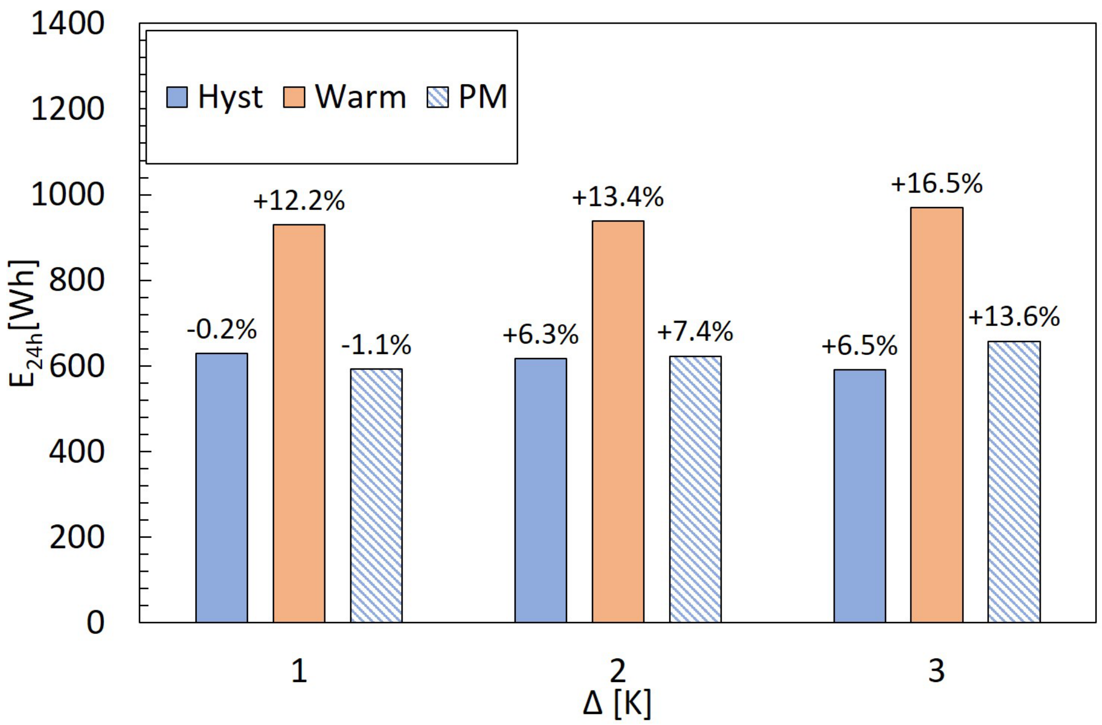


Figure 7. *Influence of different hysteresis values on electric daily energy consumption. The labels report the difference between the test with and without PCM*

Component	Type	Characteristic	Value
Compressor	Hermetic,	Swept volume	14.28 cm^3
	Free cooled	Electrical Power	180 W
Condenser	Statically cooled,	External	5.0 mm

	Wire-on-tube	diameter of the tube	
Expansion system	Non-adiabatic capillary tube	External diameter	2.0 mm
Evaporator	Statically cooled, Bare tube	External diameter of the tube	8.9 mm

Table 1. *Main components of the vapor compression system and their characteristics*

T_{set} [°C]	Δ [K]	$T_{set,amb}$ [°C]	m_{prod} [kg]	Label
2	1	25	12	**Hyst1**
2	2	25	12	**Hyst2 (BASELINE)**
2	3	25	12	**Hyst3**
2	1	32	12	**Warm1**
2	2	32	12	**Warm2**
2	3	32	12	**Warm3**
2	1	25	18	**PM1**
2	2	25	18	**PM2**
2	3	25	18	**PM3**

