

Universitat de Lleida
Escola Politècnica Superior
Màster en Ciències Aplicades a l'Enginyeria

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**Improvement of the thermal performance of
commercial freezers using phase change materials
(PCM)**

Autor: Eduard Oró Prim
Directors: Cristian Solé i Luisa F. Cabeza
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1 Introduction

Food transport and storage at low temperatures has always been an important matter worldwide and is becoming even more important due to dietary needs and population growth. The issue of improving food storage applies to food transportation in refrigerated trucks or vans and food storage in domestic or commercial refrigerators and freezers.

The aim of this work is to improve the thermal performance of commercial freezers using phase change materials (PCM) and to prove the importance of the correct PCM selection (melting temperature) for each application. To develop these objectives, a commercial freezer, with and without macro encapsulated PCM is used to assess the benefits of using PCM in minimizing temperature fluctuation and to maintain at the lowest possible temperature the freezer under heat of loss due to door openings and electrical power failure. The PCM was contained in 10 mm thick stainless steel panels placed at different locations in the freezer. A commercial PCM was selected (Climsel-18) from the company CLIMATOR. The melting temperature of this PCM (-18 °C) makes it suitable for this application. To ensure that the PCM follow the necessary thermal cycles it must be cooled below its freezing point.

The PCM plates were located in the centre of the evaporator plates, leaving enough room on the sides for a proper air circulation inside de cabinet. This distribution allows charging the plates and even the PCM for future applications, with a new storage temperature.

Initially, mapping air temperature inside the freezer (no plates, no PCM, no food products) using temperature sensors helped to ensure that the PCM undergo phase change. For this purpose, 16 PT100 sensors were distributed in the available space of the freezer, and were connected to a data logger and computer.

Following these initial measurements, the effects on air temperature and frozen products temperature inside a commercial freezer with and without PCM are measured and discussed with regards electrical power failure and door opening. The freezer in these

experiments were filled with packs (M-pack) having similar properties to frozen meat. The results show that the temperature of the air in the freezer and that of the frozen packs remains at acceptable level for much longer time when PCM was employed in the case of electrical power failure. Moreover, in terms of door opening the benefit of the PCM is conditioned on the storage temperature of the system. Therefore, when the temperature of the cabinet is nearly the melting temperature of the PCM, it helps the system, decreasing the temperature drop and minimizing temperature fluctuations. Furthermore, related to product quality the benefit of using PCM has been clearly demonstrated.

2 Brief survey on related work

Generally, frozen food must be kept below $-18\text{ }^{\circ}\text{C}$, and this temperature should be maintained in commercial freezers. It is well known that temperature fluctuations during the storage in freezers could cause dramatic effect to the quality of the frozen food. Furthermore, many researchers have been studied the problems associated with this type of storage of different frozen products. Donhowe and Hartel (1996) studied the ice recrystallization during bulk storage of ice cream in containers. The temperature of the freezer was controlled with and without fluctuations, $\pm 1.0\text{ }^{\circ}\text{C}$ and $\pm 0.01\text{ }^{\circ}\text{C}$ respectively, at temperatures between -15 and $-5\text{ }^{\circ}\text{C}$. They concluded that recrystallization rate increased with storage temperature and extent of temperature fluctuations. Moreover, Phimolsiripol et al. (2008) also studied the effects of freezing and temperature fluctuations during frozen storage on frozen dough and bread quality. The rates of quality and weight loss were significantly greater when temperature fluctuations ($-18 \pm 5\text{ }^{\circ}\text{C}$) where storage temperatures were higher. Since those temperature fluctuations are unavoidable, it is suggested that temperature variations should be kept minimum or not more than $\pm 3\text{ }^{\circ}\text{C}$.

Another problem associated with the quality of frozen food is the high fluctuations due to door opening; defrost system or electrical power failure when the temperatures inside the freezer change significantly. In that regard Gormley et al. (2002) studied the effect of fluctuating (fluctuations cycles of -30°C to -10°C to $-30\text{ }^{\circ}\text{C}$) versus constant frozen storage temperatures regimes (-60 and $-30\text{ }^{\circ}\text{C}$) on some quality parameters of selected food products. Temperature fluctuations cycles could be expected to produce stress damage and other deleterious effects such as fat oxidation and changes in colour and texture. Moreover, the fluctuating regime gave the highest values of some of the parameters studied such as peroxide and free fatty acid production.

Additionally, the way to freeze and to defrost the products is important in quality aspects. Ngapo et al. (1999) studied the freezing and thawing rate effects on drip loss from samples of pork. They concluded that at slower freezing rates, drip loss was significantly different from that obtained from the fresh samples.

Unfortunately it is common that the storage temperature in commercial freezers do vary significantly, which may be caused by frequent door openings of the costumers at commercial locations, heat loads gained from the outside environment through the walls and the glass of the freezer, heat gained through the defrost system and potential electrical power failure, which may have a dramatic effect. In many countries around the world such as India, there are restrictions on the use of electricity daily due to its shortage. Food losses from electrical power failure of few hours daily could induce great economical losses to the supermarkets and devalue the quality of frozen food.

It is widely known that phase change materials (PCM) allow absorbing a large amount of heat during melting at almost constant temperature (Zalba et al. 2003). Therefore PCM are capable of reducing temperature fluctuations, and have been successfully applied in building applications (Cabeza et al. 2010; Mehling and Cabeza 2008) and in domestic refrigerators and freezers (Gin et al. 2010b). Furthermore, the use of these PCM can be utilized to minimize product and air temperature fluctuations inside commercial freezers.

The incorporation of PCM in household refrigerators and freezers has been studied over the years. Onyejekwe (1989) incorporated PCM into a domestically freezer and from the experimentation achieved the optimal performance of the container inside the freezer. Their work concluded the possibility of using an easily available and very cheap PCM ($\text{NaCl} + \text{H}_2\text{O}$) for thermal energy storage (TES). However, that PCM is not appropriate due to its bad corrosion performance.

Wang et al. (2007a) developed and tested a prototype of a refrigeration system that incorporates PCM. They located a heat exchanger of PCM after the compressor (A), after the condenser (B) and before the compressor (C). The experimental results showed that the integration of PCM heat exchangers into the refrigeration system improved the COP of the system both in positions A and B by marginal 6-8%. At position C, temperature stabilization benefits are evident and lower superheat is of benefit to the compressor and the system. Furthermore, Wang et al. (2007b) developed a dynamic of the novel system which can be used to design and optimize the performance of the system and was validated with the experimental data. And Wang et al. (2007c)

concluded that for energy savings, PCM located at B is the suitable application and improves the system COP upon the phase transition temperature, which is determined by the climate. At position A and C further benefits such as system stabilization were also observed. Furthermore, Subramaniam et al. (2010) designed a method of a novel dual evaporator based on a domestic refrigerator with PCM which provided thermal storage in order to improve food quality and prolong compressor off time. However, the incorporation of PCM into the system is fixed in both cases and if the customer wants to change the temperature of the storage the implementation of the PCM will be obsolete. For that reason it is extremely interesting that the PCM module-system could be replaced by the user without difficulties.

Using numerical investigations, Azzouz et al. (2008) showed that the addition of a thick slab of PCM on the back side of a refrigerator evaporator may result in a higher evaporating temperature, 5-15% increase in the COP and a significant decrease in the number of starts and stops of the compressor with lower air temperature fluctuations in the freezer. Experimentally, Azzouz et al. (2009) showed that the use of PCM on the back evaporator in a household refrigerator improves its performance and allows several hours of refrigeration without electrical power supply. Going to bigger chambers, Cheralathan et al. (2007) carried out an experimental investigation on the performance of an industrial refrigeration system integrated with encapsulated PCM based on cold TES system. In the experimental set-up a vertical storage tank is integrated with the evaporator of the vapour compression refrigeration system. They concluded that the ratio of useful latent cold energy stored to the useful sensible cold energy stored will be much higher (4-7 times) that will reduce the size of the PCM-based TES system compared with the chilled water system. Thus, it was concluded that thermal performance of the storage system may be improved by charging the system at lower condensing and optimal evaporator temperatures.

More recently, Gin et al. (2010b) investigated the incorporation of PCM panels placed against the internal walls of a domestic freezer to maintain stable temperature in the presence of heat loads. Moreover, energy consumption tests have shown that the inclusion of PCM into the freezer has decreased the energy consumption during a defrost cycle by 8%, and by 7% during door openings. Furthermore they observed

that the introduction of PCM has improved the quality of the frozen foods during the storage (Gin and Farid 2010a).

To the best of the authors knowledge, there are no studies in the literature with regards to the effects of PCM systems on the behaviour of commercial freezers, looking into the effect of door opening and power loss. It is the objective of this work to investigate the effect of using low freezing point PCM in thin plates to improve the thermal performance of commercial freezers and to prove the importance of the correct PCM selection for each working temperature.

3 Experimental planning

3.1 Methodology

No standard tests for commercial freezers were found in the literature; therefore, the standard test for household refrigerator-freezer with some modifications was followed.

The International Organization for Standardization (ISO) is a worldwide federation of national standards bodies. ISO 15502:2005/AC:2008 is the newest standard for testing the energy consumption of household refrigerator-freezers in Europe. Excellent overviews of the most actual standards in the world have been summarized by Bansal and Krüger (1995) and Bansal (2003). According to the ISO standard, the ambient temperature during the testing has to be 25 ± 0.5 °C and 32 ± 0.5 °C in tropical zones and a humidity relativity of 40-60%. However, none of these temperatures reflect the actual prevailing temperatures in the frozen food areas in real supermarkets.

In order to know exactly the boundary conditions in a common supermarket, some measurements were done in a supermarket in Lleida (Spain). Table 1 shows the measured temperature and the humidity of the frozen food area in a typical supermarket. In order to do the experimentation at the same boundary conditions, the temperature and the humidity in the space where the freezer was placed were controlled at 21 ± 0.5 °C and $50 \pm 10\%$, respectively. This fluctuation is inside the fluctuation allowed by the standard.

	Ambient temperature (°C)	Humidity (%)
Morning	21.3	58.6
Afternoon	20.8	57.2
Evening	20.9	57.2
Average	21.0	57.7

Table 1. Measurements in the frozen food area of a supermarket in Lleida (Spain).

3.2 Freezer

The experimental set-up consists of a vertical freezer (370 UFR DIFRIHO) with a capacity of 270 L (Fig. 1 and Fig. 2). The characteristics of the freezer used are presented in Table 2. The static freezing cabinet has a double glass door with an aluminium frame and a digital thermometer.

Characteristics	Units	Value
Width	mm	595
Depth	mm	640
High	mm	1840
Capacity	L	270
Power	W	628
Working temperatures	°C	-14/-30

Table 2. Characteristics of the experimental 370 UFR freezer.



Fig. 1. Frontal view of the freezer used in this study.



Fig. 2. Frontal view of the freezer used in this study.

During the normal freezer cycle, except when the door was opened, a fan positioned at the top of the back wall of the freezer provided air circulation into the cabinet. The fan stopped operating only when the door was opened. The evaporator was located in 7 different plates inside the freezer. Food could be placed directly on these evaporators with the exception of the upper one. The freezer did not have defrosting system, so defrosting ice deposits on the evaporator was controlled by the user.

3.3 Phase change material

The PCM studied in this work was Climsel C-18 from the company Climator (Patent: PCT/SE 95/01309, 9404056-5). Its chemical composition is sodium nitrate, water and additives. The physical data of the PCM given by the manufacturer are presented in Table 3.

Characteristics	Units	Value
Phase change temperature	°C	-18
Maximum temperature	°C	40
Latent heat of fusion	kJ kg ⁻¹	306
Approx. specific heat in PCM	kJ kg ⁻¹ °C ⁻¹	3.6
Density (liquid)	Kg m ⁻³	1300
Thermal conductivity	W m ⁻¹ °C ⁻¹	0.5-0.7

Table 3. Physical characteristics for ClimSel C-18 given by the manufacturer.

In most of the studies done by the researchers related to the incorporation of PCM plates inside refrigerators or domestic freezers, the plates of PCM were located on the walls of the evaporator or even in the walls of the cabinet (Azzouz et al., 2009; Gin et al., 2010b). These locations do not allow the user to change the plates or even the PCM correctly because it has become another part of the cabinet. Due to this problem, the authors of this work wanted to develop a new system of the incorporation of the PCM plates inside the freezer. The PCM plates are located in the centre of the evaporator plates, leaving enough room on the sides for proper air circulation inside de cabinet.

As Fig. 3 shows, the frozen product could be located without problems on the plates being this system possible in a commercial application.



Fig. 3. Freezer used in the experimentation and location of the plates inside it.

As the PCM used is corrosive, a suitable storage vessel has to be used. Therefore, the encapsulation of the PCM was done using plates made by stainless steel (Fig. 4).

Due to the lower temperature at the very top of the cabinet and the lack of space, no plates were located on that location. In order to do the experimentation correctly and to be able to compare the results, the same material has to be included in the freezer during different experimentation. Therefore, during the experimentation without PCM, the freezer had the same number of encapsulation plates as the freezer when the experimentation with PCM is done; obviously without PCM.

The total volume of each PCM plate was $1.3 \cdot 10^{-3} \text{ m}^3$ (340 x 255 x 15 mm each plate), occupying 3.36% of the internal volume of the freezer, and each empty plate weighed

2.2 kg. Each plate had 1.12 kg of Climsel C-18; therefore the total amount of PCM inside the freezer was 7.84 kg. Each plate had a Pt-100 sensor in the middle of it in order to measure the temperature of the PCM.



Fig. 4. Stainless steel plate used to encapsulate the PCM.

3.4 Test packages

Test packages (M-packs) are intended to simulate the thermal mass in the freezer under real conditions. In some experiments the freezer was filled up with these M-packs in order to simulate real operation in the freezer. The chemical composition by mass was: 76.42wt% of water, 23.0wt% of oxyethylmethylcellulose, 5.0wt% of sodium chloride, and 0.08wt% of parachloromethacresol.

These M-packs (50x100x100mm) had a freezing point near -5 °C. Temperature sensors were inserted in some of these M-packs, which represented the food products, in order to measure the temperature fluctuations in them. Fig. 5 shows the location of the M-pack inside the freezer during a normal test.



Fig. 5. Location of the M-pack inside the freezer.

3.5 Temperature measurements

The following temperatures were measured and monitored continuously during the experimentation:

- Air temperature inside the freezer
- Product temperature (M-pack)
- PCM temperature
- Ambient temperature

Sixteen air temperature sensors were located inside the cabinet as showing Fig. 6. Some experiments have been done in order to know the best location of the air temperature sensors inside the freezer (Annex 1). Air temperature was measured using Pt-100 1/5 DIN Class B inserted into a 4 mm diameter steel cylinder having a length of 30 mm. Product temperature was measured using temperature sensors inserted into a 500 g test packs (M-pack). There were four product temperature sensors in the freezer. The temperature sensor used was Pt-100 1/5 DIN Class B inserted into a 4 mm diameter steel cylinder and a length of 60 mm. PCM temperature sensors were used in six

plates and they were the same used for air temperature. To sum up, Table 4 shows all the temperature sensors installed in the freezer during the experimentation. All Pt-100 used in the experimentation were calibrated from 20 to -30 °C in MICROCAL T100 equipment to an accuracy of 0.1 °C.

Measurement	Freezer
Air temperature	16 sensors
Product temperature (M-pack)	4 sensors
PCM temperature	6 sensors
Ambient temperature	1 sensor

Table 4. Temperature sensors located in each freezer.

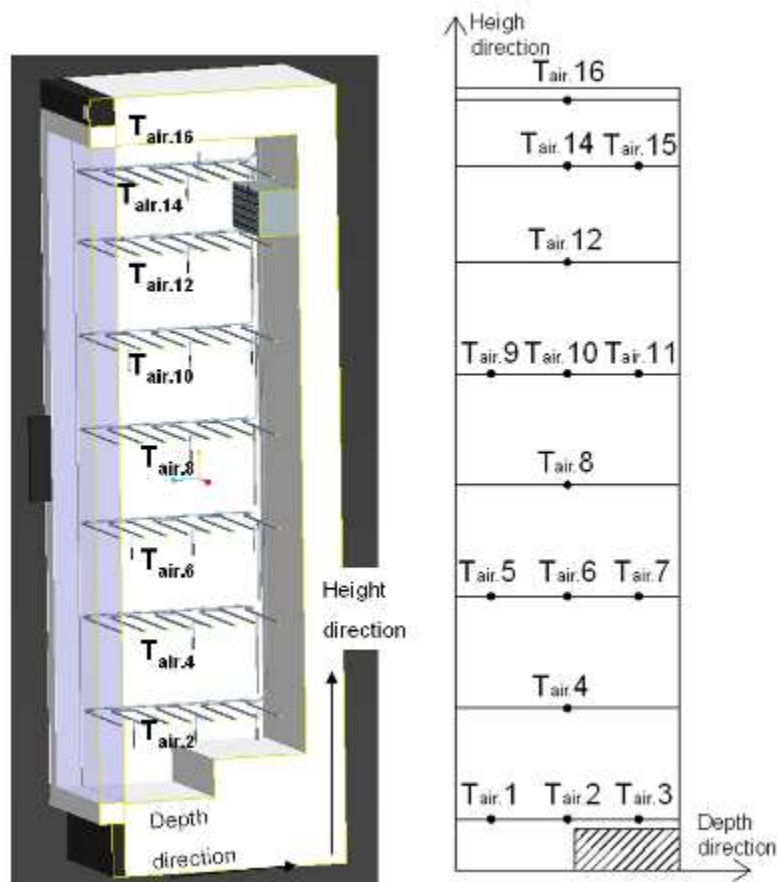


Fig. 6. Air temperature sensors location inside the freezer.

As expected, there was air stratification inside the freezer (Fig. 7). It is clear that there was a big difference between the air temperature at the bottom ($-22\text{ }^{\circ}\text{C}$) and the air temperature at the top of the freezer ($-17.5\text{ }^{\circ}\text{C}$). However, the main section of the freezer had a temperature variation between -20.5 to $-18.5\text{ }^{\circ}\text{C}$. This fact allows working using an average of the air temperature in the main part of the freezer. The stratification test done showed that, three average temperatures (bottom, medium and top average) are enough to understand the behaviour of the air temperature inside the freezer. The medium average temperature was calculated with the average of the air temperature values from $T_{\text{air},4}$ to $T_{\text{air},12}$; the bottom average temperature was calculated with the average of the $T_{\text{air},1}$, $T_{\text{air},2}$, and $T_{\text{air},3}$, and the top average was calculated using $T_{\text{air},13}$, $T_{\text{air},14}$, and $T_{\text{air},15}$. Note that due to the location of the fan in the middle part of the cabinet, high temperatures were detected in that zone.

Fig. 8 shows the average temperature ($T_{\text{ave.bot}}$, $T_{\text{ave.med}}$, and $T_{\text{ave.top}}$) of the freezer empty of stainless steel plates, PCM, and test packages. As always happens in refrigerators and in freezers during steady state, the air temperature fluctuates between two values. When the compressor of the system is switched on, the air temperature decreases until it reaches a low set point value, after that the compressor is switched off and the temperature increases due to heat losses to the ambient until reaching the high set point value. This cycle occurs along the working process of the freezer.

As the top and the bottom part of the freezer is not accessible at all to store frozen product it is understandable that both average temperatures ($T_{\text{ave.bot}}$ and $T_{\text{ave.top}}$) are not being considered in the results of the experimentation. Therefore, only the medium average temperature is considered in the discussion of this work.

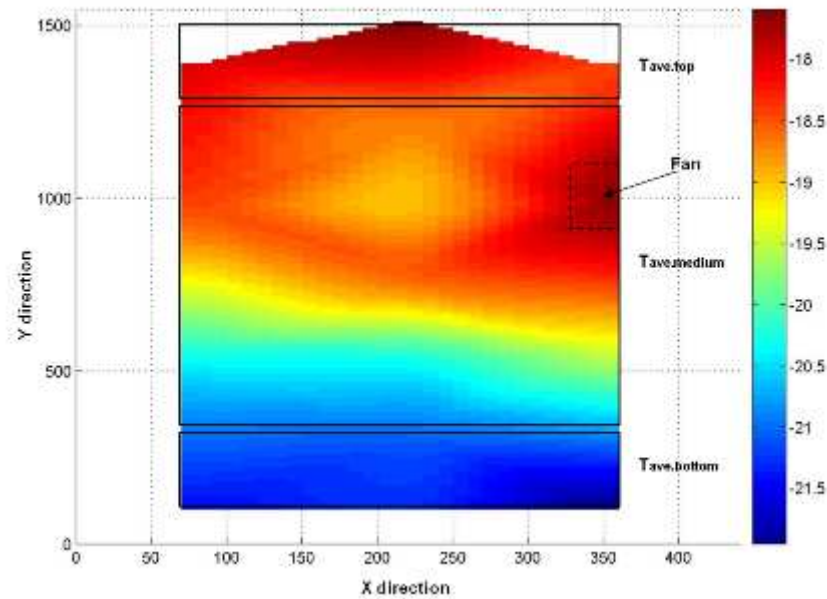


Fig. 7. Air map temperature of the freezer during a normal operational running.

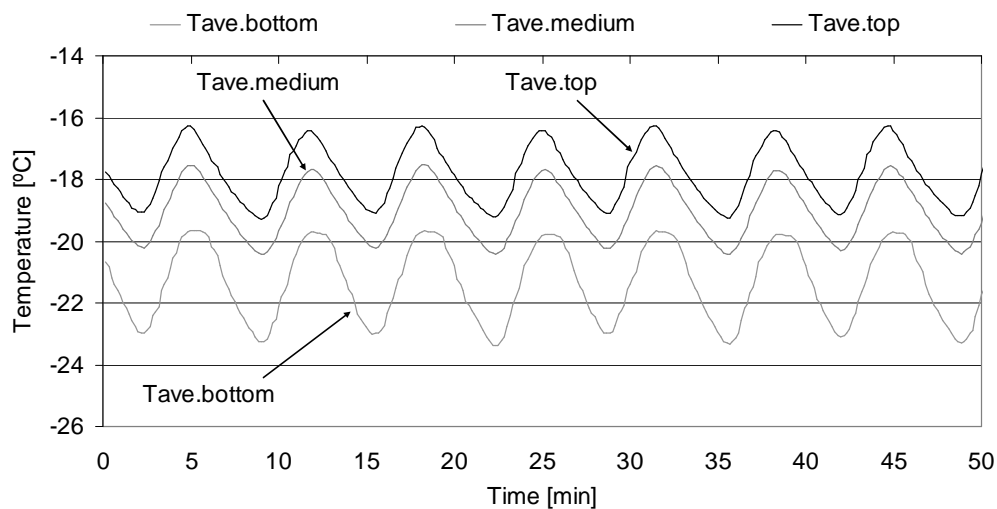


Fig. 8. Average air temperature profile inside the freezer.

3.6 Test procedure

Experiments related to door opening and electrical power failure were conducted with different duration of door opening and electrical power failure, respectively. Experiments were conducted with and without the M-packs in order to simulate what happen when the freezer is empty and fully loaded and obviously, all the experiments

were done with and without PCM. Table 5 and Table 6 show the characteristics of the door opening and electrical power failure experiments, respectively.

In order to study the importance between the storage temperature (air temperature inside the freezer) and the melting temperature of the PCM (-18 °C), all these experiments were done with two different set points of the freezer. The first set point was set at an average medium temperature of -22 °C and the second set point was set at an average medium temperature of -19 °C.

Test scenarios	Number of door opening	Time that the door is opened for (sec)	Time between openings (min)
Test 1a. Door opening	5	10	20
Test 1b. Door opening	5	30	20
Test 1c. Door opening	2	180	20
Test 1d. Door opening	1	300	-
Test 1e. Door opening	1	600	-

Table 5. Set of experiments related to door opening conducted for the experimentation.

Test scenarios	Time of electrical power failure (min)
Test 2a. electrical power failure	15
Test 2b. electrical power failure	30
Test 2c. electrical power failure	60
Test 2d. electrical power failure	120
Test 2e. electrical power failure	180

Table 6. Set of experiments related to electrical power failure conducted for the experimentation.

4 Results analysis

The measurements done included air freezer temperatures, PCM temperatures, M-pack temperatures, and ambient room temperature under real boundary conditions (ambient temperature of 21 ± 0.5 °C and HR of 40-60 %). All the experimentation was done with two different temperature storage of the freezer.

4.1 Air temperature response to door openings

A series of door openings have been done with the freezer loaded and unloaded with the M-packs with and without PCM under the same boundary conditions. Five different tests

(Table 5) were performed in order to study the behaviour of the freezer analysed under two different set points of the storage temperature.

Fig. 9 and Fig. 10 show the average air temperature during test 1b (5 door openings of 30 seconds each) with and without PCM and the freezer loaded with the M-packs in both set points respectively. Operating with a storage temperature of -19 °C the benefit of the introduction of PCM inside the freezer is clear, in four of five door openings there was important differences on the temperatures reached with and without PCM, being the temperature of the air in the case of no PCM higher (Fig. 9). On the other hand, when the experimentation was done using a storage temperature of -22 °C, no differences between the experimentation with and without PCM were found (Fig. 10).

Fig. 11 and Fig. 12 show the average air temperature during test 1e (one door opening of 10 minutes) with and without PCM and the freezer loaded with the M-packs in both set points. Here, again, the difference of the storage temperature between both set points and the results of the implementation of PCM inside the freezer is clear. Working with the set point of -22 °C, the values of the air temperature in the freezer between with and without PCM was 0.5 °C while in the set point of -19 °C, this difference was 4 °C. Therefore, the incorporation of PCM in the freezer is beneficial in terms of enhancement of the thermal properties inside the freezer in both cases but when the storage temperature is nearly the phase change temperature of the PCM, the benefit of

using PCM is much greater.

Furthermore, this is not the only benefit of the incorporation of PCM. As Fig. 11 and Fig. 12 show, once the air temperature reached the normal temperature operation, after the door was closed (-22°C and -19°C for the first and the second set point, respectively) the air temperature is nearly constant till it reaches the low set point value and starts to fluctuate as a steady state conditions. The time while the profile of the air temperature is almost constant increased when PCM is used due to the thermal mass added by the PCM at the system. Obviously, when the freezer was unloaded of M-pack the difference between the incorporation or not the PCM became higher due to the much higher thermal mass difference.

Moreover, it is well known that the storage of the product at constant temperature is much better than the storage at fluctuation temperatures. Therefore the addition of PCM at the system would be beneficial in terms of food quality.

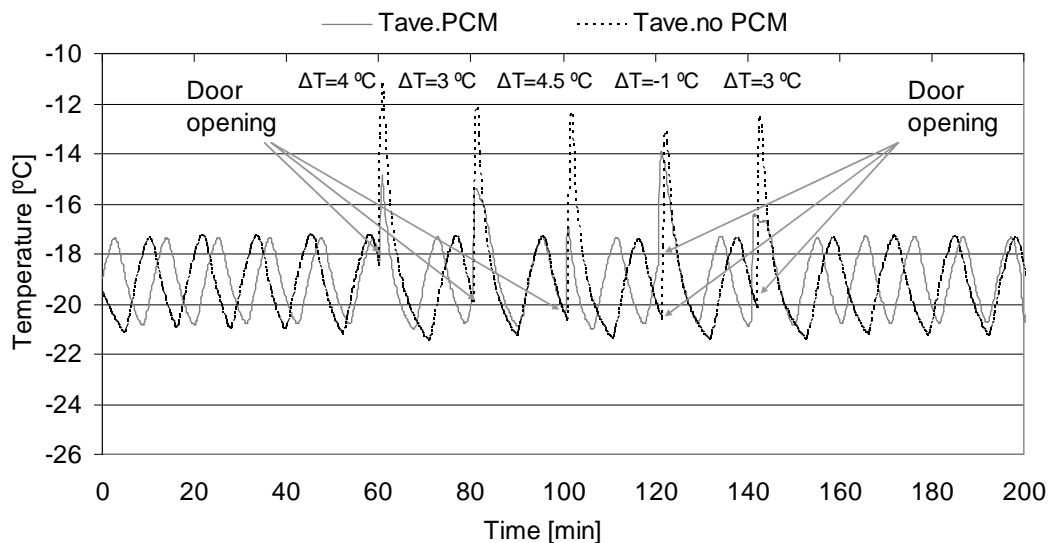


Fig. 9. Average air temperature during test 1b with M-pack (set point of -22°C).

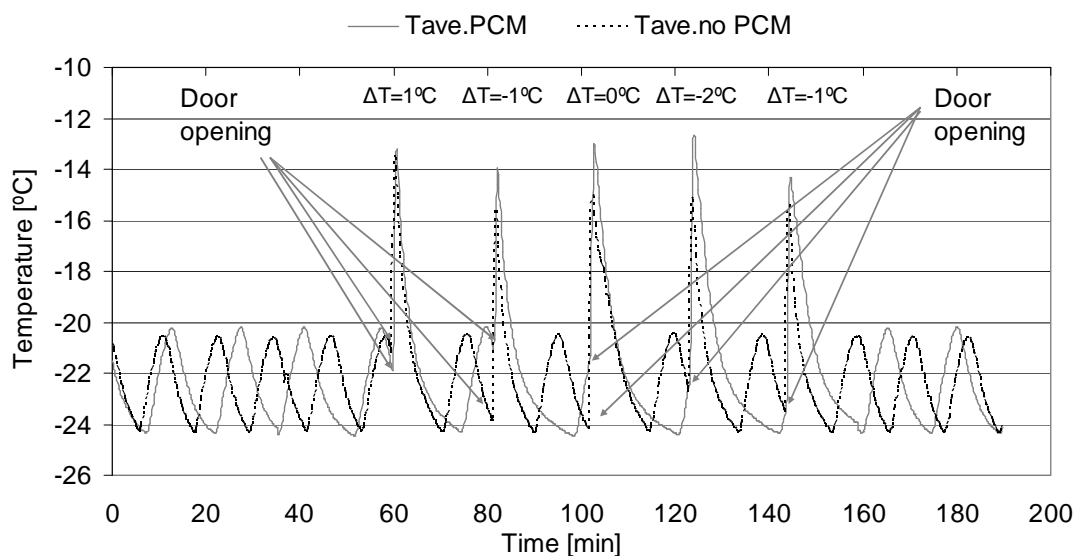


Fig. 10. Average air temperature during test 1b with M-pack (set point of -19 °C).

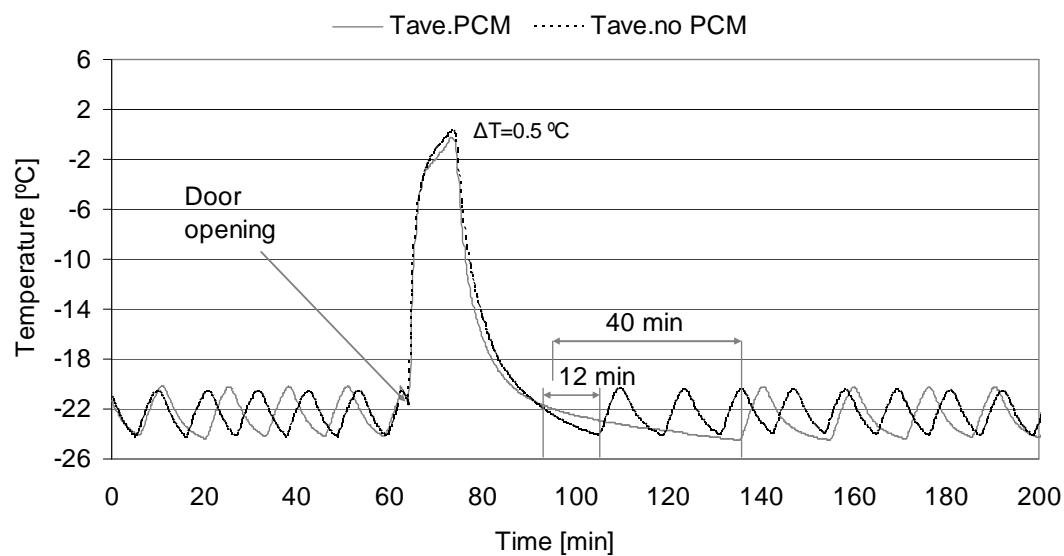


Fig. 11. Average air temperature during test 1e with M-pack (set point of -19 °C).

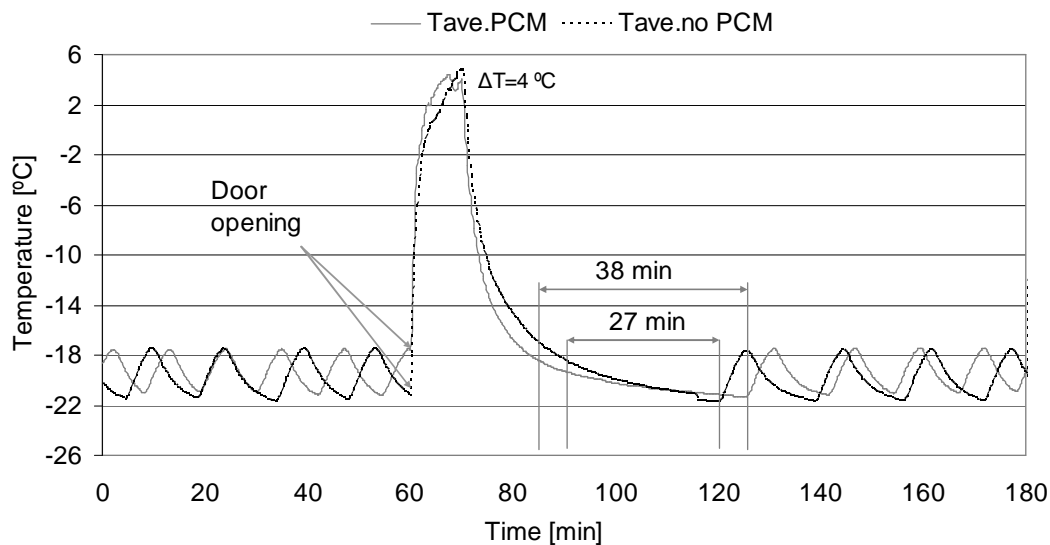


Fig. 12. Average air temperature during test 1e with M-pack (set point of -22 °C).

4.2 Air temperature response to electrical power failure

A series of electrical power failure have been done with the freezer loaded and unloaded with M-packs, with and without PCM under the same boundary conditions. Five different tests (Table 6) were performed in order to study the behaviour of the freezers analysed under two different storage temperature.

Fig. 13 and Fig. 14 show the average air temperature immediately after test 1b (electrical power failure of 30 minutes) in the freezer unloaded of M-pack with and without PCM, respectively. Fig. 15 and Fig. 16 show the same test 1b but with the freezer loaded of M-pack. These results are from the experimentation done with the storage temperature set at -19 °C. As it was expected, the freezer unloaded of M-pack reached high temperatures due to the lower thermal mass of the system. Moreover, the temperatures of the freezer just after the electrical power failure test clearly show the benefit of the addition of PCM in the system, reaching lower temperatures after an electrical power failure. In conclusion, in terms of air temperature of the cabinet after an electrical power failure, the use of PCM is beneficial to the system, keeping lower temperatures under the same conditions.

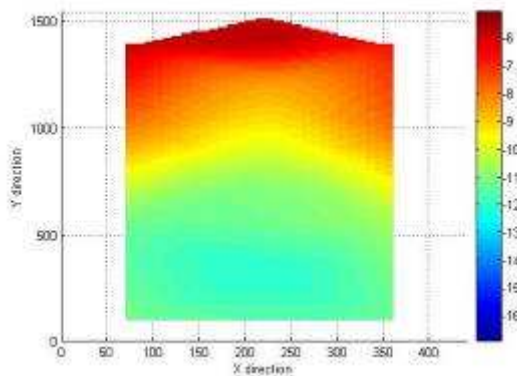


Fig. 13. Map air temperature after test 2b without PCM and unloaded of M-pack.

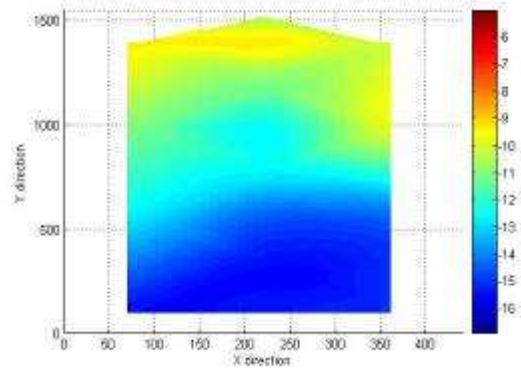


Fig. 14. Map air temperature after 2b with PCM and unloaded of M-pack.

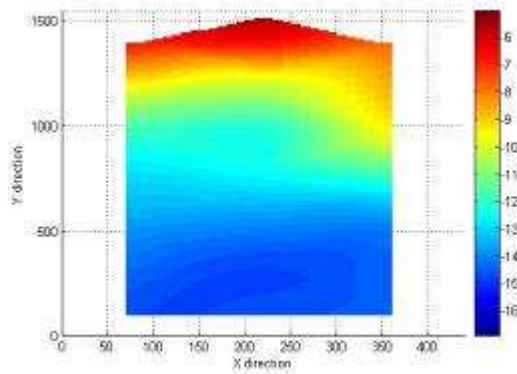


Fig. 15. Map air temperature after test 2b without PCM and loaded of M-pack.

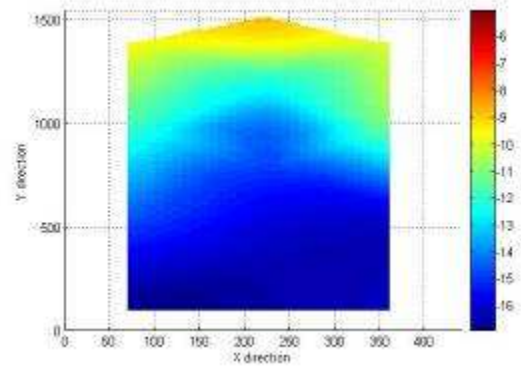


Fig. 16. Map air temperature after test 2b with PCM and loaded of M-pack.

Fig. 17 and Fig. 18 show the average air temperature during test 2e (electrical power failure of 3 hours) with and without PCM and the freezer loaded with the M-packs at both set points, respectively. As happened with the previous electrical power failure test, the addition of PCM in the system had a great benefit and the freezer kept lower temperatures during the electrical power failure. Operating at the set point of $-22\text{ }^{\circ}\text{C}$ the temperature difference after the electrical power failure was $4\text{ }^{\circ}\text{C}$ and working with an storage temperature of $-19\text{ }^{\circ}\text{C}$, this difference became $6\text{ }^{\circ}\text{C}$.

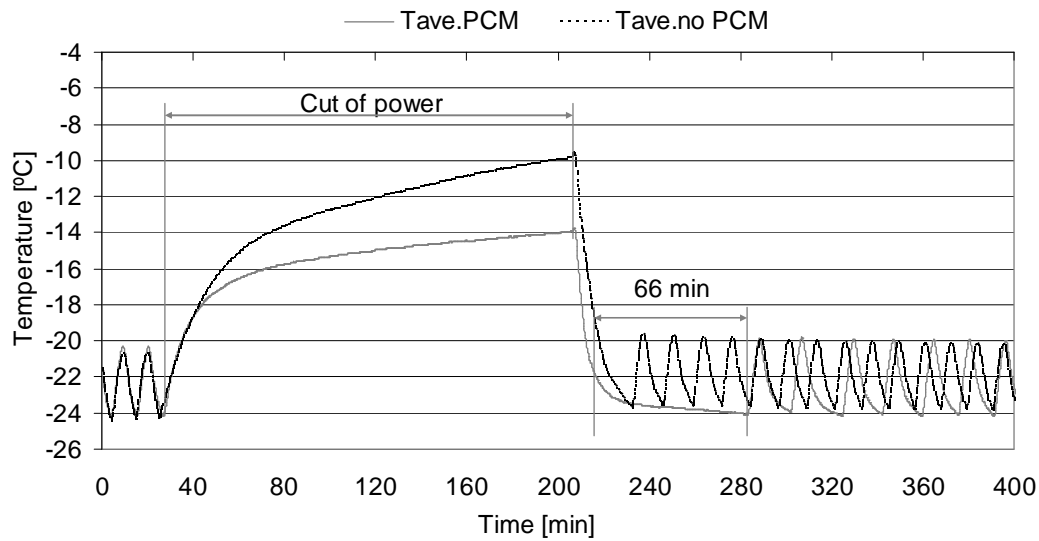


Fig. 17. Average air temperature during test 2e with M-pack (set point of -19 °C).

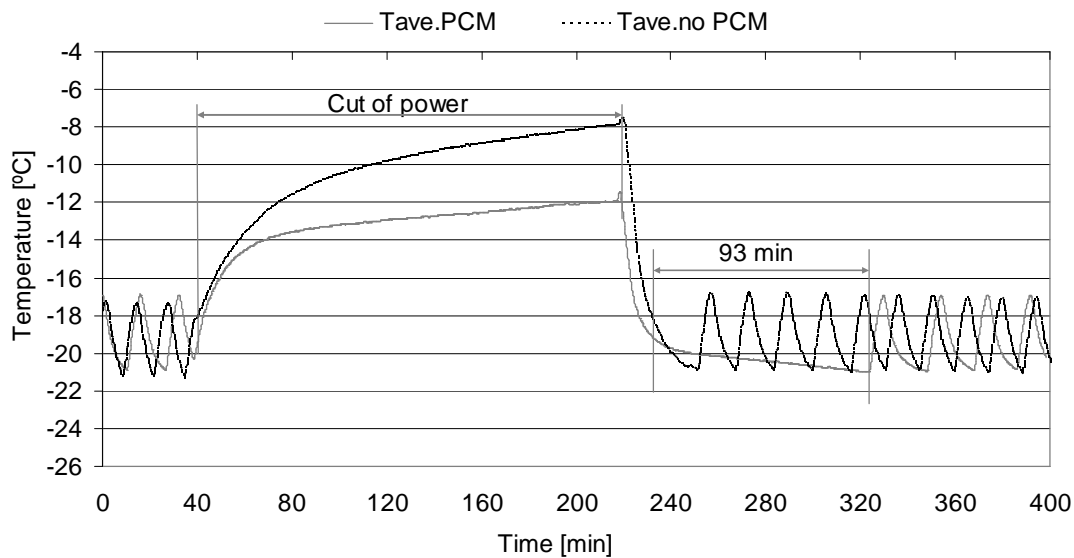


Fig. 18. Average air temperature during test 2e with M-pack (set point of -22 °C).

Furthermore, as it happened with the door opening tests, there is another interesting benefit of using PCM in terms of food quality. After the power was switched on again, the temperature of the cabinet started to decrease until it reached the low set point value (-24 °C and -21 °C in the 1st and the 2nd set point, respectively) and then started to fluctuate. In the freezer without PCM the time to reach the lower set point from normal temperature operation (-22 °C and -19 °C) were 9 and 16 minutes in the first and in the

second set point, respectively; while using PCM were 66 and 93 minutes. Besides in both cases, the profile of the air temperature was almost constant for longer time when the PCM was used due to the thermal mass added by the PCM to the system. Therefore the use of PCM is beneficial in terms of food quality in electrical power failure experiences.

4.3 PCM response

It is important to evaluate the behaviour of the PCM during these experiments and to insure that the PCM undergoes phase transition; otherwise it will store only sensible heat, which is small compared to latent heat storage. Furthermore, it is important to know the state of the PCM after these different tests, that is to say which amount of energy has given and can still give the PCM to the system. For that reason the temperature of the PCM during test 2e (3 hours of electrical power failure), which is the most critical case studied, will be analysed here. Fig. 19 shows the most representative temperature of the PCM during test 2e working at two different storage temperatures with the freezer loaded of M-pack.

After 30 minutes without power, the PCM started to melt, however, when the power was recovered, the PCM did not completely melt. However, it is not possible to say which amount of energy could give the PCM to the system and maintain the cabinet at almost constant temperature with the experimentation done. The melting temperature of the PCM was not the same for all the cases measured, nevertheless this temperature was between -16 and -18 °C. Furthermore, because the stainless steel plates where the PCM was encapsulated were on the evaporator plate, the thermal response of the PCM was different to the thermal response of the frozen product. the main difference was a bigger amplitude of the temperature oscillations during steady state.

The presence of M-pack (simulating food) added significant thermal mass that prevented melting of the PCM, suggesting that a fully loaded freezer could sustain for longer time an electrical power failure.

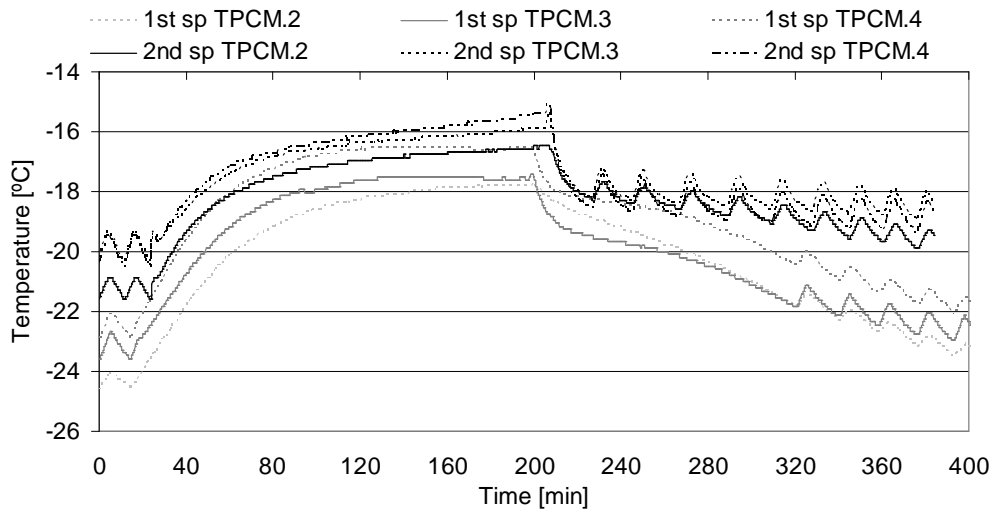


Fig. 19. PCM temperatures during test 2e loaded of M-pack with two different storage temperatures.

4.4 M-pack response

In order to analyse the behaviour of the frozen product, measurements of the temperature of different M-pack were done, and following the ISO standard (ISO 15502:2005/AC:2008), the hottest M-pack temperature in each experiment had to be taken into account. As expected, the M-pack located at the highest position inside the freezer was the hottest one in each test.

Fig. 20 shows the M-pack temperature during test 1c with and without PCM at two different storage temperatures. There were no differences between the temperatures reached in each case due to the short period under heat losses, nevertheless in other tests, such as 1d and 1e the temperature reached was higher in the products where no PCM was added, therefore there were benefit of using PCM. On the other hand, in some tests done, the temperature of the frozen product after the tests was almost constant during a while in the cases where PCM was inside the system.

Moreover, in the experiments of electrical power failure the benefit of using PCM was clear. In all the cases studied, the temperature reached by the products stored in the freezer without PCM was always higher. Fig. 21 shows the temperature of the M-pack during test 2e, where the benefit of using PCM is clear. In addition the M-pack

experiences less temperature fluctuation after the power is switched on again.

It is well known that the size of ice crystals in ice cream grow larger when the ice cream is stored under fluctuating conditions. Therefore, the results demonstrated in Figure 9 show clear evidence of potential improvement of frozen products storage through the application of PCM.

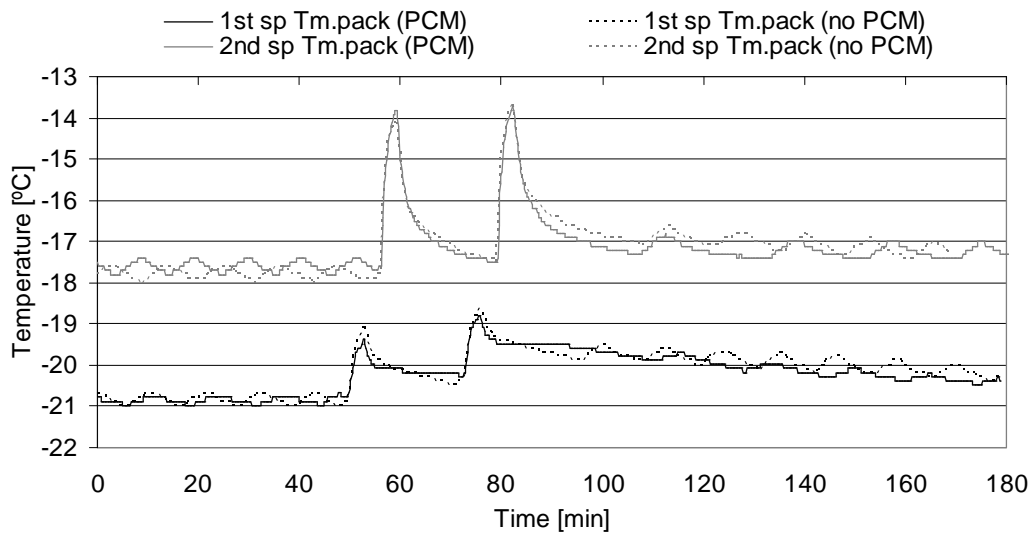


Fig. 20. M-pack temperatures during test 1c with two different storage temperatures.