Table 2. *Working conditions used during the experiments*

				$T_{prod,min}$ [°C]				$T_{prod,max}$ [°C]				$T_{prod,ave}$ [°C]			
				Rack 2		Rack 5		Rack 2		Rack 5		Rack 2		Rack 5	
	Δ [K]	$T_{set,amb}$ [°C]	m_{prod} [kg]	PCM	No PCM	PCM	No PCM	PCM	No PCM	PCM	No PCM	PCM	No PCM	PCM	No PCM
Hyst1	1	25	12	-0.2	-0.3	2.8	4.0	0.8	-0.1	3.5	4.2	0.3	-0.2	3.1	4.0
	Distance to set-point			-2.2	-2.3	0.8	2.0	-1.2	-2.1	1.5	2.2	-1.7	-2.2	1.1	2.0
Hyst2	2	25	12	-0.9	-0.3	0.5	4.1	2.0	0.5	3.4	4.6	0.7	0.1	1.8	4.3
(BASELINE)	*Distance to set-point*			-2.9	-2.3	-1.5	2.1	0.0	-1.5	1.4	2.6	-1.3	-1.9	-0.2	2.3
Hyst3	3	25	12	-1.8	-0.2	-0.1	4.0	2.8	1.3	3.4	5.1	0.9	0.5	1.2	4.4
	Distance to set-point			-3.8	-2.2	-2.1	2.0	0.8	-0.7	1.4	3.1	-1.1	-1.5	-0.8	2.4
Hot1	1	32	12	-0.7	-0.2	0.5	3.0	0.5	0.0	1.1	3.2	0.0	-0.1	0.7	3.1
	Distance to set-point			-2.7	-2.2	-1.5	1.0	-1.5	-2.0	-0.9	1.2	-2.0	-2.1	-1.3	1.1
Hot2	2	32	12	-1.8	0.3	-0.2	2.5	0.9	0.8	0.9	3.1	0.0	0.5	0.3	2.7
	Distance to set-point			-3.8	-1.7	-2.2	0.5	-1.1	-1.2	-1.1	1.1	-2.0	-1.5	-1.7	0.7
Hot3	3	32	12	-2.6	0.3	-0.4	2.2	1.2	1.5	0.5	3.5	0.1	0.8	-0.1	2.7
	Distance to set-point			-4.6	-1.7	-2.4	0.2	-0.8	-0.5	-1.5	1.5	-1.9	-1.2	-2.1	0.7
PM1	1	25	18	-0.8	-0.4	2.8	4.0	0.5	-0.1	3.7	4.2	-0.1	-0.3	3.2	4.1
	Distance to set-point			-2.8	-2.4	0.8	2.0	-1.5	-2.1	1.7	2.2	-2.1	-2.3	1.2	2.1
PM2	2	25	18	-1.6	-0.4	0.3	4.3	1.2	0.5	3.6	4.8	0.1	0.1	1.5	4.4
	Distance to set-point			-3.6	-2.4	-1.7	2.3	-0.8	-1.5	1.6	2.8	-1.9	-1.9	-0.5	2.4

PM3	3	25	18	-2.7	-0.1	-0.3	3.8	3.1	1.5	1.9	4.8	0.4	0.6	0.5	4.2
	Distance to set-point			-4.7	-2.1	-2.3	1.8	1.1	-0.5	-0.1	2.8	-1.6	-1.4	-1.5	2.2

Table 3. *Minimum, maximum and average values of product temperature in the second and the fifth rack during the cycling operations of the refrigerator with different testing conditions*

	$\lvert\Delta T_{prod,rack2-5}\rvert$ [°C]					
	Δ_{min}		Δ_{max}		Δ_{ave}	
Test	PCM	No PCM	PCM	No PCM	PCM	No PCM
Hyst1	3.0	4.3	2.8	4.2	2.8	4.3
Hyst2 (BASELINE)	1.4	4.5	1.4	4.1	1.1	4.2
Hyst3	1.8	4.2	0.6	3.7	0.3	3.9
Warm1	1.2	3.2	0.6	3.2	0.7	3.2
Warm2	1.6	2.2	0.1	2.3	0.3	2.2
Warm3	2.2	1.9	0.7	2.0	0.1	1.9
PM1	3.6	4.5	3.2	4.3	3.3	4.4
PM2	1.9	4.6	2.4	4.3	1.4	4.4
PM3	2.4	3.9	1.1	3.3	0.0	3.6

Table 4. *The absolute deviation between product temperatures within rack 2 and 5 during the different tests with and without PCM.*

Test	τ_{off} **[min]**	τ_{cycle} **[min]**	δ **[%]**
Hyst1	27.6	31.4	12.4%
Hyst2 (BASELINE)	82.0	92.7	11.5%
Hyst3	138.8	155.9	11.0%
Warm1	26.3	31.0	15.0%
Warm2	55.7	65.4	14.9%
Warm3	93.9	110.4	14.9%
PM1	30.2	34.3	11.9%
PM2	87.2	98.5	11.5%
PM3	138.4	156.2	11.4%

Table 5. *Values of* τ_{off}, τ_{cycle} *and duty cycle calculated for the different tests without PCM. The data are referred to the average ON/OFF period.*