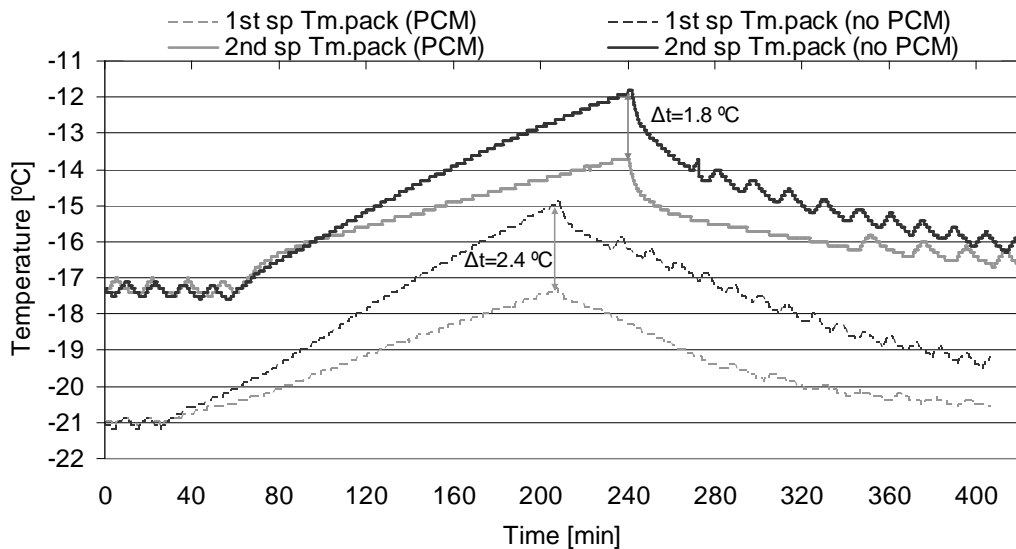


Fig. 21. M-pack temperatures during test 2e with two different storage temperatures.

5 Conclusions remarks

Restrictions on daily use of the electricity in some countries and regular electrical power failure could induce to great economical losses to supermarkets due to devaluation of frozen food quality. Moreover, the customers in every supermarket unconsciously cause significant heat losses to the ambient due to door opening of commercial freezers.

The aim of this work was to improve the thermal performance of commercial freezers using phase change materials (PCM) and to prove the importance of the correct PCM selection (melting temperature) for each application. A commercial freezer, with and without macro encapsulated PCM in stainless steel panels was used to assess the benefits of using PCM in minimizing temperature fluctuation and to maintain the cabinet at the lowest temperature possible under heat losses due to door openings and electrical power failure. A commercial PCM (Climsel-18, from Climator) which melts at -18°C was used.

The PCM plates were located horizontally on the evaporator plates, leaving enough room on the sides for a proper air circulation inside the freezer. Additionally, this new concept allows to the user the feasibility to change, if needed, the PCM plates and even the PCM without problems.

In this work, the use of PCM in a commercial freezer was positive in minimizing temperature rise of the freezer and the products in it during door opening and electrical power failure. In the most dramatical scenario, which was the longer electrical power failure (3 hours), the PCM started to melt but did not melt completely. This fact demonstrates that the freezer with PCM can sustain interior temperature almost constant (from -12 to -14°C) for much longer than 3 hours without power.

The results of the door opening test demonstrated the importance of the correct selection of the PCM (melting temperature) in each application. It is important to select a PCM that has the phase change nearly the storage temperature if not the PCM will not interact with the system as desired.

In all the tests related to electrical power failure and in most of the cases related to door

opening, the temperature of the M-pack, used to simulate food, were lower when PCM was used and in addition, the M-pack experiences less temperature fluctuation after the power was switched on again or when the door was closed. Therefore, in terms of product quality, the benefit of using PCM was clearly demonstrated.

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Annex 1. Location of the air temperature sensors inside the freezer

Summary

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1 Introduction

The aim of this annex is to study the best location of the air temperature sensors inside the studied commercial freezers. This experimentation was done with one freezer empty (no plates, no PCM, no meat), with the aim to know how the air circulates inside it, and know the air temperature in different positions inside the freezer. In order to know more accurately the air distribution inside the freezer, such as the variation of the air in the depth and in the width direction, some experiments were done.

2 Temperature measurements

In order to measure the air temperature, 16 temperature sensors were located inside the cabinet. Air temperature was measured using Pt-100 1/5 DIN Class B insert into a 4 mm diameter steel cylinder and a length of 30 mm. All the Pt-100 used in the experimentation was calibrated from 20 to -30°C in MICROCALT100 equipment to an accuracy of 0.1°C.

It is well known that inside the cabinet there will be air stratification even though the fan. Due to this fact, it is very important to know the air temperature in different heights inside the cabinet. Since there are eight spaces between the evaporator plates inside the freezer, there were located air temperature sensors at eight different levels.

However, it is not too clear the behaviour of the air in the depth and in the width direction inside the freezer. For this reason three different experiments were done to compare it.

Due to the location of the fan inside the freezer, that is located at the top of the freezer, and the behaviour of the fan, that throw the air to the bottom of the freezer and suck the air perpendicularly at the back wall, the air will circulate as Fig. 22 shows.

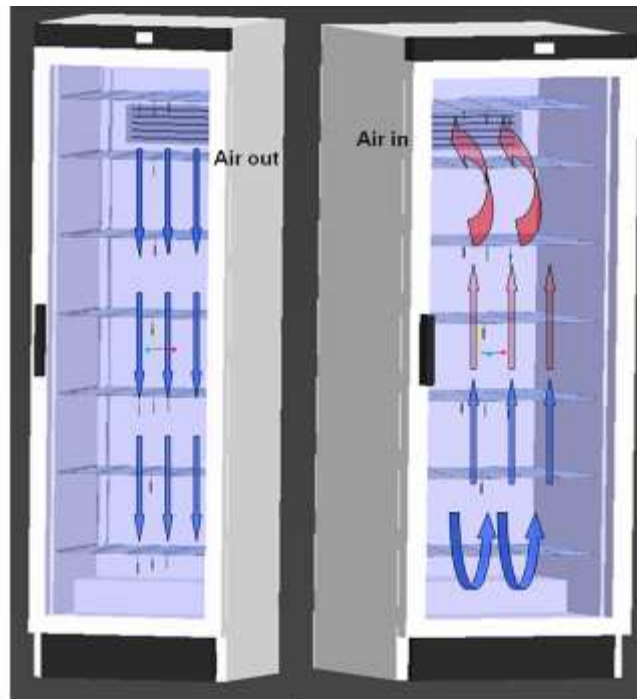


Fig. 22. Convective flux inside the freezer.

For that reason, in the first experiment the air temperature sensors were located in the way to know the air temperature distribution in the depth direction as Fig. 23 shows. There were air temperature sensors in 8 different heights; in four of them there were located 3 sensors in the depth of the freezer and the other four heights there were located one temperature sensor in the middle of the evaporator plate. All the sensors were installed in the middle of the freezer and in depth direction in order to do a 2D map of the air temperatures in this direction.

In the second experiment, some temperature sensors ($T_{\text{air}.1}$, $T_{\text{air}.3}$, $T_{\text{air}.5}$, $T_{\text{air}.6}$, $T_{\text{air}.7}$, $T_{\text{air}.9}$, $T_{\text{air}.10}$, $T_{\text{air}.11}$, $T_{\text{air}.13}$, and $T_{\text{air}.14}$) were moved in the width direction as it can see in Fig. 24. The temperature sensors that there were not moved allow to compare the second and the first experiment and see the air temperature difference in the depth direction but in another width.

In the third experiment some air temperature sensors were moved again, in order to know the temperature profile in the width direction of the freezer (Fig. 25). Not all the temperature sensors were moved due to it is interesting to check if there are some

differences in the normal behaviour of the freezer. This configuration allows not only checking the air temperature profile in the width direction but also in the depth direction.



Fig. 23. Location of the air temperature sensors in the freezer in experiment 1.



Fig. 24. Location of the air temperature sensors in the freezer in experiment 2.



Fig. 25. Location of the air temperature sensors in the freezer in experiment 3.

3 Results and discussion

During the first experimentation the behaviour of the compressor was regular as Fig. 26 shows. When the compressor is switched on there is a peak at the beginning and after that, the electrical power consumed is almost constant (0.54 kW). When the compressor is switched off the energy consumption is not zero due to there are more elements in the freezer such as a light of 0.15 kW.

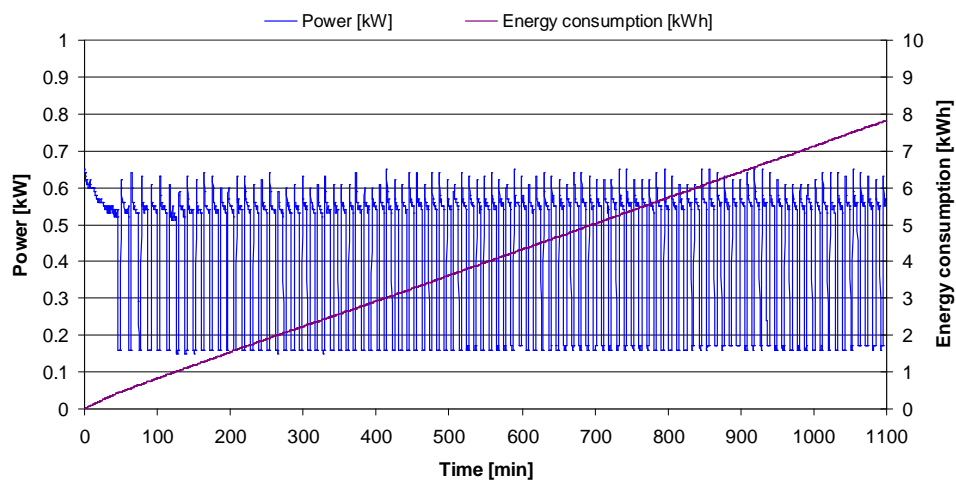


Fig. 26. Power consumption and energy consumption of the freezer during the experiment 1.

As it was expected, there was air stratification inside the freezer. Obviously, the top of the freezer is the hottest part and the bottom is the coldest part. However, the main part of the freezer has a similar behaviour and there is no high stratification in this part. Fig. 27 shows a 2D air temperature map during the experimentation where it can see the stratification of the air.

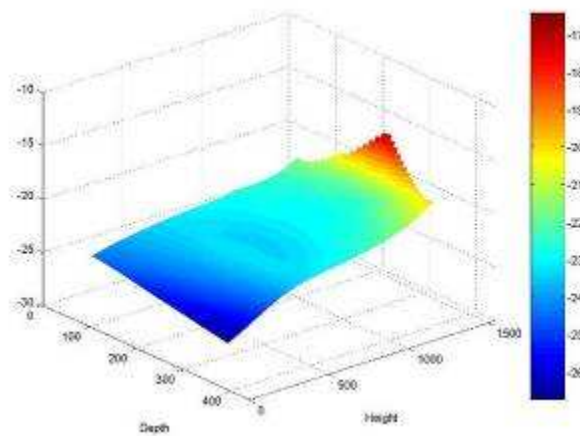


Fig. 27. Air map temperature during the experiment 1.

The air temperature inside the cabinet fluctuates between two values during the experimentation and the temperature range is almost 6°C. The hottest temperature depends on the set point that it had set before; and the lowest temperature depends on the position of the air temperature sensor inside the freezer and the boundary conditions during the experimentation.

At the bottom of the freezer it was detected an important difference of the temperature in the depth direction (T_{air1} , T_{air2} , and T_{air3}). This effect is due to the geometry of the freezer, doing that the air located at the bottom-back (T_{air3}) is the coldest in the entire freezer because of the smaller volume between the evaporator plate and the bottom of the freezer reaching with this boundary conditions -29°C.

It was observed that the central part of the freezer presented homogeneous air temperature distribution in the depth of the freezer. However T_{air11} shows a little difference between the other values.

In the top of the freezer it was detected a difference of the temperatures but only when the compressor didn't work reaching the air near the suction fan (T_{air15}) almost 2°C less than the other.

In order to know the difference of the air temperatures in the depth of the freezer at the same height, figures from Fig. 28 to Fig. 31 show the air temperatures of each group (T_{air1} , T_{air2} , and T_{air3}), (T_{air5} , T_{air6} , and T_{air7}), (T_{air9} , T_{air10} , and T_{air11}), and (T_{air13} , T_{air14} , and T_{air15}).

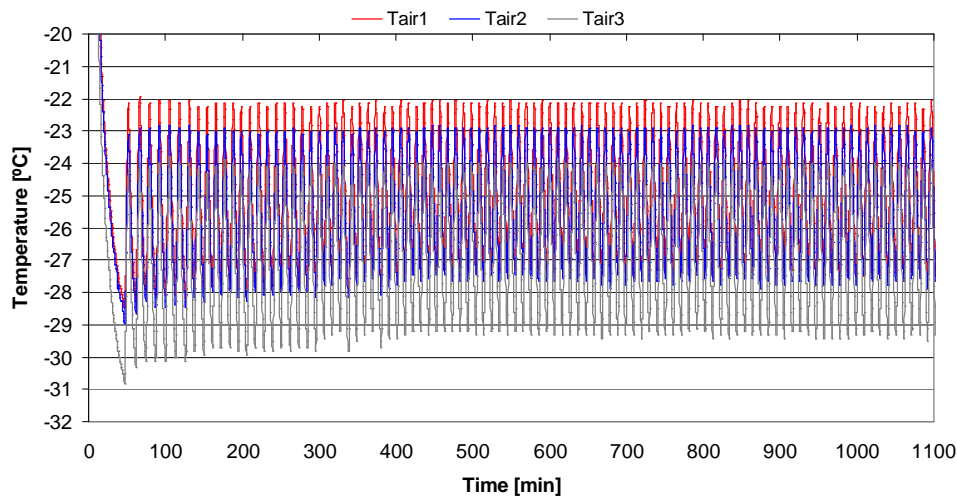


Fig. 28. Air temperature at the bottom of the freezer during the experiment 1.

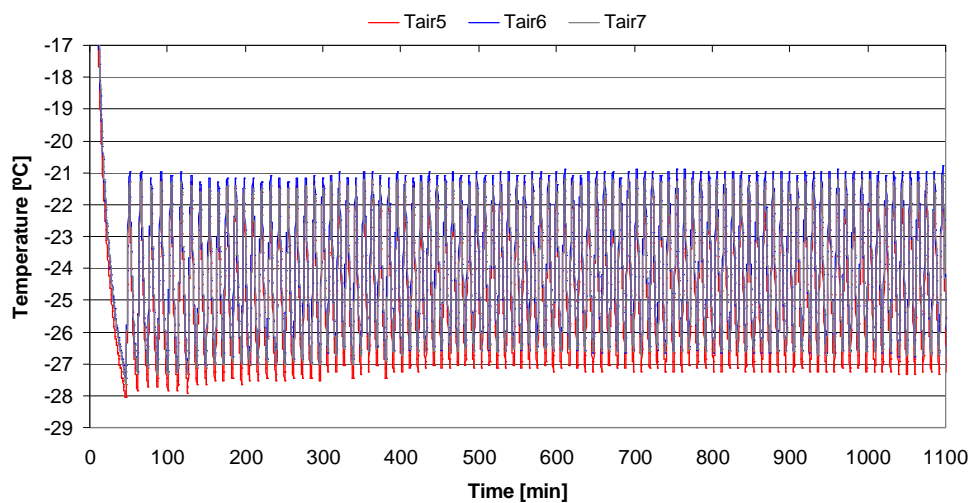


Fig. 29. Air temperature at the medium-bottom of the freezer during the experiment 1.

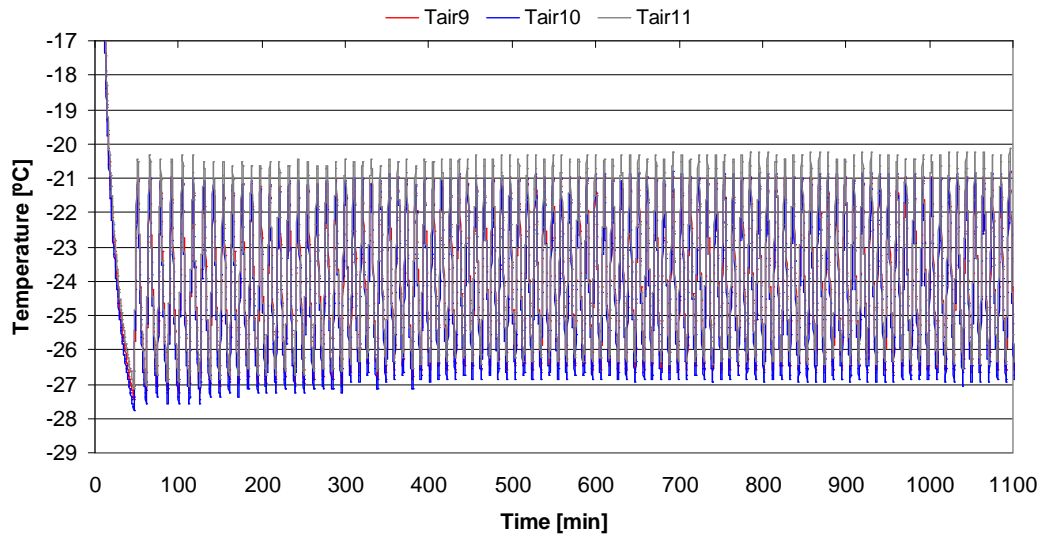


Fig. 30. Air temperature at the medium-top of the freezer during the experiment 1.

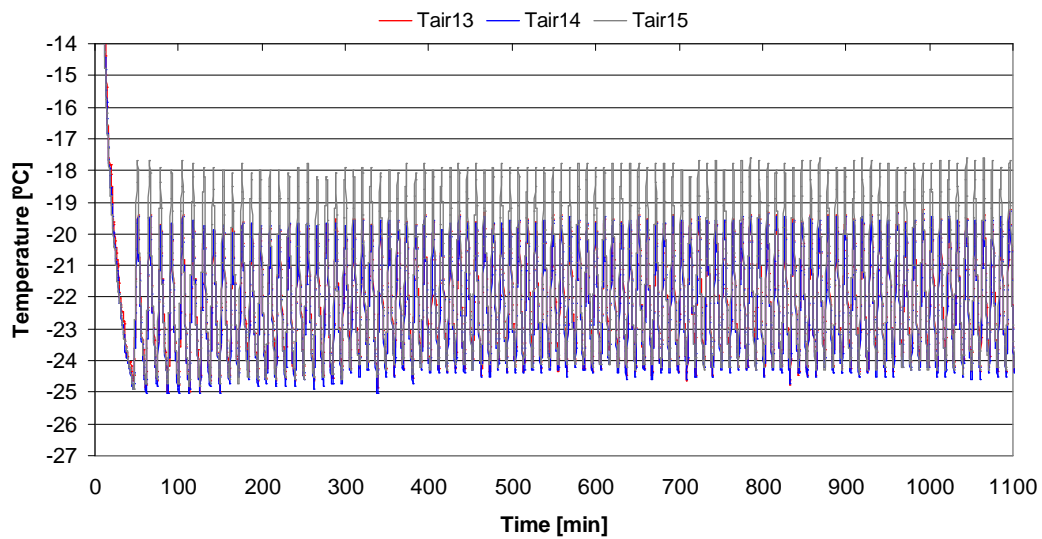


Fig. 31. Air temperature at the top of the freezer during the experiment 1.

The objective of the second experiment was to study the temperature profile in the width direction inside the freezer but in another depth in order to have more information and to decide the best location of the air temperature sensors.

During the second experimentation the behaviour of the compressor was regular as it was in the first experimentation. Fig. 32 shows the power and the energy consumption of the system and it is lightly higher than the first experimentation. When the

compressor is switched off the consumption is higher than the other experiment; therefore the compressor consumption is the same in both experiments.

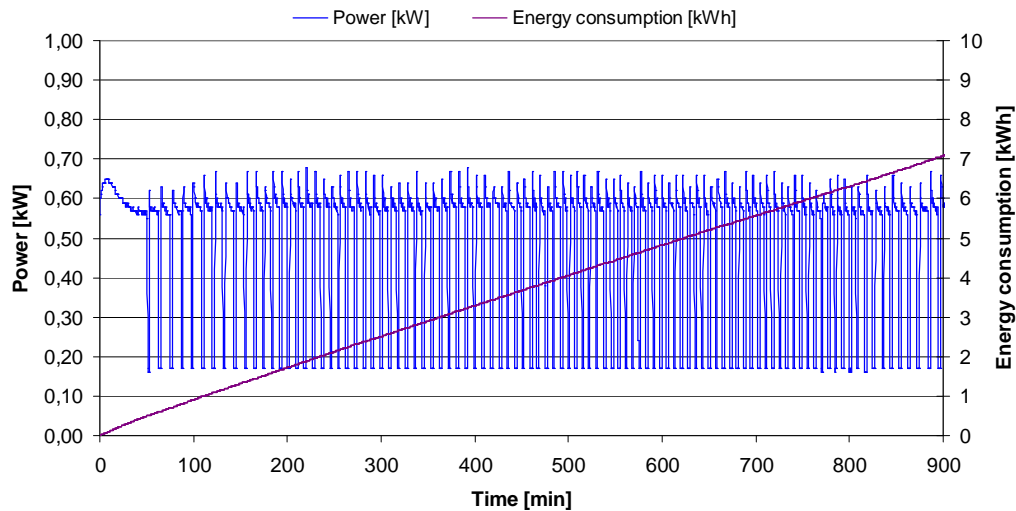


Fig. 32. Power consumption and energy consumption of the freezer during the experiment 2.

The results show that the profile of the air during the second experiment is the same that the results got in the first experimentation even though the air temperature sensors were moved in the depth direction on the freezer. From Fig. 33 to Fig. 36 the air temperature during the second experimentation are showed.

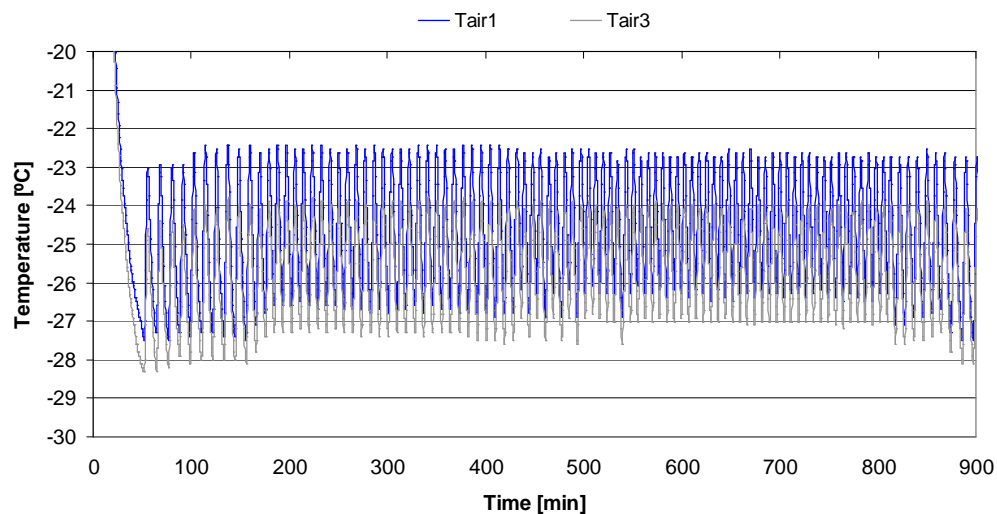


Fig. 33. Air temperature at the bottom of the freezer during the experiment 2.

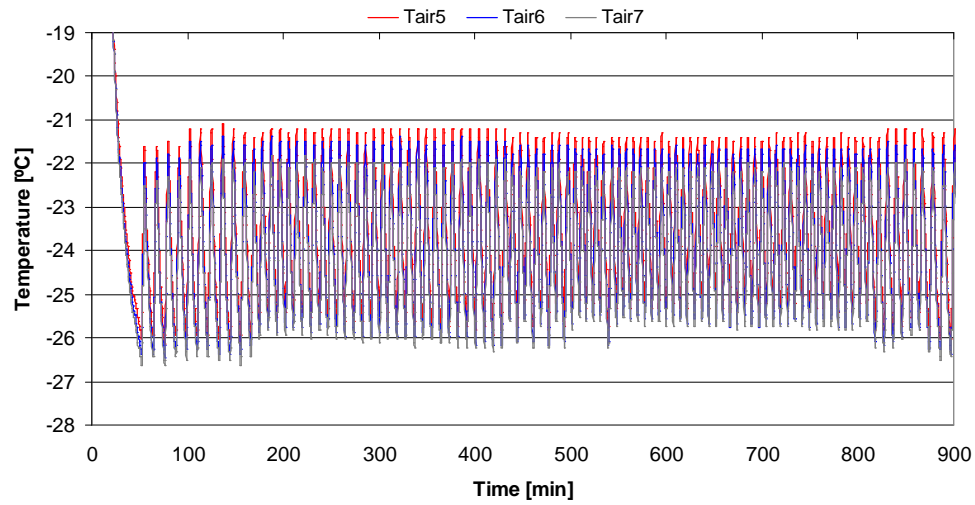


Fig. 34. Air temperature at the medium-bottom of the freezer during the experiment 2.

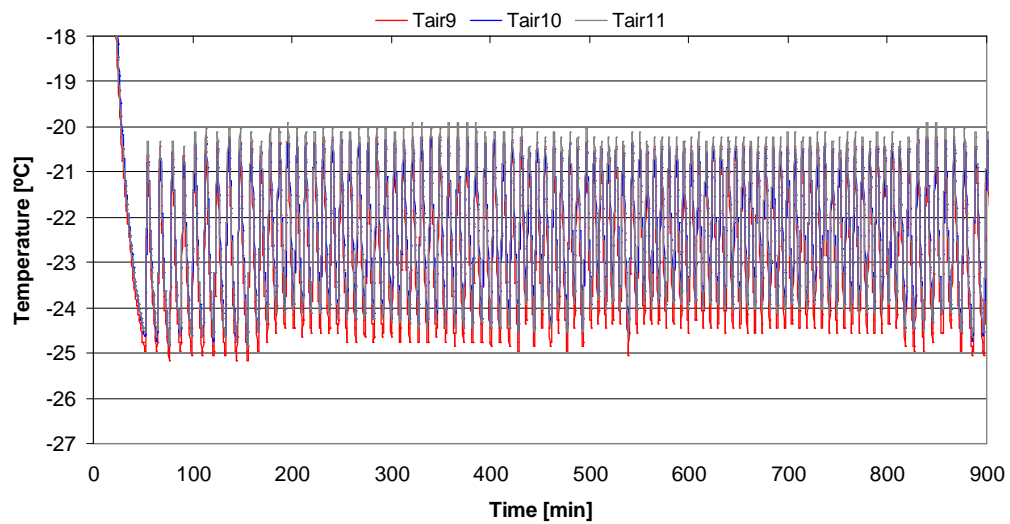


Fig. 35. Air temperature at the medium-top of the freezer during the experiment 2.

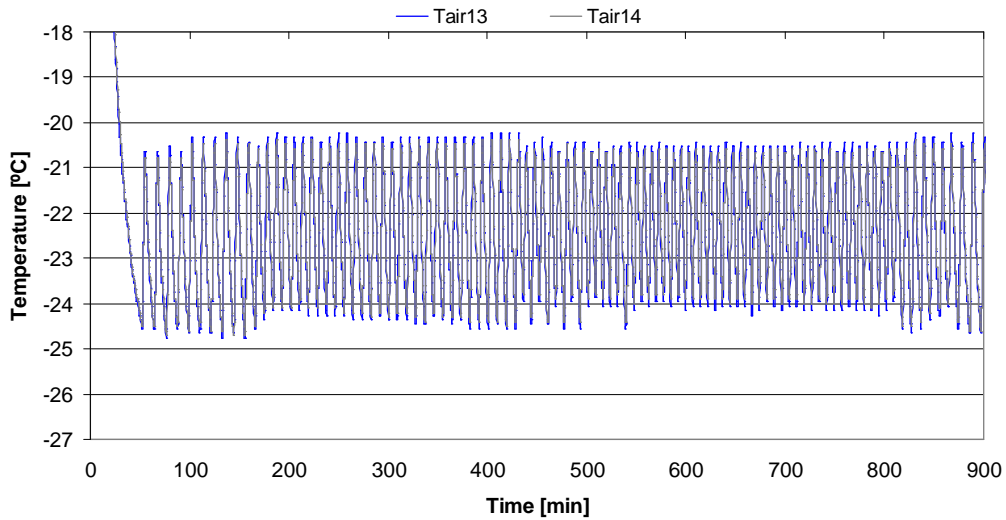


Fig. 36. Air temperature at the top of the freezer during the experiment 2.

The objective of the third experiment was to study the temperature profile in the depth direction inside the freezer in order to have more information and to decide the best location of the air temperature sensors. During the third experimentation the behaviour of the compressor was regular as it was in the previous experimentations. Fig. 37 shows the power and the energy consumption of the system and it is identically to the second experiment.

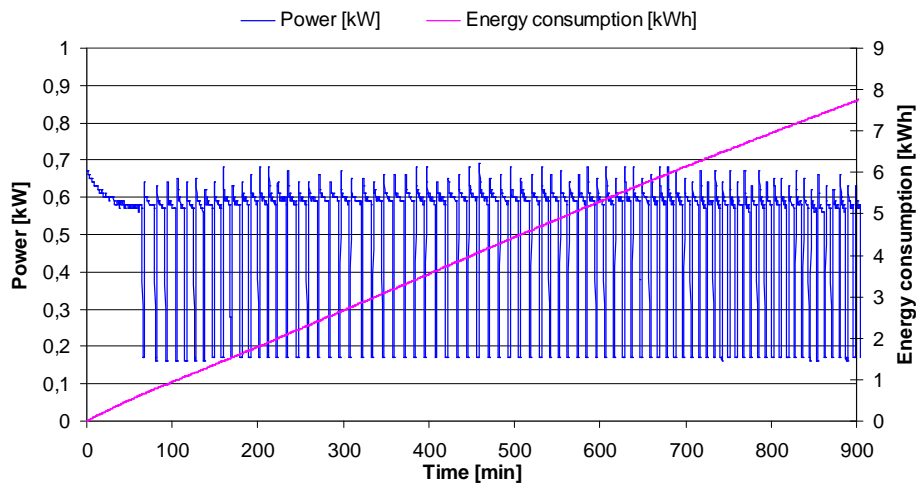


Fig. 37. Power consumption and energy consumption of the freezer during the experiment 3.

The results show that the profile of the air in the width direction at the same height is almost identically in the whole freezer unless the top of it, where the fan is located. From Fig. 38 to Fig. 40 the air temperature during the experimentation is showed, where it can see the low difference of the air temperature in the width direction. Fig. 41 shows the air temperature at the top of the freezer, where the profile changes very much in the width direction due to the air circulation in that zone. The air temperature sensor ($T_{\text{air.15}}$) was not move so it was at the same position as the other experiments. Analysing the results it can be observed that in the top of the freezer is more important to know the difference of the air temperature in the width direction than in the depth direction.

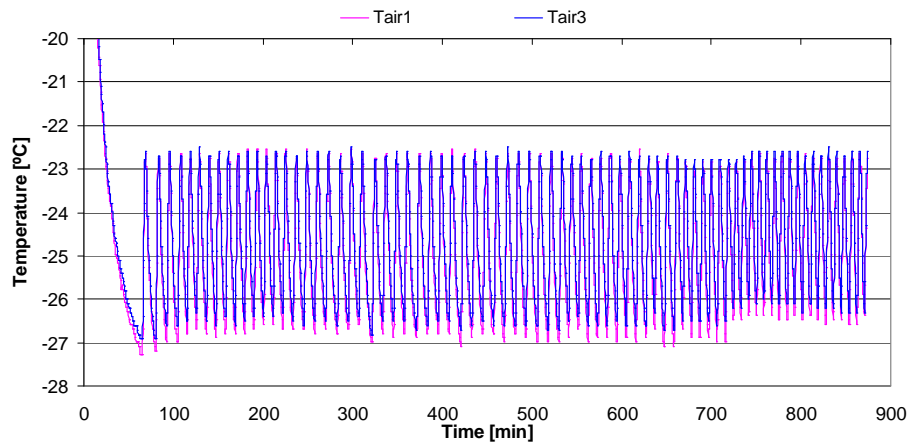


Fig. 38. Air temperature at the bottom of the freezer during the experiment 3.

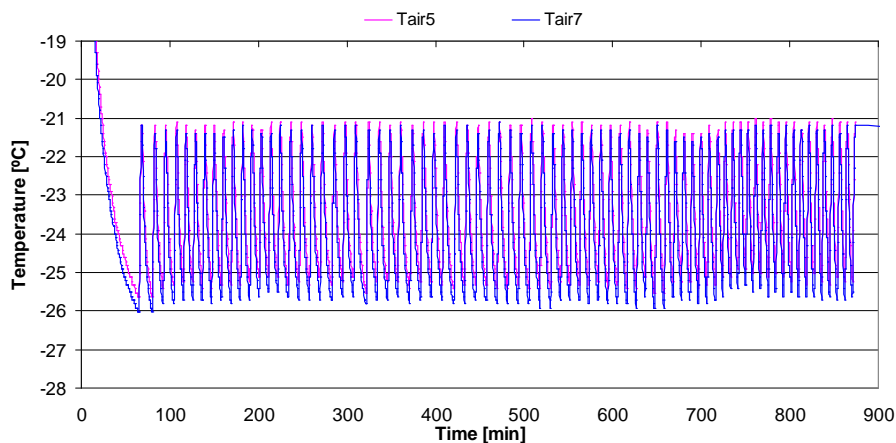


Fig. 39. Air temperature at the medium-bottom of the freezer during the experiment 3.

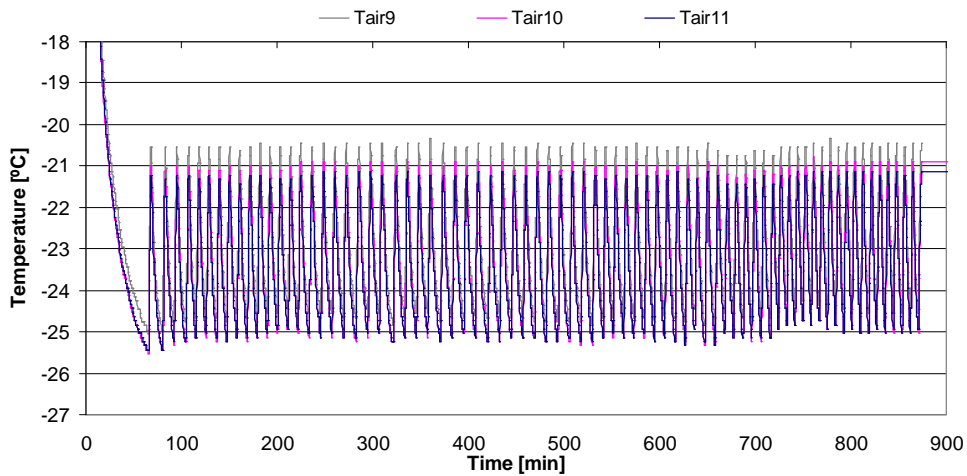


Fig. 40. Air temperature at the medium-top of the freezer during the experiment 3.

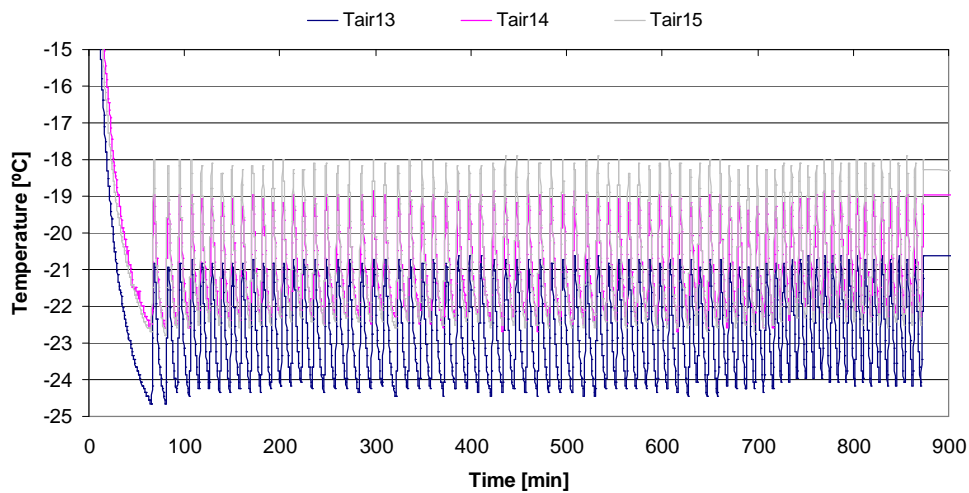


Fig. 41. Air temperature at the top of the freezer during the experiment 3.

To sum up, relating to the best location of the air temperature sensors, the most important thing is to know the profile in the height direction, as it was expected. After these experiments, it can be concluded that is more important to know the air temperature profile in the depth direction than in the width direction due to the results that were got.

The air temperature sensors will be located as in the first experiment but with one change. The temperature sensor ($T_{air.13}$) will be located as in the third experimentation due to the difference of the air temperature in this zone during the experimentation.

Looking the results of the experiments done, the temperature of the air where $T_{\text{air.13}}$ was located in the first and second experiment can be assumed as the value of $T_{\text{air.14}}$.

Therefore, with this configuration it can assume that the air temperature in the width direction doesn't change less in the top of the freezer, where it will be located an air temperature sensor. Concluding that with a 2D air temperature map using the data from the middle of the freezer it can be done a 3D map for the whole freezer using the data from the air temperature sensor $T_{\text{air.13}}$.

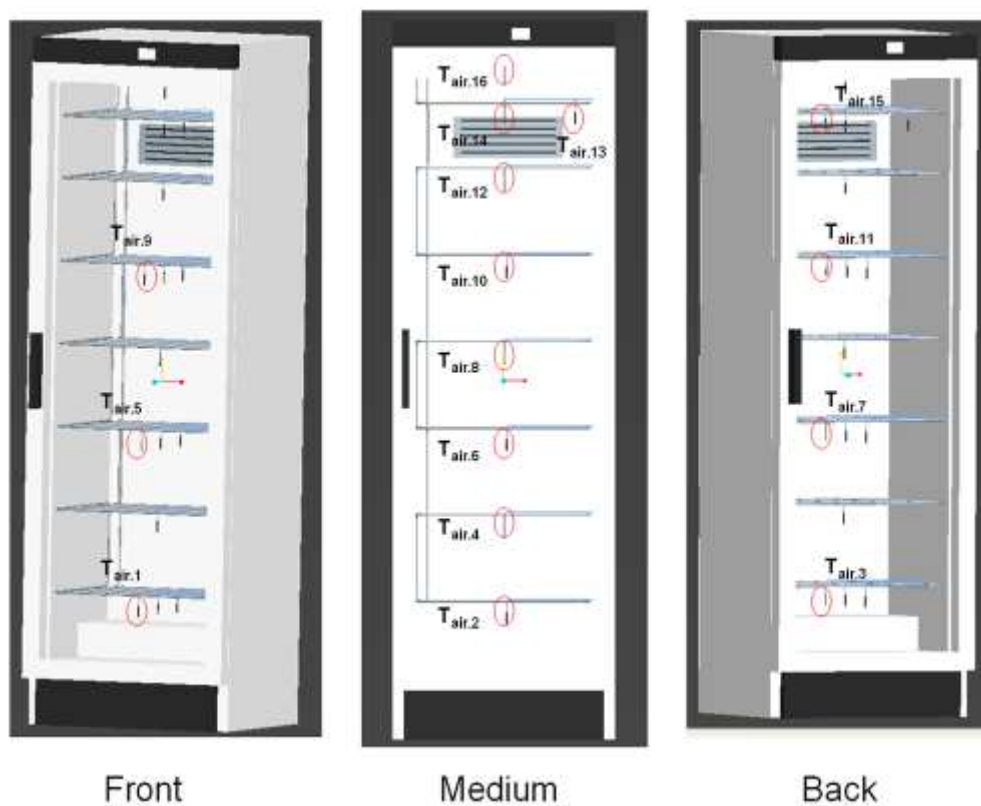


Fig. 42. Definitive location of the air temperature sensors.

Annex 2. Results of the experimentation using PCM in commercial freezers

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1 Introduction

The aim of the present document is to expose the results and the discussion of the experimentation related to the introduction of ClimseIC-18 as PCM in commercial freezers.

2 Results and discussion

The measurements included energy consumption, cabinet temperature, PCM temperature, and M-pack temperature under real boundary conditions (ambient temperature of 21 ± 0.5 °C and HR of 50 ± 10 %). All the experimentation was done with two different temperature storage of the freezer.

2.1 Results with storage temperature at -22 °C

2.1.1 Air temperature response to door opening

A series of door openings with the freezers loaded and unloaded with the M-packs and with and without PCM under the same boundary conditions were done. Five different tests were performed in order to study the behaviour of the freezer (from Fig. 43 to Fig. 52).

Notice that the data acquisition system used only gets one value every 10 seconds. In experiments of door opening for a period of 10 seconds or even of 30 seconds, it was the possibility to get unreal values of the temperature.

It is expected that when door opening occurs the air temperature inside the freezer increase quickly until the door is closed again. If the time that the door is open is enough, the air temperature reached is higher than the set point temperature and therefore the compressor will switch on.

The behaviour of the air temperature is not the same for all the experiments. When the freezers were loaded of M-pack no big differences between using PCM or not were found. On the other hand, when the freezers were unloaded of M-pack (not common in a real situation) some improvement due to the use of PCM was found. Table 7 shows the air temperature drop after the door opening and the comparison between

using PCM or not for each experiment done. As the door openings were done every certain time and without knowing the real state of the freezers (compressor working or stopped), different answers were obtained due to door openings.

When the air temperature reached was not too low (less than $-10\text{ }^{\circ}\text{C}$) the system was able to continue with the normal operation mode. However, when the period of door opening was longer and the air temperature reached inside the freezer was low (near $0\text{ }^{\circ}\text{C}$) the system needed more time in order to reach the normal operation mode.

Looking at the experiments with no M-pack, the addition of PCM inside the freezer caused different results related to air temperature, doing in some tests good benefit (test 1a, 1b, 1c, and 1e) decreasing the temperature drop, but in test 1d bad results were found, increasing the temperature drop in the freezer with PCM. These results could be caused by the sensible heat stored in the PCM while in the freezer without PCM this heat could not be stored.

On the other hand, when M-packs were inside it is clear that this addition did not affect the behaviour of the air temperature because the thermal mass added by the M-packs was much bigger than the thermal mass added by the PCM. Since the most realistic experiments are when M-pack is inside the freezers, with this configuration benefits appear when PCM is used in commercial freezers.

However, when M-packs were inside the freezers, the fluctuation of the air temperature between before and after the door opening was always lower or equal than in the air temperature in the freezer without PCM. In addition, this effect is beneficial for the frozen product.

In test 1a (Fig. 43 and Fig. 44), when the door was opening for a period of time of 10 seconds, the air temperature inside the freezer did not reach high temperature values and frequency of the temperature was the same even door opening occurs. Working with this set point (average of $-22.5\text{ }^{\circ}\text{C}$) door opening for a period of 10 seconds has not significant effect on the air temperature inside the freezers, with or without PCM or M-pack inside it.

	Test 1a	Test 1b	Test 1c	Test 1d	Test 1e
Freezer without M-pack					
Without PCM [°C]	5	9	18.5	20	24
With PCM [°C]	4.5	8	17	22	23
Temperature difference [°C]	0.5	1	1.5	-2	1
Freezer with M-pack					
Without PCM [°C]	5	8	16	22	22
With PCM [°C]	4	8	16	22	22
Temperature difference [°C]	1	0	0	0	0

Table 7. Temperature difference in the air temperature due to the door opening.

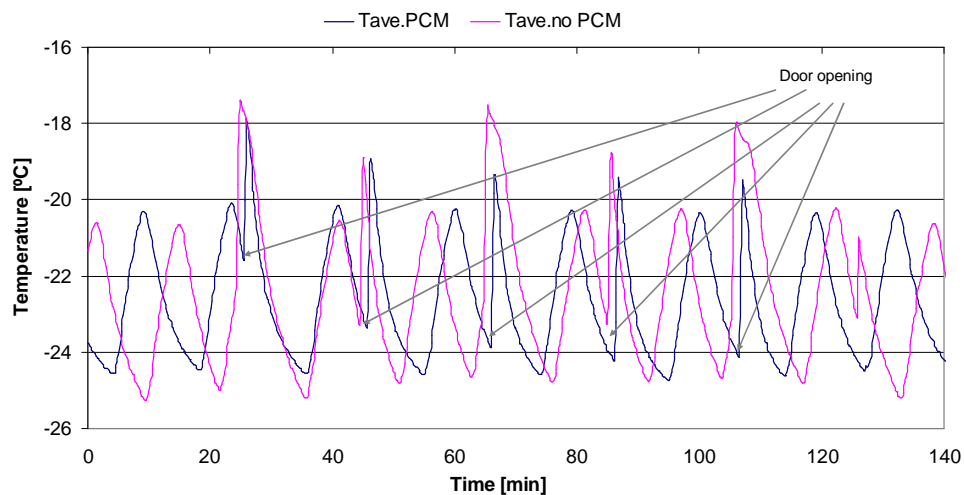


Fig. 43. Average air temperature during test 1a without M-pack.

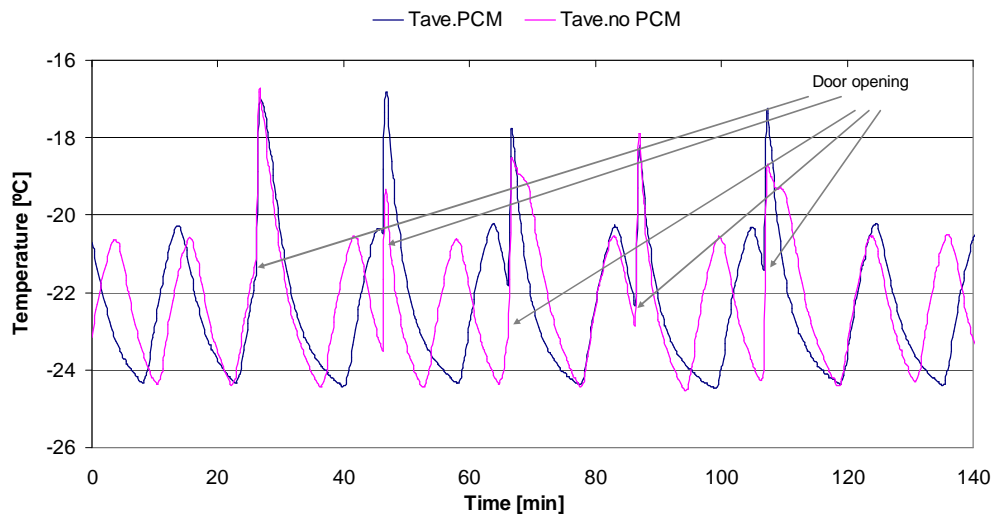


Fig. 44. Average air temperature during test 1a with M-pack.

Test 1b (Fig. 45 and Fig. 46) shows big differences between the freezer with and without PCM. However, these differences were mainly due to the initial conditions. In some tests, when the door was opened the air temperature in each freezer was quite different so the temperature reach in each freezer was different. The values reached in the experimentation were not higher than -12°C and quickly both freezers reached again normal values of operation, being the time in the freezer with PCM bigger.

As Table 7 shows, the difference of the temperature in the freezer without PCM (temperature before and after the door opening) was higher for the case without M-pack but not in the case with M-pack, where there was no difference.

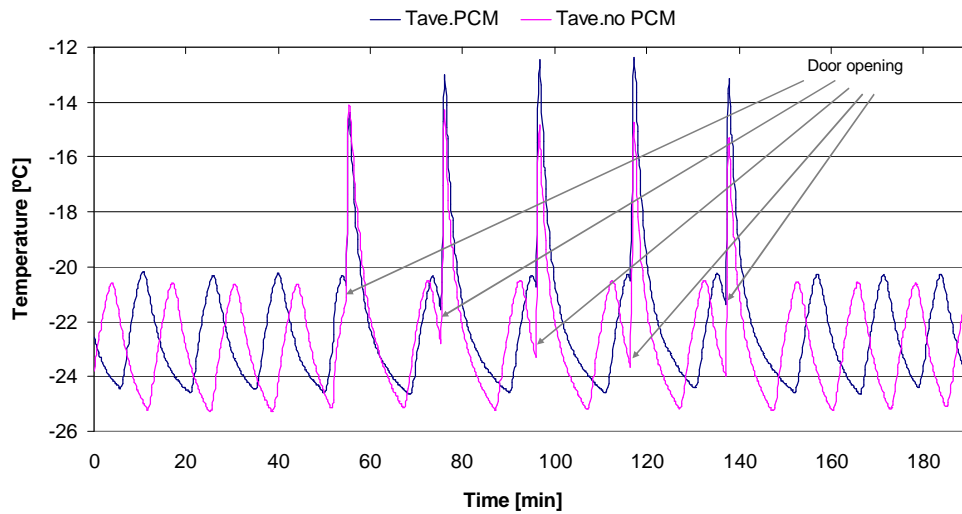


Fig. 45. Average air temperature during test 1b without M-pack.

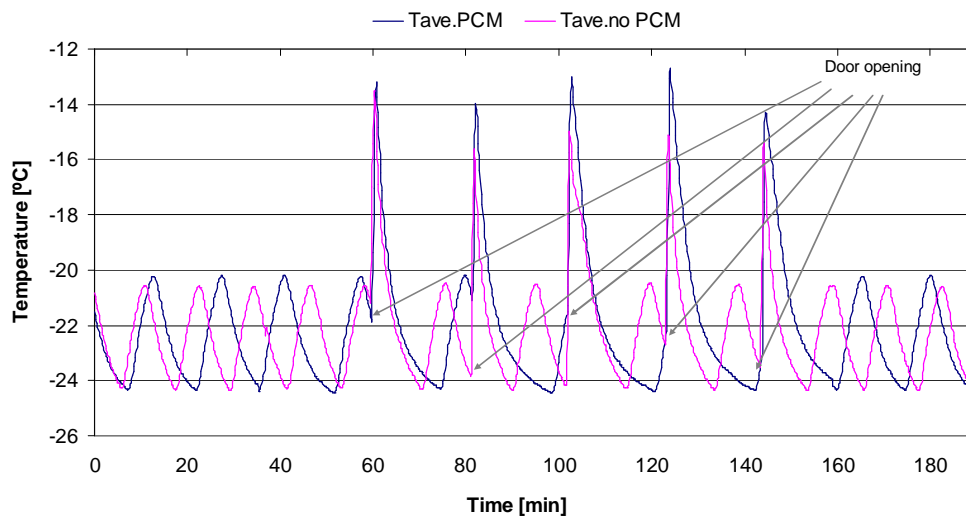


Fig. 46. Average air temperature during test 1b with M-pack.

Test 1c (Fig. 47 and Fig. 48) was when the introduction of PCM in the freezer had a major benefit. Here, a two door openings of 3 minutes was done. In the case with no M-pack inside the freezer, big difference between both cases (with and without PCM) due to the thermal mass of the PCM was detected. On the other hand, in the freezer without PCM the behaviour of the air temperature between the door openings was the same as a normal operational mode (fluctuation between -22 and -24 °C) while in the freezer with PCM there was no air temperature fluctuation due to the thermal mass of the PCM.

In the experimentation with M-pack is when high difference between the gradient of temperature were detected. In the case of the freezer without PCM, no fluctuation of the air was detected between the door openings due to the thermal mass of the M-pack. The same fact was detected in the freezer with PCM.

Notice that the temperature profile when the door was open and when the door was closed was the same in both cases until the temperature reached close values to the lower set point (-24°C), when the temperature profile changed and in the case of the freezer which included PCM this ramp becomes flatter.

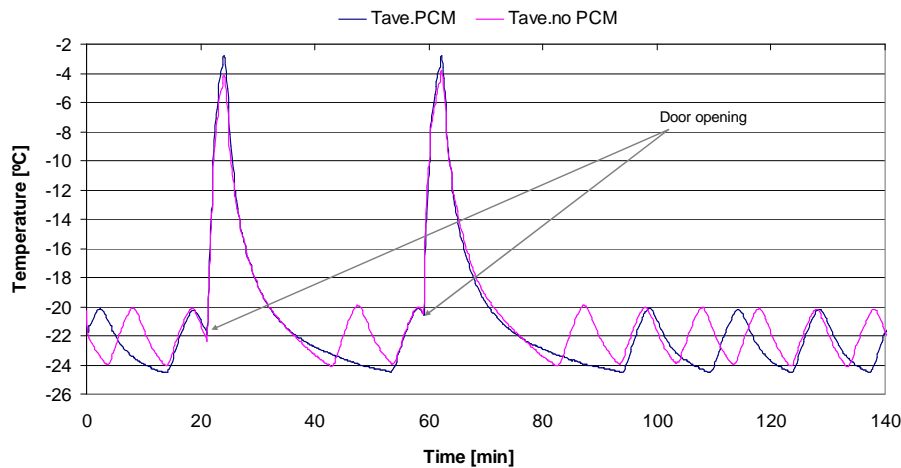


Fig. 47. Average air temperature during test 1c without M-pack.

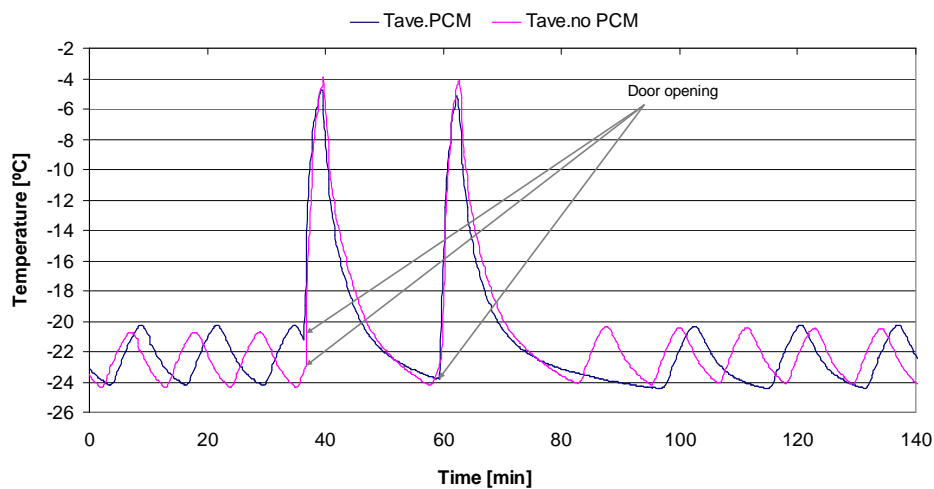


Fig. 48. Average air temperature during test 1c with M-pack.

In test 1d (Fig. 49 and Fig. 50), differences with the experimentation with and without M-pack were found out. The air temperature in the freezer with PCM and without M-pack reached higher values than the freezer without PCM. However, in the test with M-pack no difference was detected between both freezers.

Furthermore, the most important fact is not the difference of the temperature peak but the capacity of the freezers to reach again the normal operating values. There was a big difference between both cases in this aspect (with and without PCM). In the case with no PCM the air temperature reached quicker the lower set point while in the case with PCM inside the freezer this time was higher, almost 20 minutes in both cases (loaded and unloaded of M-pack).

The same effect happened in test 1e (Fig. 51 and Fig. 52), when one door opening for a period of 10 minutes occurs. The air temperature gradient was almost the same in all the cases ($24^{\circ}\text{C} - 23^{\circ}\text{C}$ without and 22°C with M-pack). As it was expected, the temperature profile after the door closing was different if PCM is used, reaching in the case without PCM the lower set point faster while in the case of PCM this time is longer, and therefore no fluctuation of air temperature was detected during almost 30 minutes in both cases.

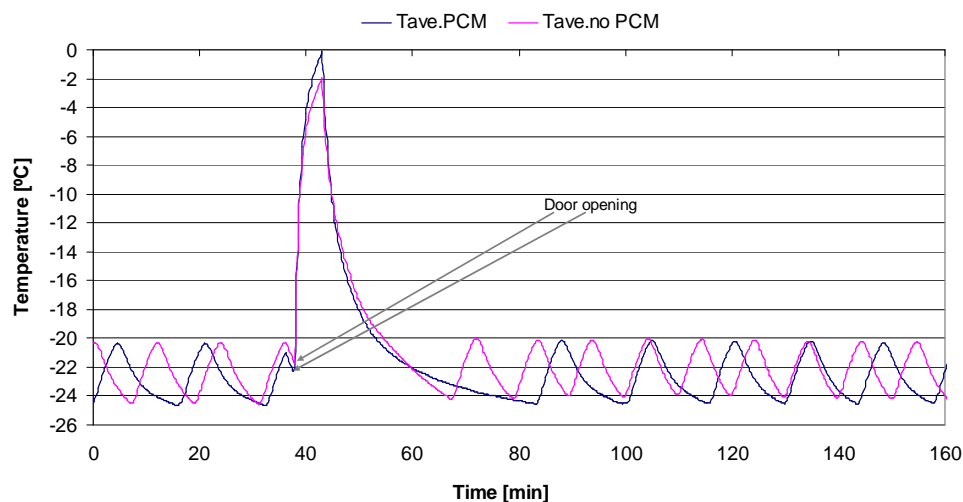


Fig. 49. Average air temperature during test 1d without M-pack.

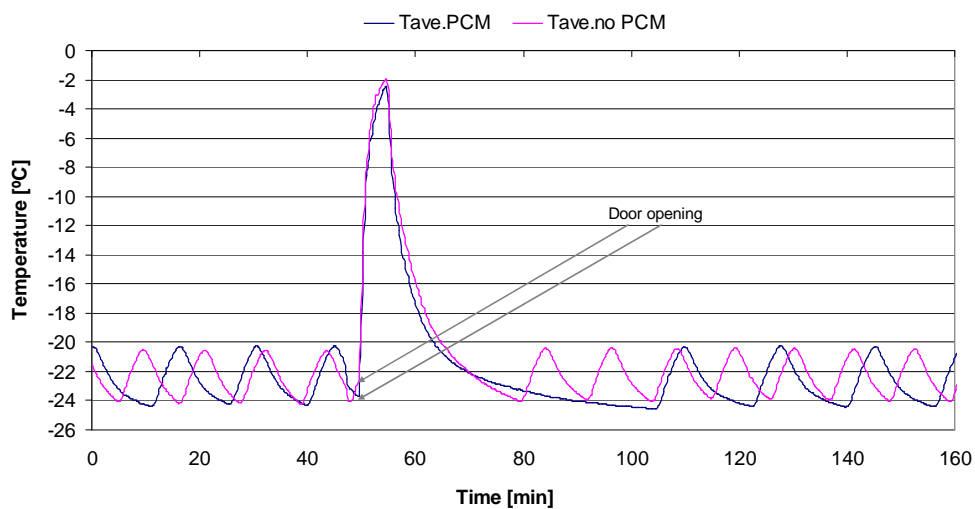


Fig. 50. Average air temperature during test 1d with M-pack.

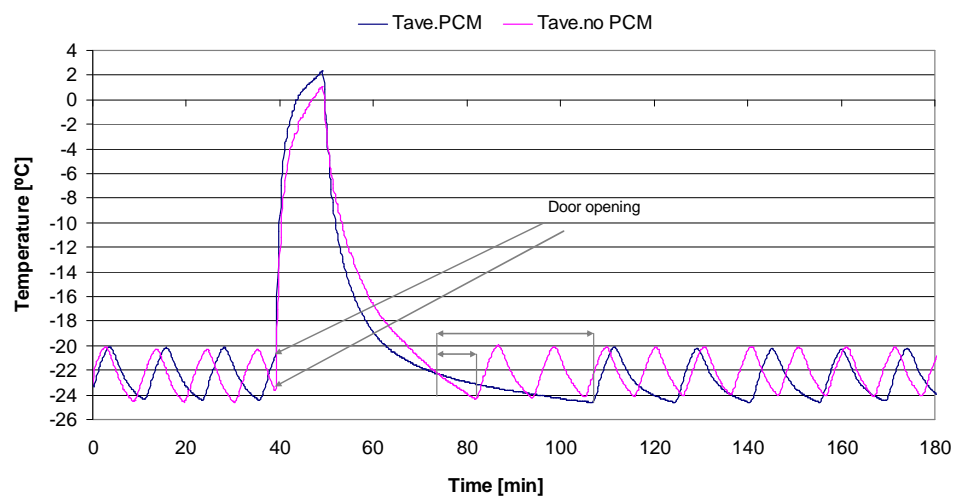


Fig. 51. Average air temperature during test 1e without M-pack.

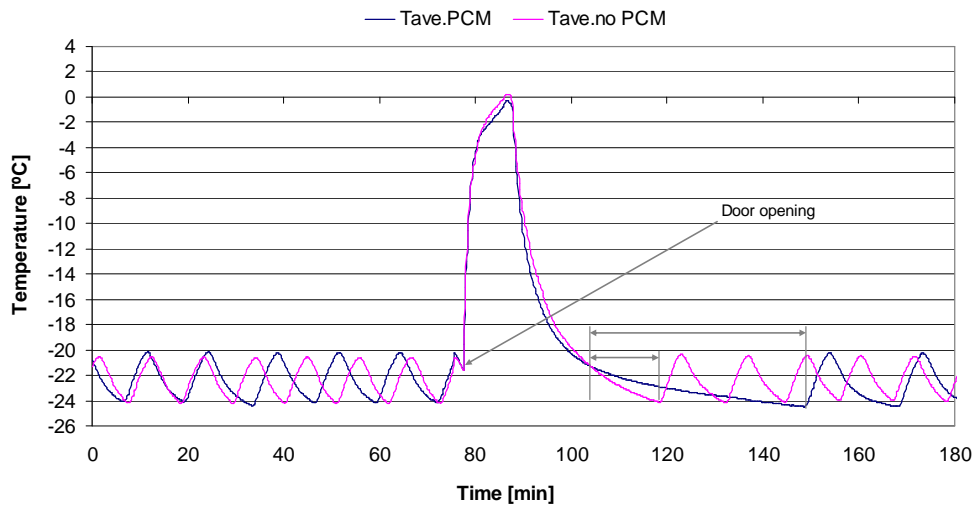


Fig. 52. Average air temperature during test 1e with M-pack.

2.1.2 Air temperature response to electrical power failure

A series of electrical power failure were done with the freezers loaded and unloaded with the M-packs with and without PCM under the same boundary conditions. In order to study the behaviour of both freezers five different tests were performed.

Here there were no problems with the data acquisition system since the duration of these experiments were much longer than the experimentation carried on in test 1.

Table 8 shows the difference of the air temperature inside the freezers before and after the electrical power failure and the temperature gradient in each experiment done. Huge difference between the freezer loaded and unloaded of M-packs was detected. Furthermore, the addition of these M-packs increased the thermal mass of the system and the values of the air temperature were higher if no M-packs were inside the freezer. In all the cases studied, the introduction of PCM in the freezers had good benefits in the drop air temperature doing these values lowers at each experiment. Note that when no M-packs were inside the freezer (less thermal mass) high values of temperature are measured in both freezers (Table 8).

	Test 2.a	Test 2.b	Test 2.c	Test 2.d	Test 2.e
Freezer without M-pack					
Without PCM	5	9	15	19	20
With PCM	4	8	8	9	8
Delta T [°C]	1	1	7	10	12
Freezer with M-pack					
Without PCM	5	6.5	9	13	11
With PCM	4	4	5.5	8	7
Delta T [°C]	1	2.5	3.5	5	4

Table 8. Temperature difference in the air temperature due to electrical power failure.

In tests 2a, 2b, and 2c the same temperature profile when the freezers were switched on was detected. However when the time that the electrical power failure was higher (test 2d and 2e, two and three hours respectively) the temperature profile was different.

As happened in other experiments, the freezer without PCM reached the lower set point (-24 °C) much quicker than the freezer with PCM. Related to the air temperature, this fact has benefit due to no fluctuations on the air temperature during this period were detected. In addition, in test 2d there were 70 minutes when no M-packs were inside the freezer and 40 minutes when M-packs were in.

This effect happens due to the fact that when no M-pack were inside the freezer, all the mass was at low temperature while in the M-pack case, more mass (addition of M-packs) was at lower temperature and when the power is switched on again, the temperature difference was obviously lower.

For that reason in the case with M-pack the time to reach the lower set point was much lower (57% less). The same effect happens in test 2e where the time to reach the lower set point in the freezer with no M-pack and with the freezer with M-pack were 80 and

50 minutes respectively (62 % less).

A temperature difference was detected in test 2a when PCM was included inside the freezer. However both freezers started their normal operation mode at the same time after switched it on.

The same happened in test 2b and test 2c, where the main difference was the air temperature value inside the freezer. With these experiments it was clear the benefit of using PCM inside the freezer in order to avoid low air temperatures when power loss or electrical power failure occurs. In these experiments the effect of the PCM is clearly shown in the temperature profile when there was an asymptotic behaviour of the temperature near -14°C in all the cases.

Fig. 53 and Fig. 54 show the average air temperature during a electrical power failure of 15 minutes (test 2a) in the freezer (PCM and no PCM) unloaded and loaded with M-packs, respectively. The freezer without PCM reached higher air temperatures in both experiments; being 1°C higher than the unloaded freezer with PCM and 1°C when the freezer was loaded with M-packs.

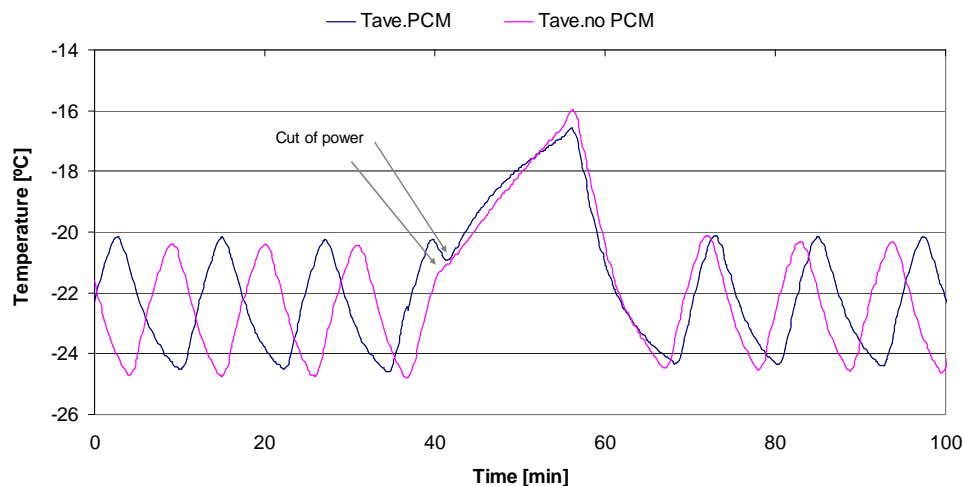


Fig. 53. Average air temperature during test 2a without M-pack.

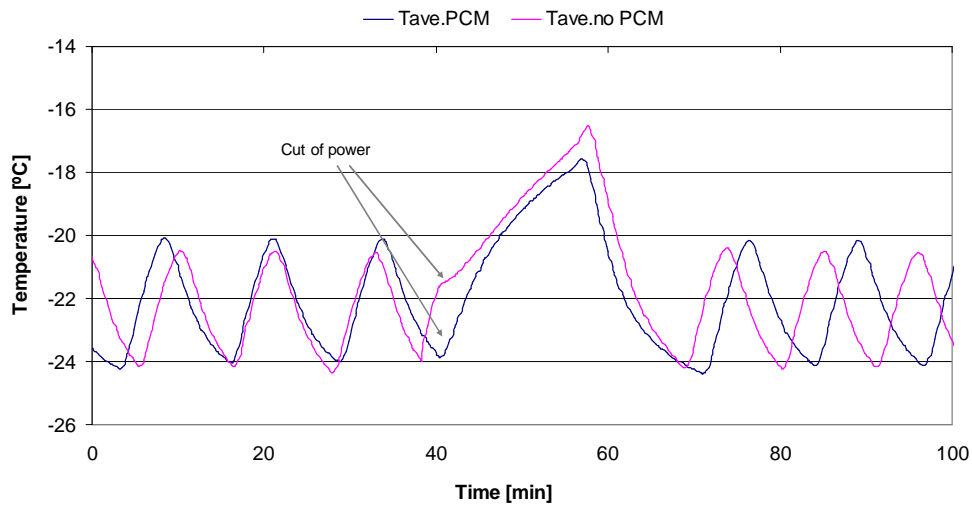


Fig. 54. Average air temperature during test 2a with M-pack.

Fig. 55 and Fig. 56 show the average air temperature during electrical power failure of 30 minutes (test 2b) in freezer (PCM and no PCM) unloaded and loaded with the M-packs, respectively. It can be seen that the air temperature of the freezer without PCM reached higher values in a shorter time. The average peak temperature of the unloaded freezer was 1 °C higher than the unloaded freezer with PCM, and 2.5 °C when the freezer was loaded with M-packs.

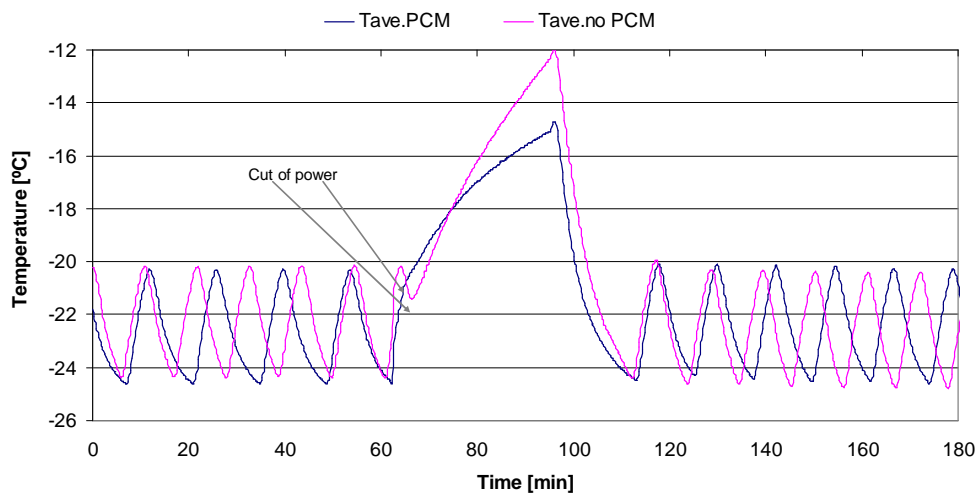


Fig. 55. Average air temperature during test 2b without M-pack.

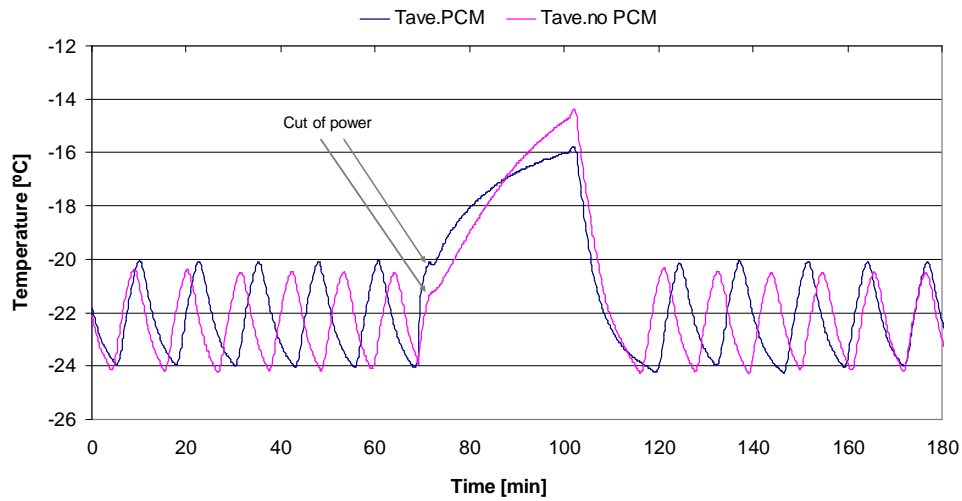


Fig. 56. Average air temperature during test 2b with M-pack.

Fig. 57 and Fig. 58 show the average air temperature during a electrical power failure of 1 hour (test 2c) in the freezer (PCM and no PCM) unloaded and loaded with M-packs, respectively. The freezer without PCM reached higher air temperatures in both experiments; being 7 °C higher than the unloaded freezer with PCM and 3.5 °C when the freezer was loaded with M-packs.

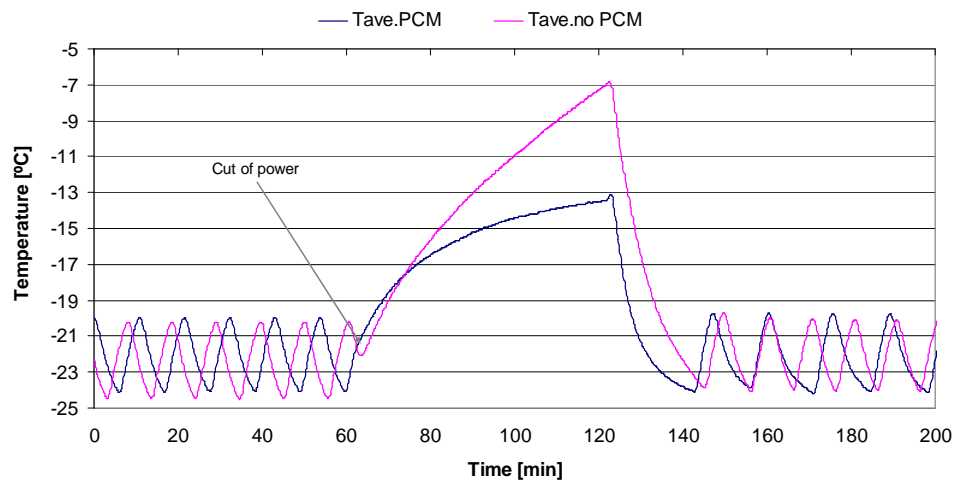


Fig. 57. Average air temperature during test 2c without M-pack.

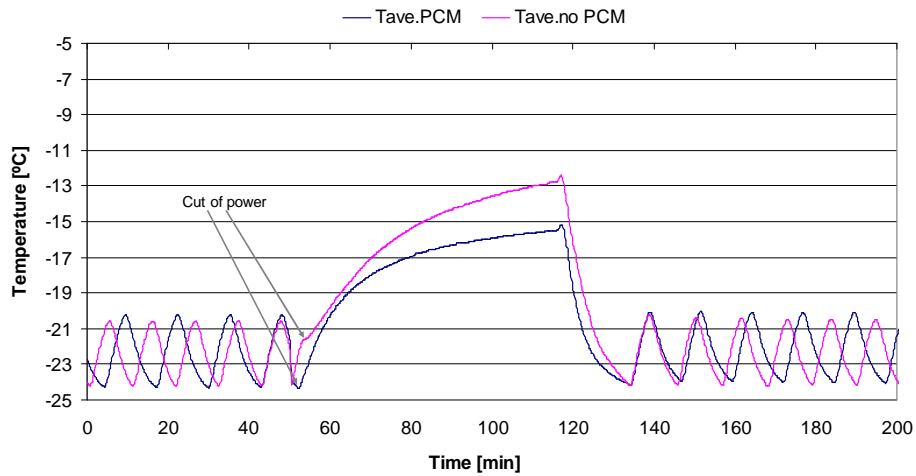


Fig. 58. Average air temperature during test 2c with M-pack.

Fig. 59 and Fig. 60 show the average air temperature during a electrical power failure of 2 hours (test 2d) in the freezer (PCM and no PCM) unloaded and loaded with M-packs, respectively. The freezers without PCM reached higher air temperatures in both experiments; being 10 °C higher than the unloaded freezer with PCM and 5 °C when the freezer was loaded with M-packs.

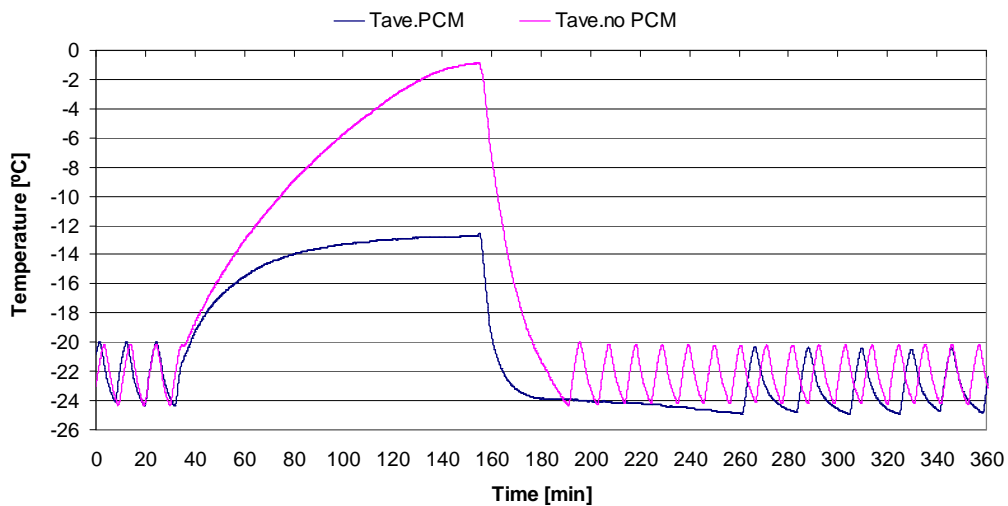


Fig. 59. Average air temperature during test 2d without M-pack.

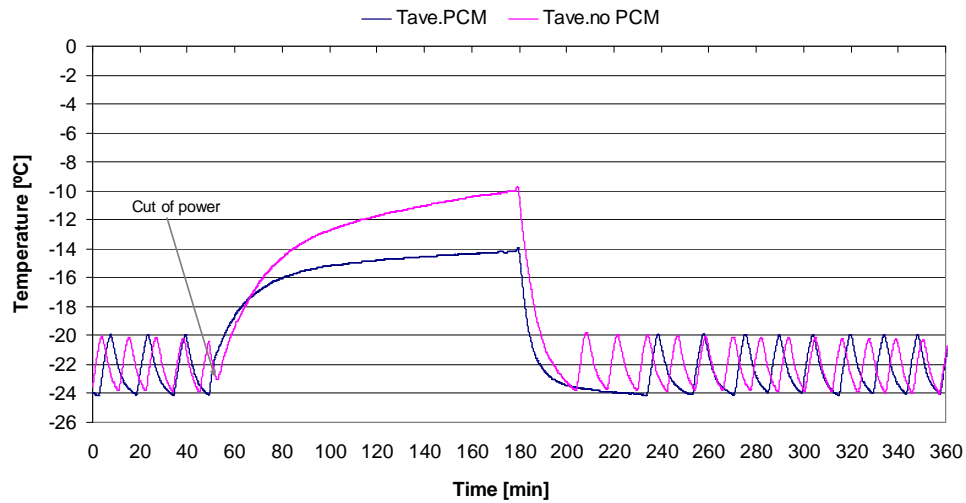


Fig. 60. Average air temperature during test 2d with M-pack.

Fig. 61 and Fig. 62 show the average air temperature during a electrical power failure of 3 hours (test 2e) in the freezer (PCM and no PCM) unloaded and loaded with M-packs, respectively. The freezer without PCM reached higher air temperatures in both experiments; being 12 °C higher than the unloaded freezer with PCM and 4 °C when the freezer was loaded with M-packs. In addition, the freezer with PCM reached much faster working air temperature values after the switched on than the freezer without PCM. The results clearly show the benefit of using PCM even loaded or unloaded with M-pack.

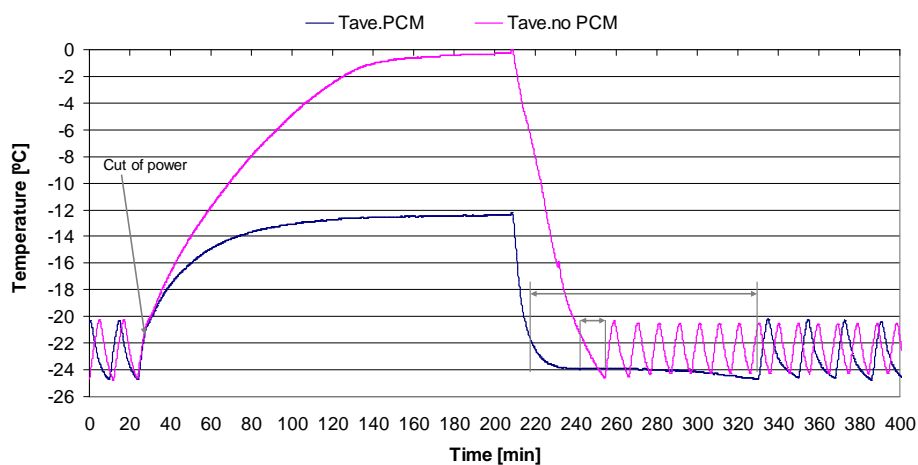


Fig. 61. Average air temperature during test 2e without M-pack.

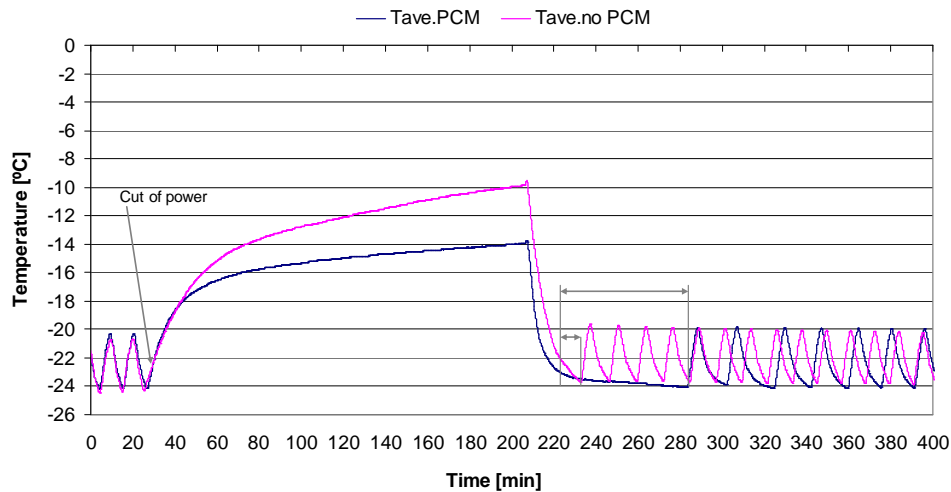


Fig. 62. Average air temperature during test 2e with M-pack.

2.1.3 M-pack response

It is well known that the size of ice crystals in ice cream grow larger when the ice cream is stored under fluctuating conditions. For that reason it is very important evaluate the M-pack response under different experiments. Following ISO standard ISO 15502:2005, only the hottest M-pack temperature has to be taken into account in each freezer. Therefore, only the hottest M-pack is showed in the results commented below.

As it was expected, the hottest M-pack was always the M-pack situated at a higher position inside the freezer, which were the M-pack 4 and M-pack 8, respectively. Fig. 63 shows the hottest M-pack during the experimentation in the freezer with PCM.

Fig. 64 and Fig. 65 show the hottest M-pack temperature in test 1a and 1b when door opening occurs, respectively. The M-pack temperature was always higher when no PCM was inside the freezer but notice that the temperature after the test was not exactly the same for both cases (PCM and no PCM). As the time that the door was opened in both experiments was not too long, the frozen product did not note the air temperature drop and no big changes appeared in the M-pack temperature.



Fig. 63. Location of the M-pack where temperature was measured in the freezer with PCM.

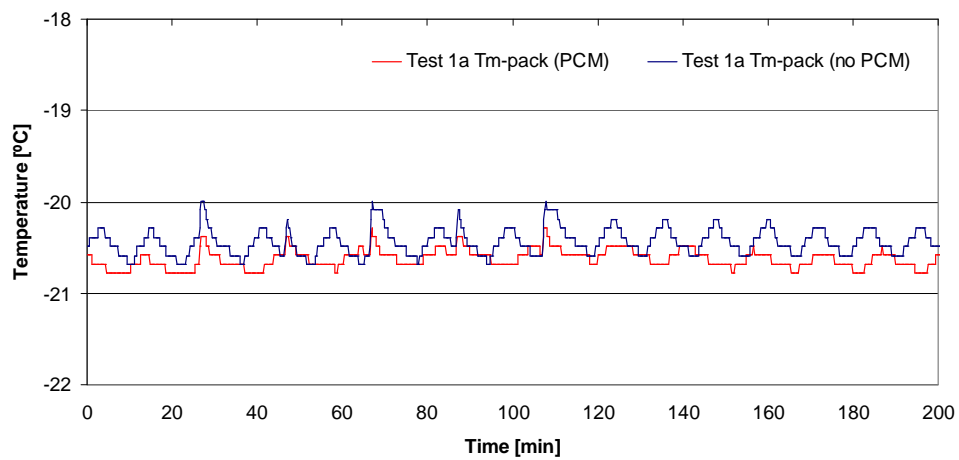


Fig. 64. Hottest M-pack temperatures during test 1a.

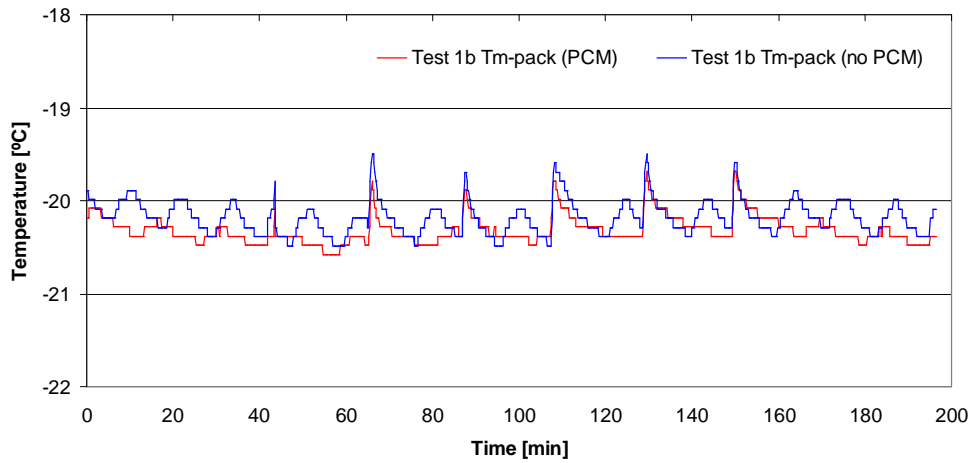


Fig. 65. Hottest M-pack temperatures during test 1b.

Fig. 66 shows the hottest M-pack temperature in test 1c when door opening occurs for a period of 1 minute. The M-pack temperature was higher when no PCM was inside the freezer and after the door opening the temperature fluctuation of the M-pack was lower in the PCM. These results show the benefit of introduction PCM in the freezers, doing that the temperature of the M-pack in the freezer with PCM was 0.5 °C less in than in the freezer with no PCM. Furthermore, the oscillation of the temperature in the case of using PCM is less as well.

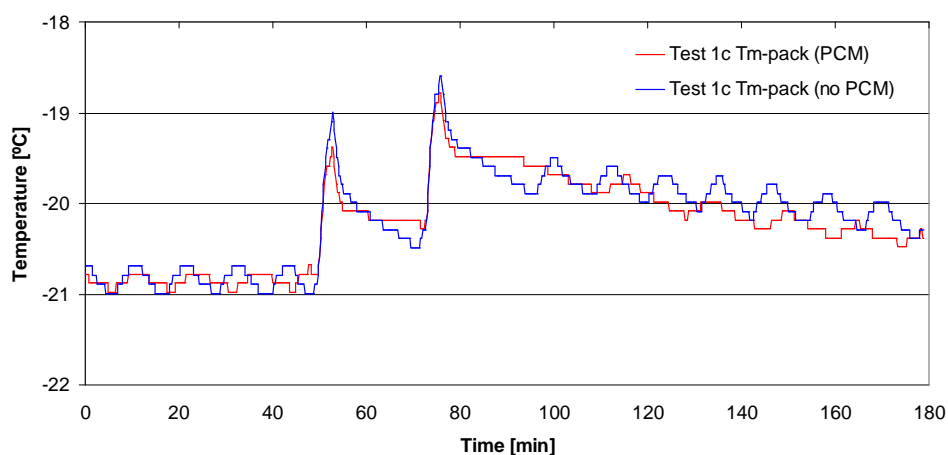


Fig. 66. Hottest M-pack temperatures during test 1c.

Fig. 67 shows the hottest M-pack temperature in test 1d and 1e when door opening occurs for a period of 5 and 10 minutes, respectively. In these experiments the evidence between using PCM or not using were much clear than in the air temperature graphs and even in the other experiments, when door opening were for a shorter period of time.

Notice that the temperature of the M-pack just before the electrical power failure was not the same; therefore the values that the M-pack reach were not definitely at all. In these tests occurs again that the M-pack temperature was higher when no PCM was inside the freezer and after the door opening the temperature fluctuation of the M-pack was lower in the PCM. Due to the air temperature inside the freezer with PCM had no fluctuations for a long period after the door closing; the M-pack had almost no fluctuations in their temperature.

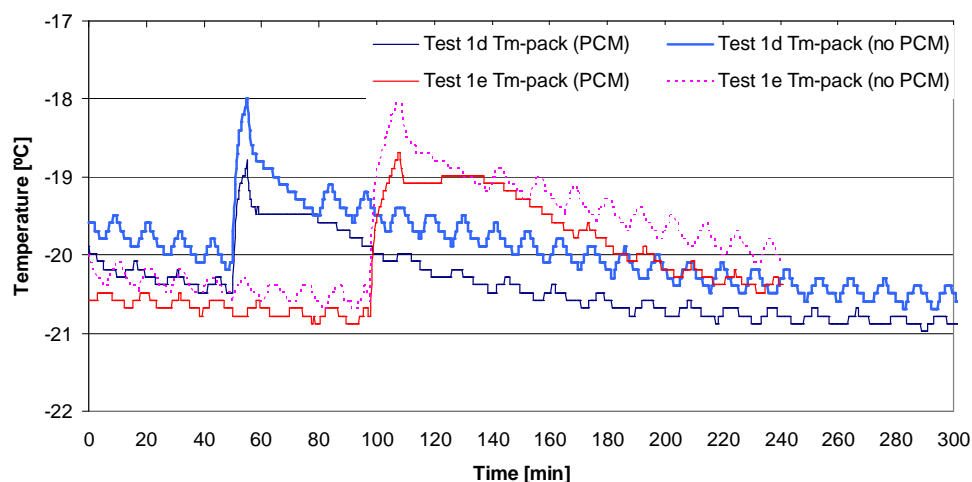


Fig. 67. Hottest M-pack temperatures during test 1d and 1e.

Fig. 68 shows the hottest M-pack temperature in test 2a and 2b when electrical power failure occurs. Due to the temperature of the M-packs before the test (switched off the freezer) were not exactly the same, it is difficult to get a good conclusion. However, the temperature fluctuation in the M-pack, when PCM was used, was not as the temperature fluctuation when PCM was not used in the system.

The M-pack temperature was always higher when no PCM was inside the freezer even the temperature before the test was not the same. However, notice that the temperature

gradient (before and after the test) was higher when no PCM was used.

For example, in test 2b, with a electrical power failure of 30 minutes, the temperature of the M-pack in the freezer without PCM decrease 1 °C while in the other freezer (with PCM) only 0.6 °C.

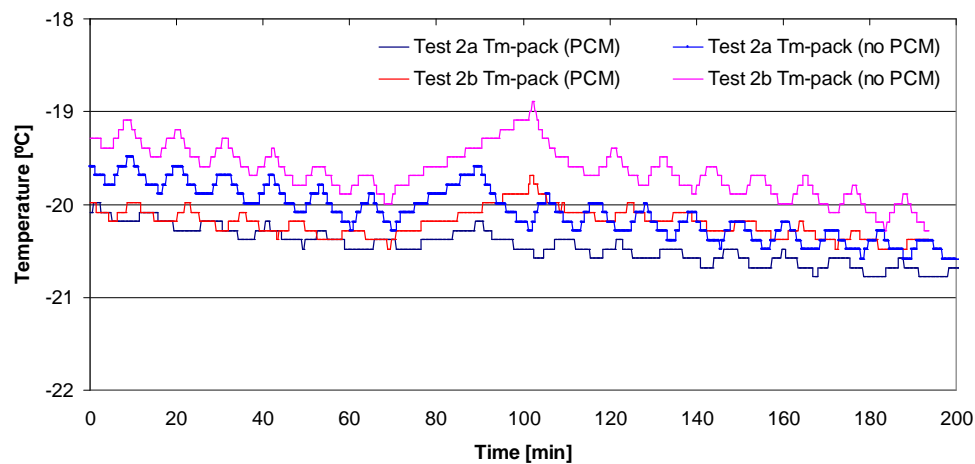


Fig. 68. Hottest M-pack temperatures during test 2a and 2b.

Fig. 69 shows the hottest M-pack temperature in test 2c when a electrical power failure of 1 hour occurs. The M-pack temperature was much higher when no PCM was inside the freezer even the temperature before the test was not exactly the same. Here the temperature of the M-pack in the freezer without PCM decreased 2.5 °C while in the other freezer (with PCM) only 1.3 °C. Notice that the temperature fluctuation in the M-pack was not the same in each case, improving the quality of the conservation in the freezer with PCM.

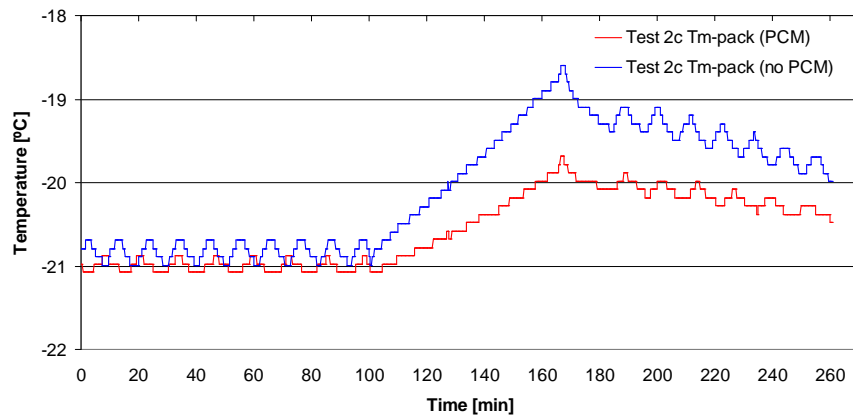


Fig. 69. Hottest M-pack temperatures during test 2c.

Fig. 70 shows the hottest M-pack temperature in test 2d and 2e, when a electrical power failure of 2 and 3 hours respectively, occurs. The M-pack temperature was much higher when no PCM was inside the freezer even the temperature before the test was not the exactly the same. Test 2d is not as clear as test 2e but the benefit of using PCM was detected as well.

In test 2d the initial temperature for both cases (PCM and no PCM) was not the same and for that reason the comparison between them was not that clear. However the temperature of the M-pack inside the freezer without PCM was 1.5 °C higher than the temperature of the M-pack in the freezer with PCM.

Results of test 2e (3 hours of electrical power failure) clearly show the efficiency of using PCM in order to improve the quality of the products stored and the efficiency of the freezers. The temperature before the test 2e started was the same for both M-pack and since the first instant the temperature in the M-pack inside the freezer without PCM was increasing more than the temperature in the other M-pack, reaching 2 °C more at the final of the electrical power failure. Once the freezers were switched on again, no temperature fluctuations were detected in the M-packs of the freezer with PCM; furthermore, 200 minutes after the temperature difference was still 1 °C.

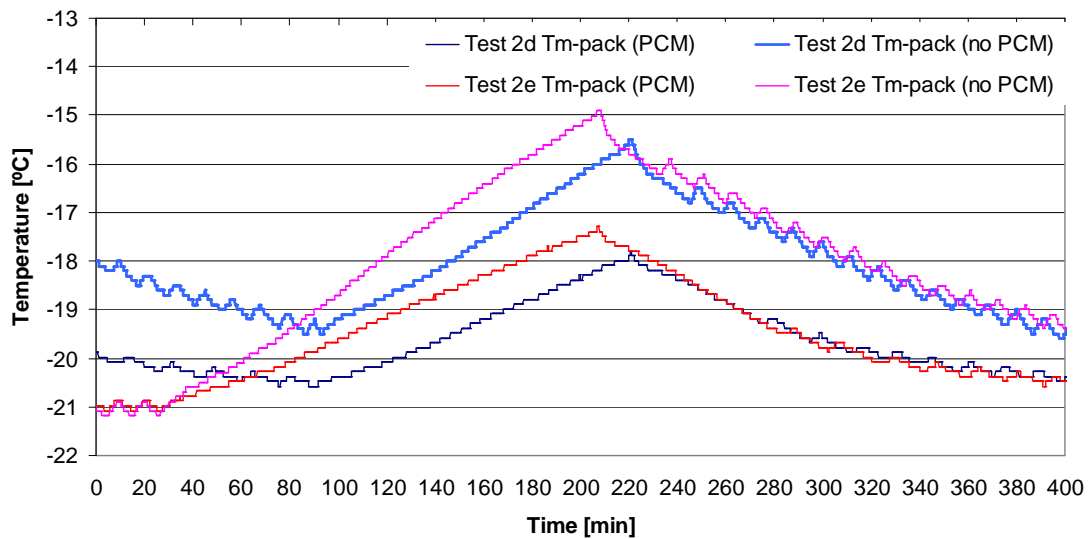


Fig. 70. Hottest M-pack temperatures during test 2d and 2e.

2.1.4 PCM response

It is important to evaluate the behaviour of the PCM during these experiments and insure that the PCM undergoes phase transition; otherwise it will act as sensible heat storage, which is small compared to latent heat storage.

Notice that the temperature of the PCM in the plate number 5 ($T_{PCM,5}$) is not represented in the graphs and in more of them are showing values that are not expected. Initially some problems with the thermocouple appeared and if there is no information in the graphs are due to there was no data acquisition during that test.

In addition when $T_{PCM,5}$ is added in the graphs (when the problem was solved) presents higher values than the $T_{PCM,6}$, which is at higher height in the freezer for that reason has to be at high temperature due to the air stratification. The problem was the location of the temperature sensor, which was not at all inside the PCM, probably there was a hole in the PCM and the thermocouple was not in complete contact with the PCM but with some air. For that reason the temperature is higher than $T_{PCM,6}$ and presents temperatures profile similar to the air.

In tests 1a, 1b, and 1c the temperature of the PCM after the door opening did not reach the temperature of the phase change which is $-18\text{ }^{\circ}\text{C}$. For that reason the effect of the

PCM is not as latent heat but as sensible heat. In test 1d and 1e the temperature of the PCM reached lower values but the temperature graphs do not show any phase change transition. The results of tests 1a, 1b, and 1c are shown from Fig. 71 to Fig. 76.

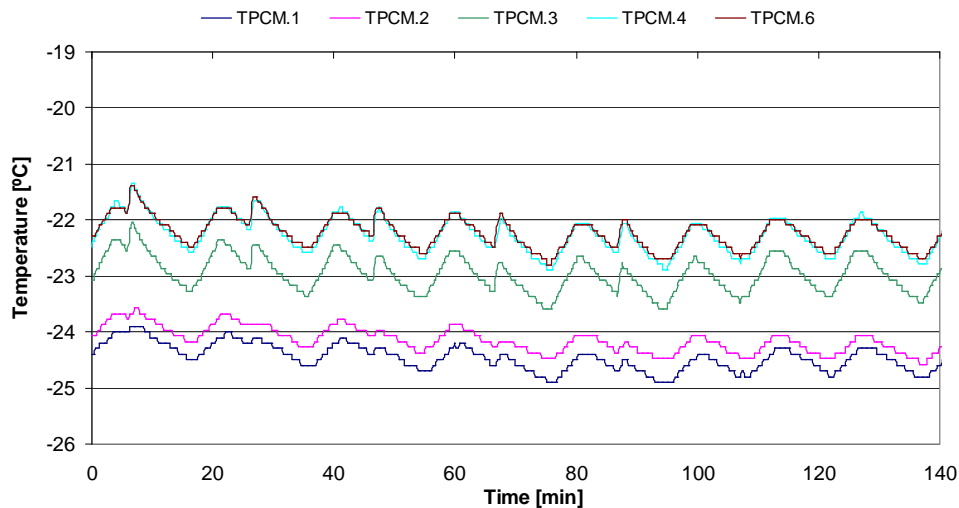


Fig. 71. PCM temperatures during test 1a without M-pack.

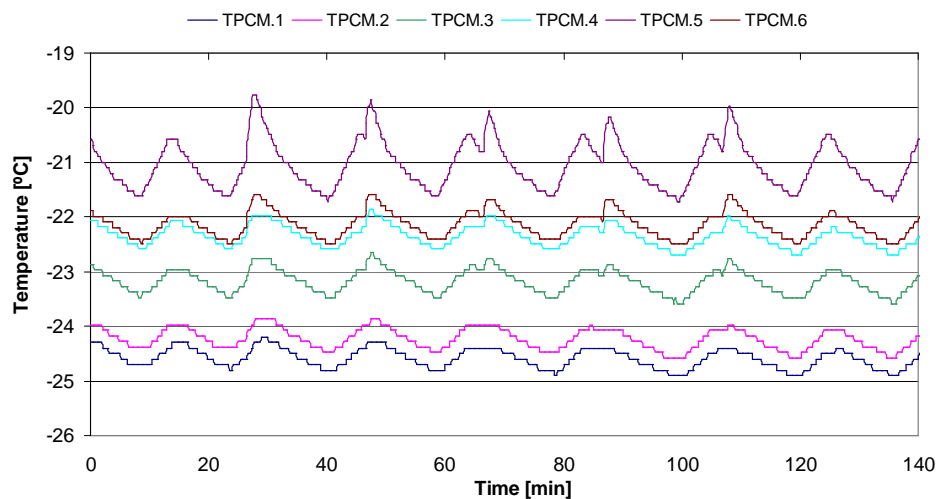


Fig. 72. PCM temperatures during test 1a with M-pack.

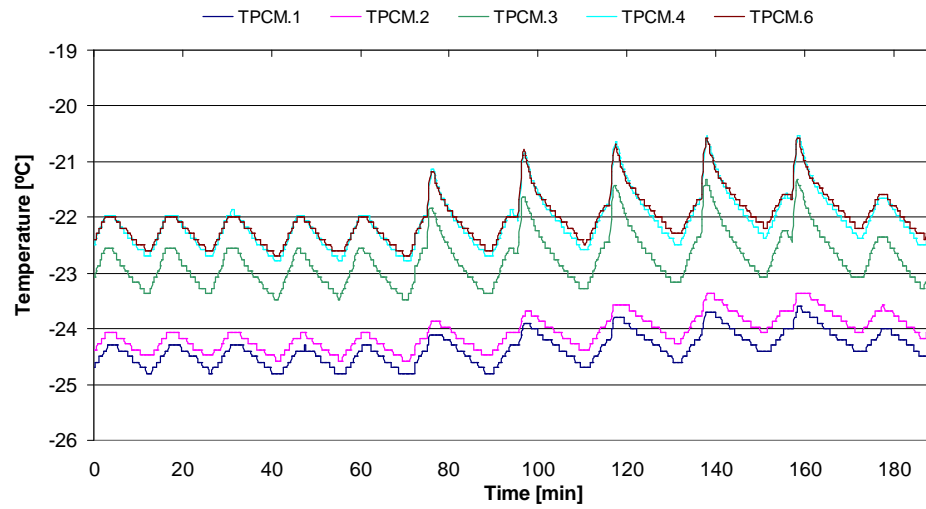


Fig. 73. PCM temperatures during test 1b without M-pack.

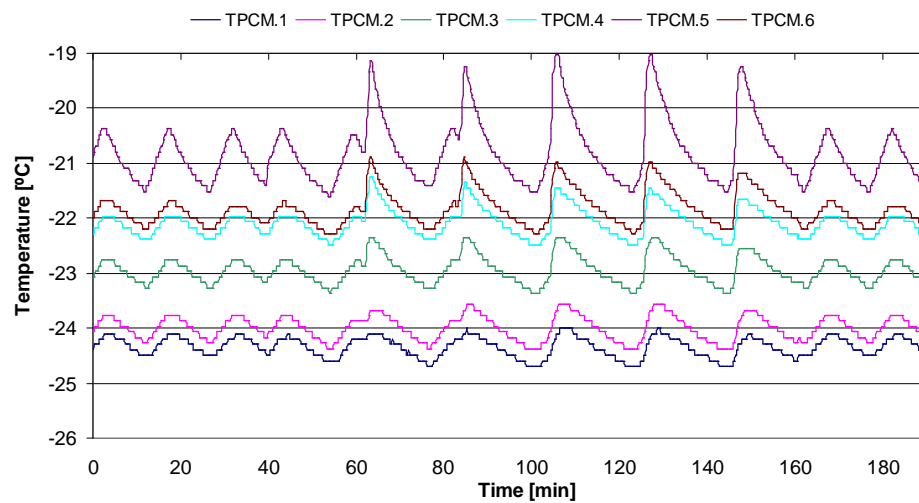


Fig. 74. PCM temperatures during test 1b with M-pack.

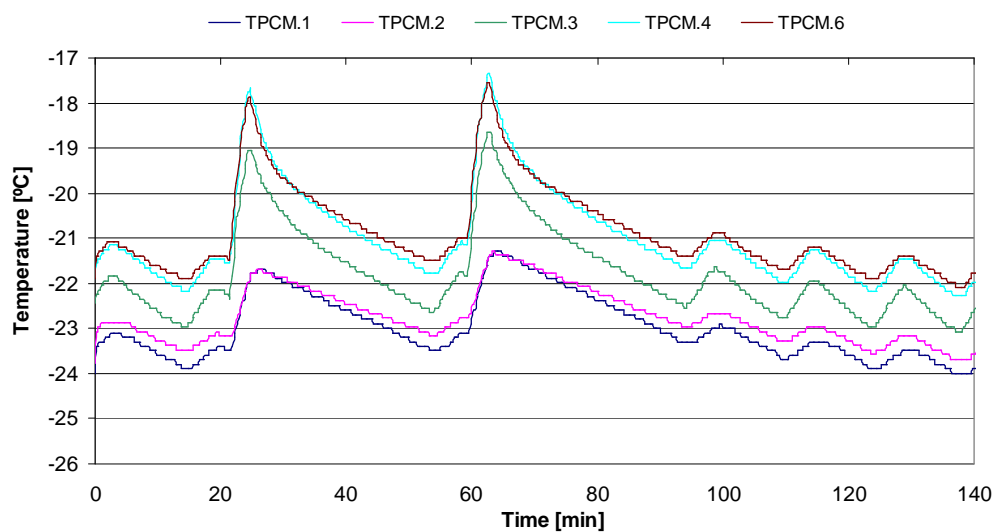


Fig. 75. PCM temperatures during test 1c without M-pack.

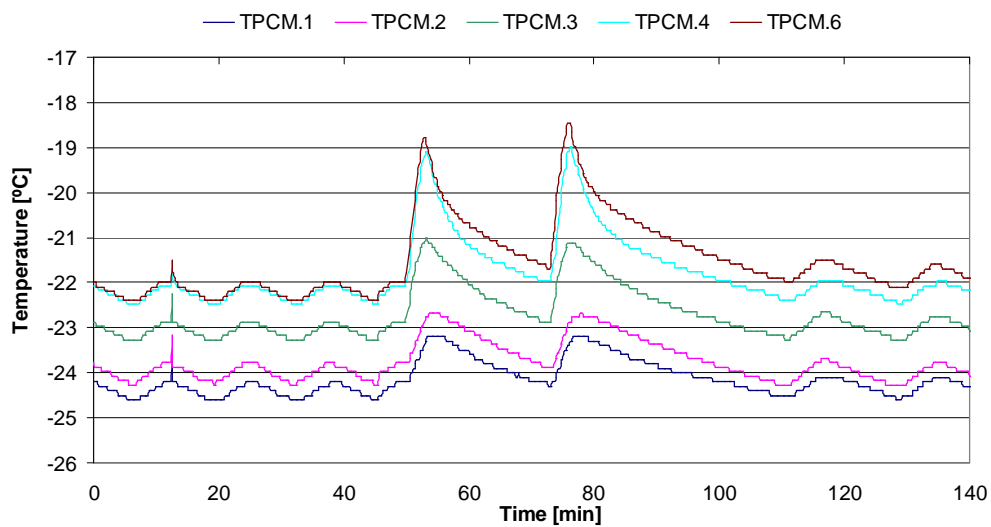


Fig. 76. PCM temperatures during test 1c with M-pack.

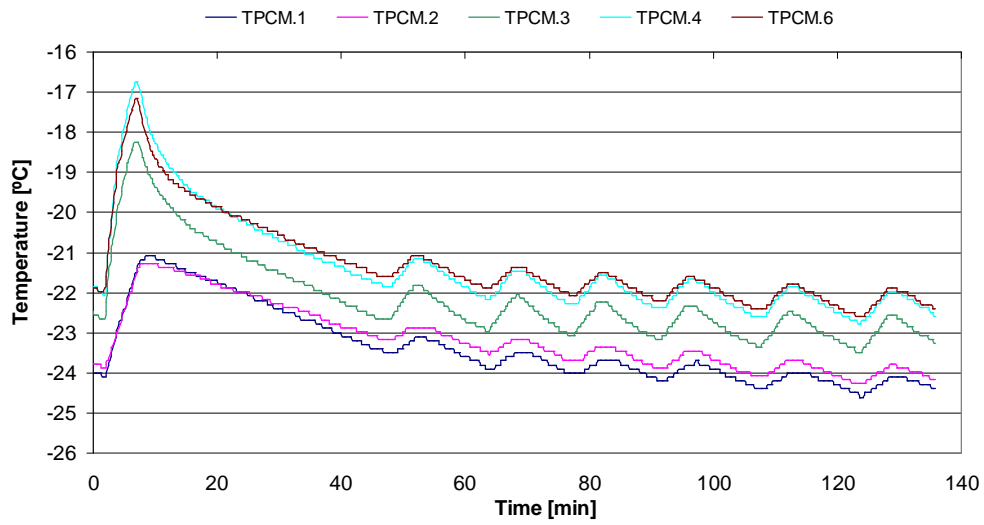


Fig. 77. PCM temperatures during test 1d without M-pack.

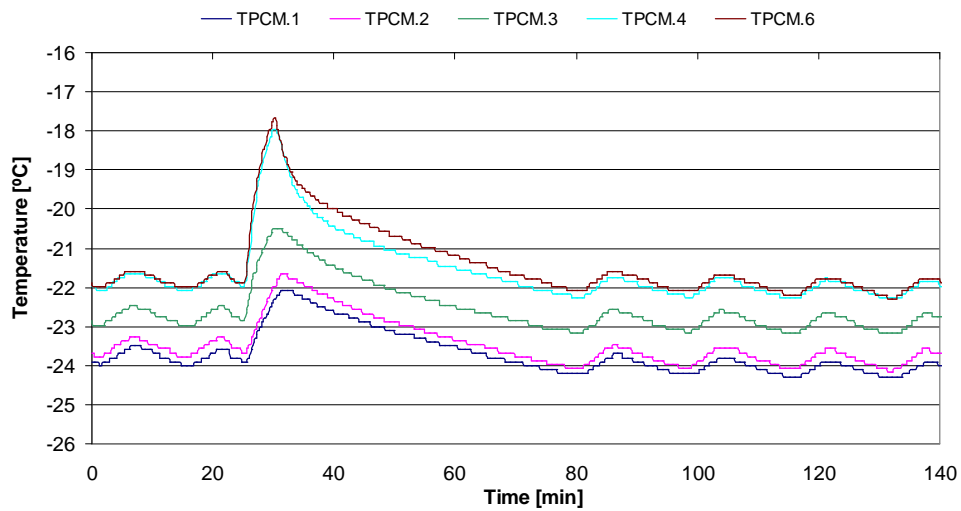


Fig. 78. PCM temperatures during test 1d with M-pack.

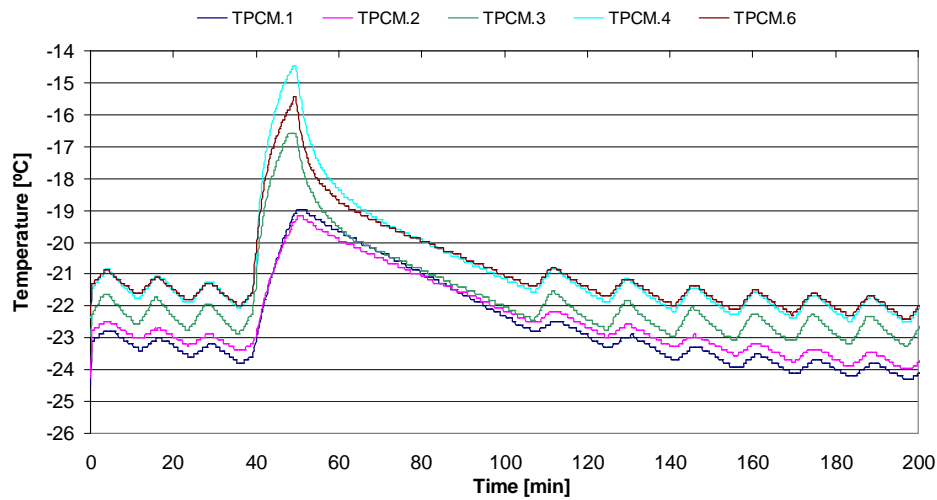


Fig. 79. PCM temperatures during test 1e without M-pack.

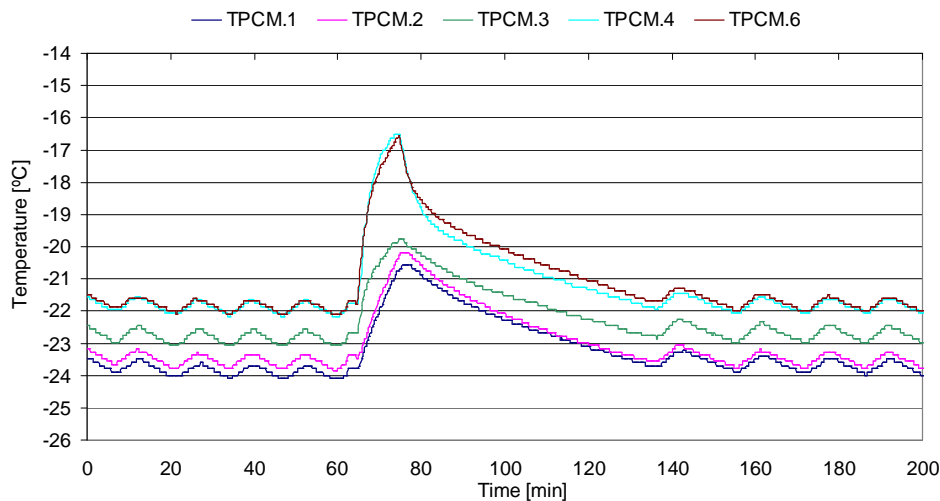


Fig. 80. PCM temperatures during test 1e with M-pack.

From Fig. 81 to Fig. 90 the PCM temperatures for all the experiments related to electrical power failure are shown. In tests 2a, 2b, and 2c the temperature of the PCM did not reach values of solidification temperatures. However, it is noticed that the temperature profile in all the cases changed; therefore solidification process started even the temperature of the PCM did not reach less than -18°C .

Fig. 87 and Fig. 88 show the temperature of the PCM during test 2d loaded and unloaded of M-pack respectively. In these tests, where 2 hours of electrical power

failure occurs, it has detected initial phases of solidification. However there was not enough time to solidify the PCM.

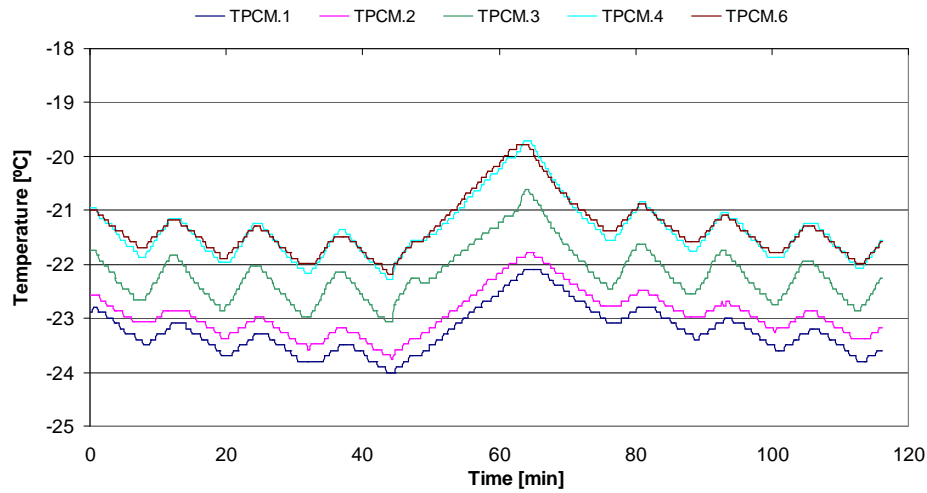


Fig. 81. PCM temperatures during test 2a without M-pack.

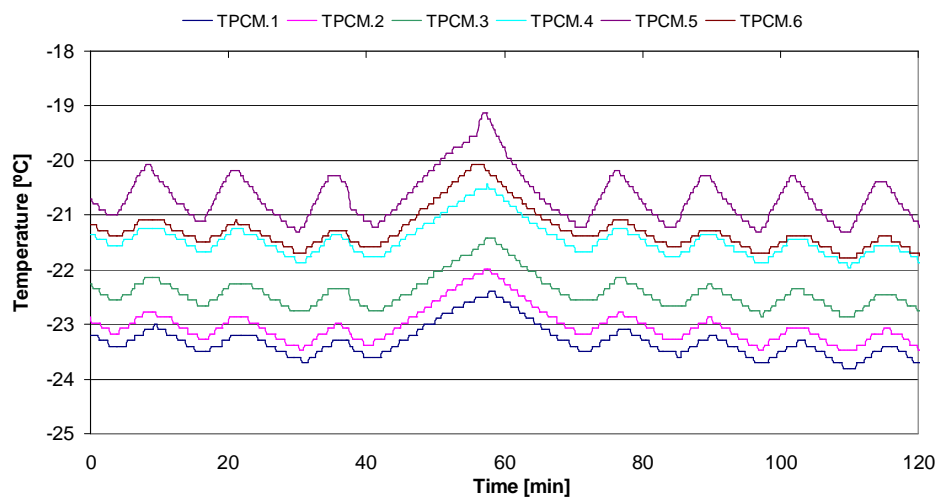


Fig. 82. PCM temperatures during test 2a with M-pack.

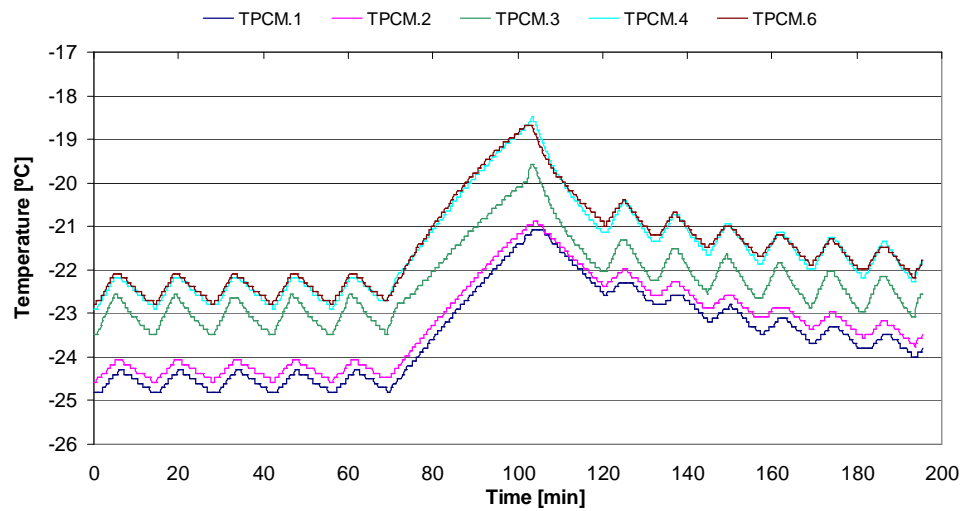


Fig. 83. PCM temperatures during test 2b without M-pack.

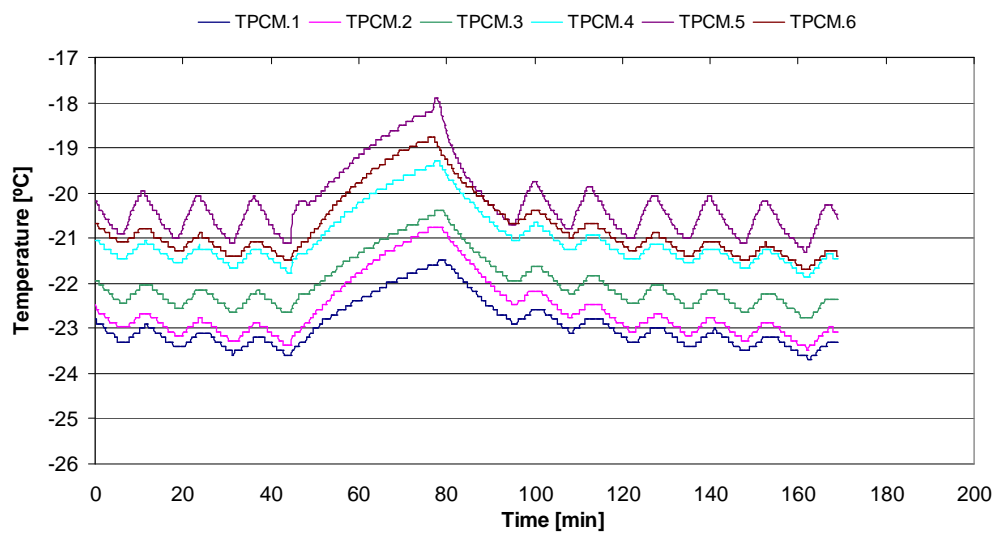


Fig. 84. PCM temperatures during test 2b with M-pack.

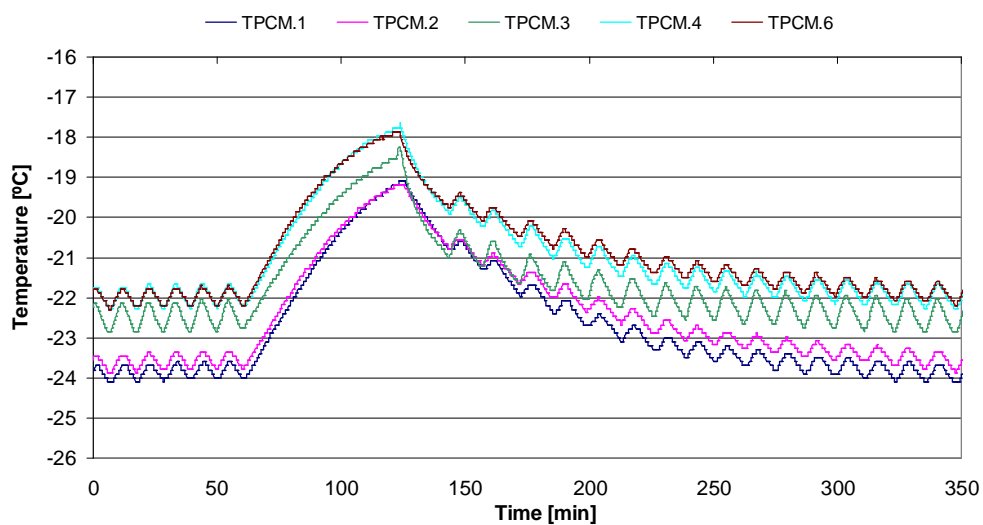


Fig. 85. PCM temperatures during test 2c without M-pack.

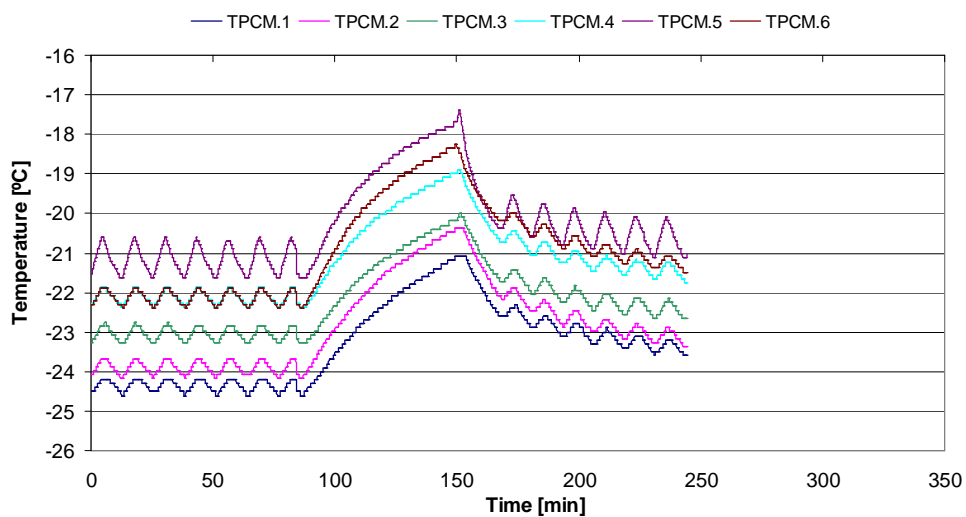


Fig. 86. PCM temperatures during test 2c with M-pack.

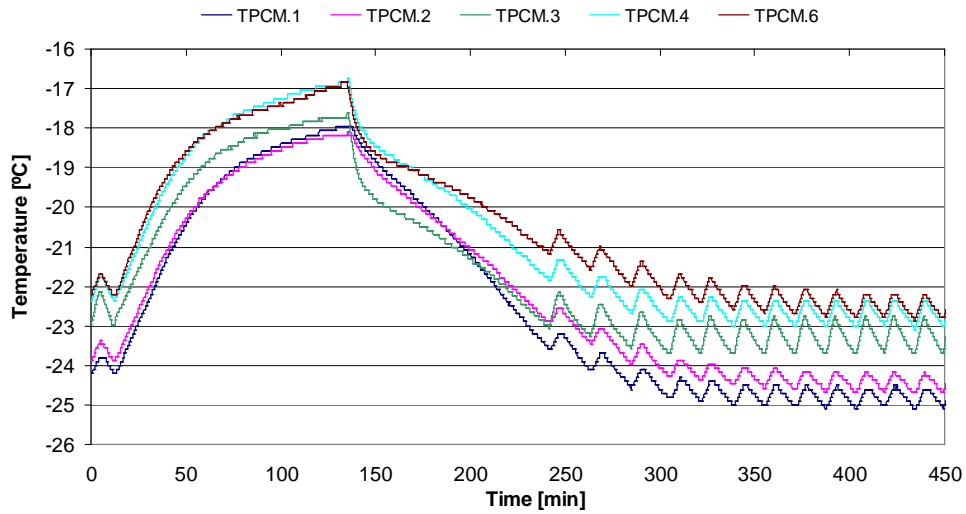


Fig. 87. PCM temperatures during test 2d without M-pack.

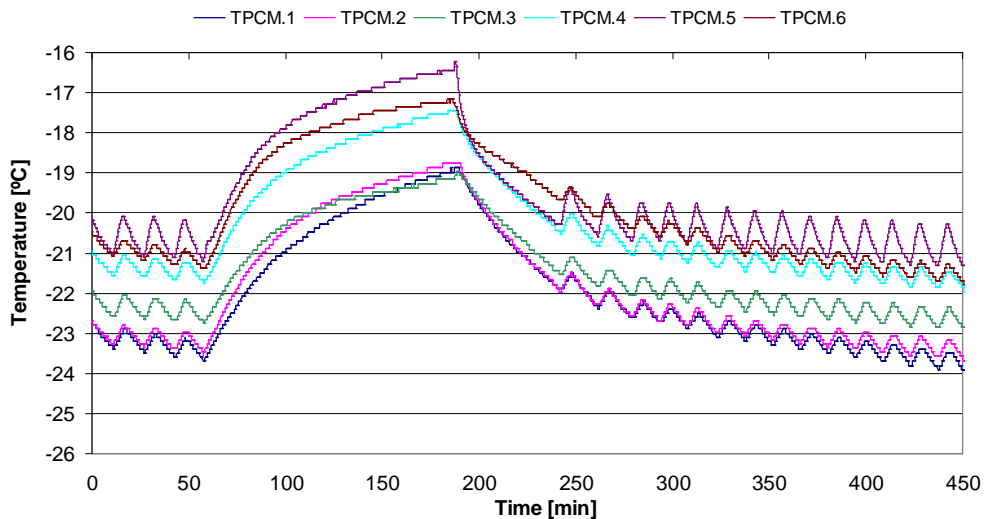


Fig. 88. PCM temperatures during test 2d with M-pack.

Fig. 89 and Fig. 90 show the temperature of the PCM during test 2e loaded and unloaded of M-pack respectively. The PCM during test 2e of unloaded M-pack started to melt but the PCM did not reach the melting temperature when the freezer was loaded with M-pack. The presence of M-pack (simulating food) add significant thermal mass that prevented solidification of the PCM, suggesting that a fully loaded freezer can sustain for longer time a electrical power failure periods.

In test 2e without M-pack not all the PCM samples had the phase change at the same temperature. $T_{PCM.1}$, $T_{PCM.2}$, and $T_{PCM.3}$ had the phase change at the same temperature (near -18°C) but in $T_{PCM.4}$ and $T_{PCM.5}$ phase change occurred at -17.5°C , 1.5°C less than the others.

As there were no M-packs inside the freezer, these values can be taken as the real behaviour of the PCM due to the fact that the other values of the PCM temperature were influenced by the M-pack. Notice that when there was time available for the PCM to solidify (test 2d) the behaviour of the PCM was similar to this but there were not enough time. Therefore, the incorporation of M-pack inside the freezer influence in the PCM temperature due to the addition of thermal mass and preventing the solidification of the PCM.

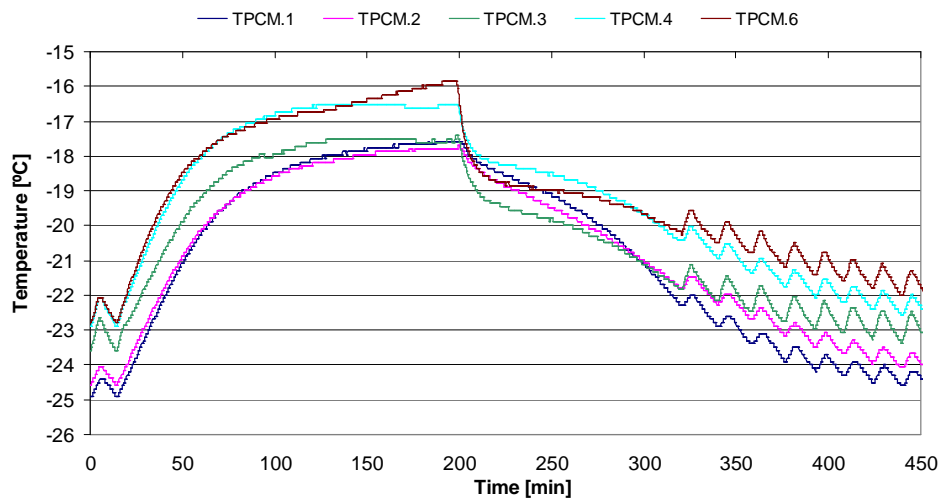


Fig. 89. PCM temperatures during test 2e without M-pack.

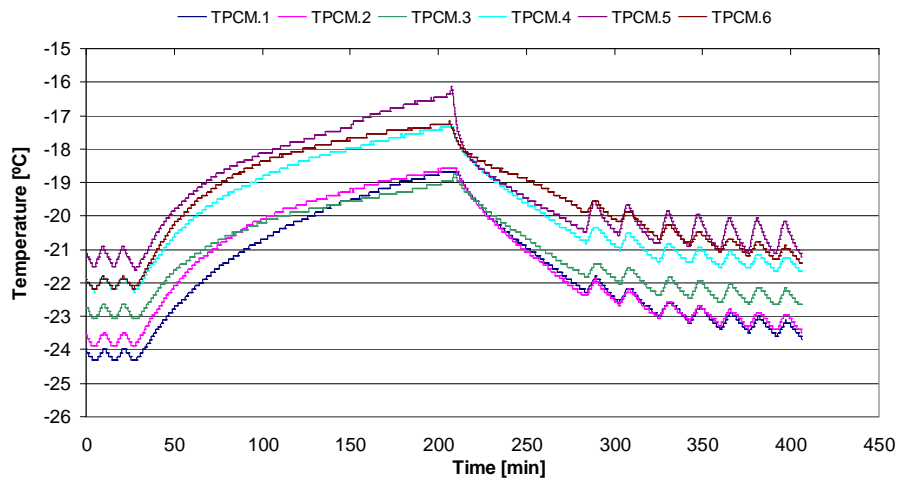


Fig. 90. PCM temperatures during test 2e with M-pack.

2.2 Results with storage temperature at -18 °C

2.2.1 Air temperature response to door opening

A series of door openings with the freezers loaded and unloaded with the M-packs and with and without PCM under the same boundary conditions were done. Five different tests were performed in order to study the behaviour of the freezer (from Fig. 91 to Fig. 100).

Notice that the data acquisition system used only gets one value every 10 seconds. In experiments of door opening for a period of 10 seconds or even of 30 seconds, it was the possibility to get unreal values of the temperature.

It is expected that when door opening occurs the air temperature inside the freezer increase quickly until the door is closed again. If the time that the door is open is enough, the air temperature reached is higher than the set point temperature and therefore the compressor will switch on.

Due to the experiments were carried on in different weeks, in some cases, the boundary conditions was not the same. Therefore, in some test it is impossible to compare both experiments (using PCM or not) due to the behaviour of the freezer in both cases was completely different. On the other hand, when the freezer was loaded with M-pack, the boundary conditions of both tests (with and without PCM) was the same,

therefore, the results could be compared at all.

When the results could be compared, the addition of PCM at the system caused benefit in terms of temperatures drop and constant temperature after the door was closed again. In addition, this effect is beneficial for the frozen product.

	Test 1a	Test 1b	Test 1c	Test 1d	Test 1e
Freezer without M-pack					
Without PCM [°C]	5	5	23	27	30
With PCM [°C]	5	5	24	27	31
Temperature difference [°C]	0	0	-1	0	-1
Freezer with M-pack					
Without PCM [°C]	3	7	16	25	26
With PCM [°C]	3.5	3	19	20	21
Temperature difference [°C]	-0.5	4	3	5	4

Table 9. Temperature difference in the air temperature due to the door opening.

In test 1a (Fig. 91 and Fig. 92), when the door was opening for a period of time of 10 seconds, the air temperature inside the freezer did not reach high temperature values and frequency of the temperature was the same even door opening occurs. Due to that the boundary conditions between both experiments (PCM and no PCM) was different, the results of this test could not compare each other. Temperature profile of both test clearly show a big difference between the experiments, mainly the frequency of operation.

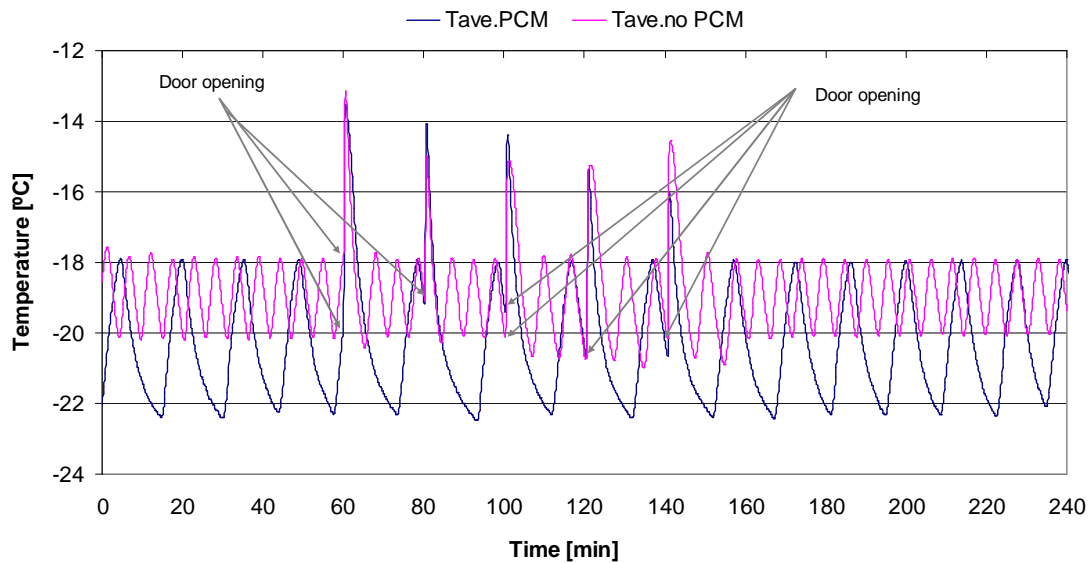


Fig. 91. Average air temperature during test 1a without M-pack.

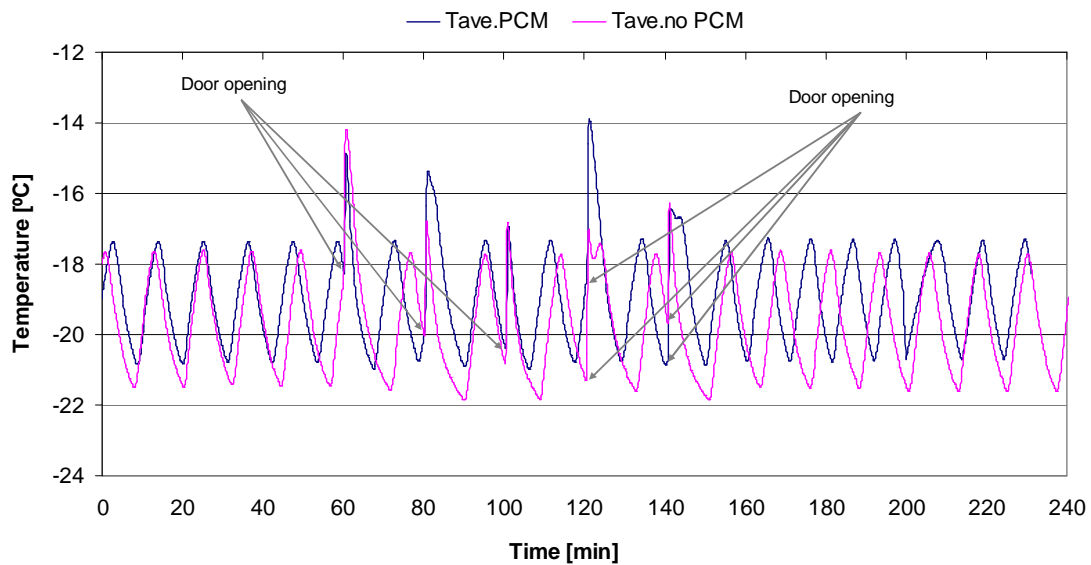


Fig. 92. Average air temperature during test 1a with M-pack.

Fig. 93 and Fig. 94 show the results of the test 1b, loaded and unloaded with M-pack, respectively. When the freezer was unloaded with M-pack, the boundary conditions were different in both tests, with and without PCM, respectively. Therefore, the results could not be comparable each other. However, when the freezer was loaded of M-pack in order to simulate real frozen food, great benefit was detected of using PCM. Furthermore, the addition of PCM in the system is positive in terms of

improvement the performance of the freezer and the food quality.

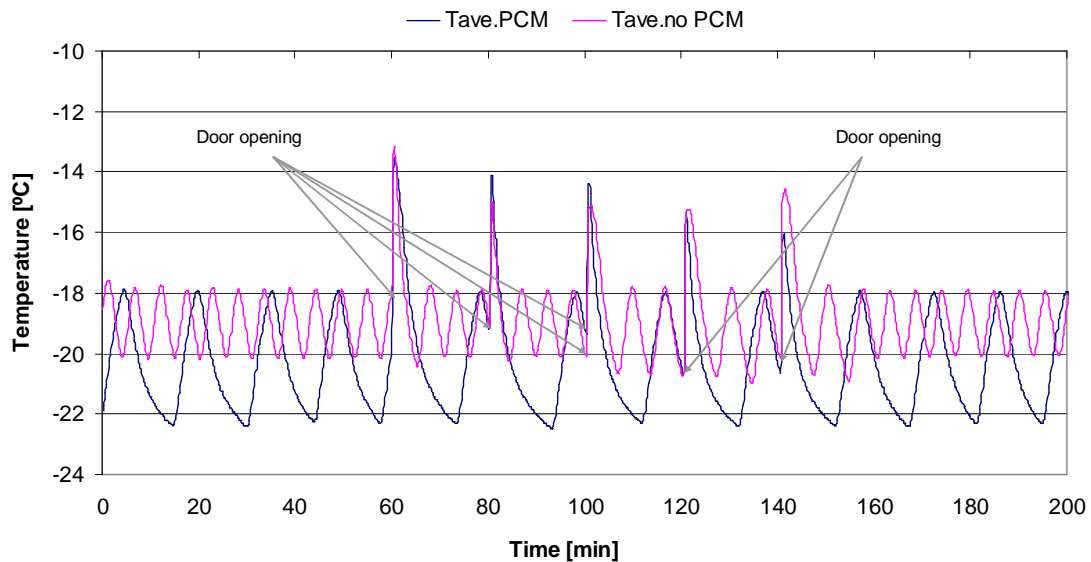


Fig. 93. Average air temperature during test 1b without M-pack.

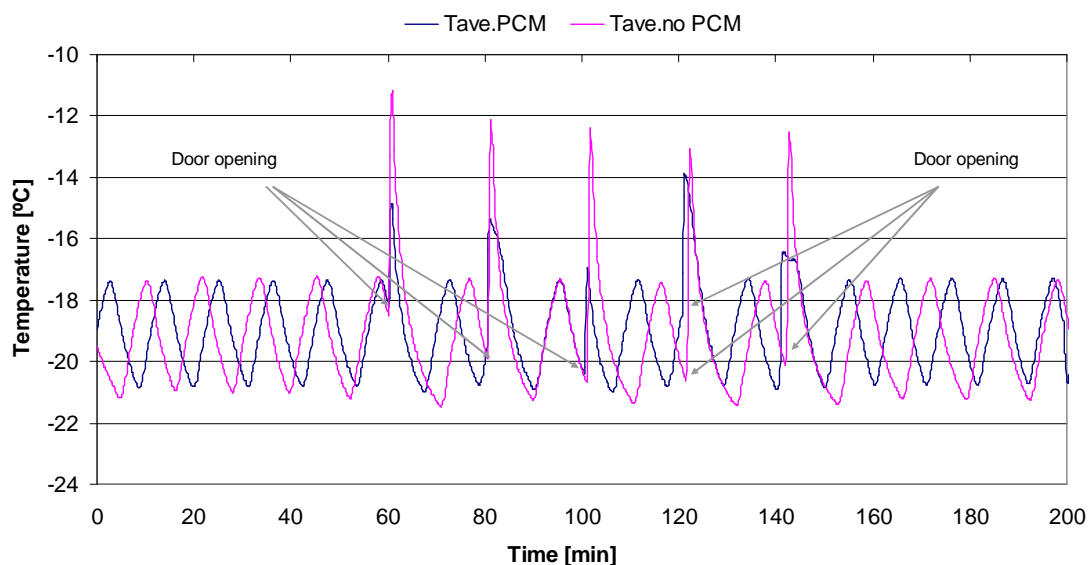


Fig. 94. Average air temperature during test 1b with M-pack.

Fig. 95 and Fig. 96 show the results from test 1c, when two door openings of 3 minutes was done. As in the other tests, there were some problems to control the boundary conditions of the experimentation. In the case with no M-pack inside the freezer, the behaviour of the freezer was extremely different when PCM was used or not. Therefore,

there is no conclusion to do with these results. Nonetheless, when the freezer was loaded of M-pack the boundary conditions of both tests were similar, therefore, the results could be compare each other. In this case, the benefit of the use of PCM is clearly demonstrate by the temperature reached in both cases (PCM or not).

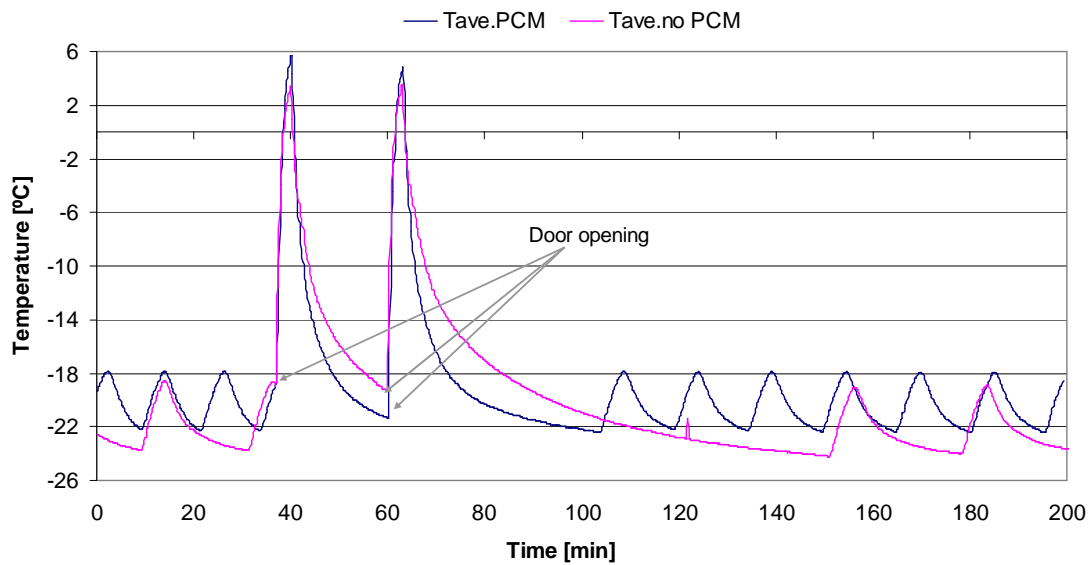


Fig. 95. Average air temperature during test 1c without M-pack.

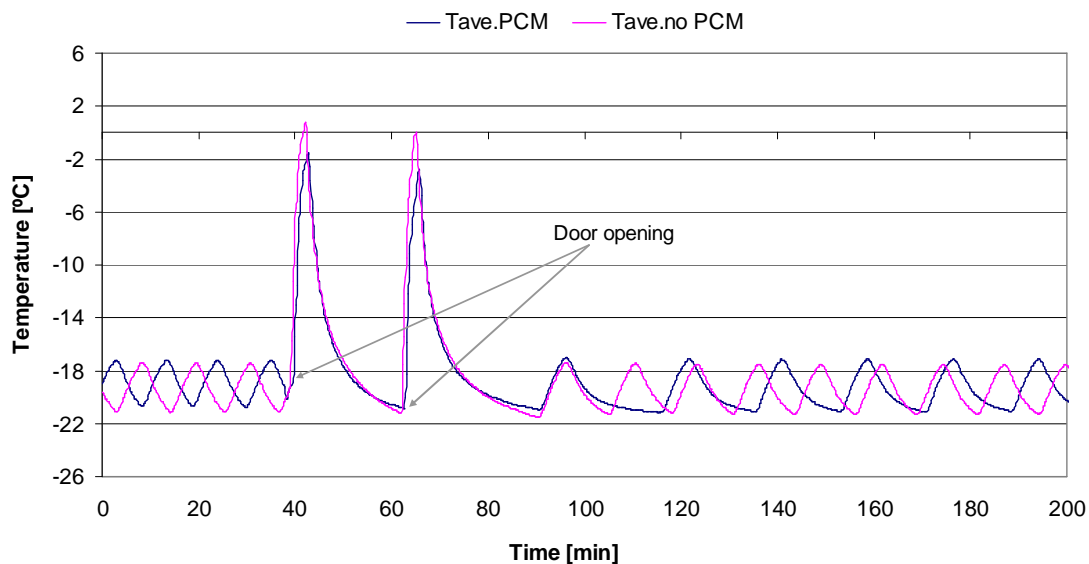


Fig. 96. Average air temperature during test 1c with M-pack.

In test 1d (Fig. 97 AND Fig. 98), differences in the experimentation with and without M-pack were found out. In the experiments done with M-pack, the use of PCM is helps to maintain the cabinet at less temperature while in the case of the freezer unloaded of M-pack, no differences of using or not PCM were found.

Furthermore, the most important fact is not the difference of the temperature peak but the capacity of the freezers to reach again the normal operating values. Both cases, PCM and no PCM delay the same time o reach the storage temperature, nearly -22°C , however, after that, the freezer with PCM stayed for much longer at constant temperature until started to fluctuate. This effect was more important in the case of the freezer unloaded of M-pack due to the lower thermal mass in the system.

The same effect happened in test 1e (Fig. 99 and Fig. 100), when one door opening for a period of 10 minutes occurs. During the experimentation with the freezer unloaded the M-packs, the boundary conditions of both cases were not exactly the same and therefore, the results could be not compared. On the other hand, when M-pack were inside the freezer the benefit of using PCM was clearly demonstrate as it happened with the test 1d.

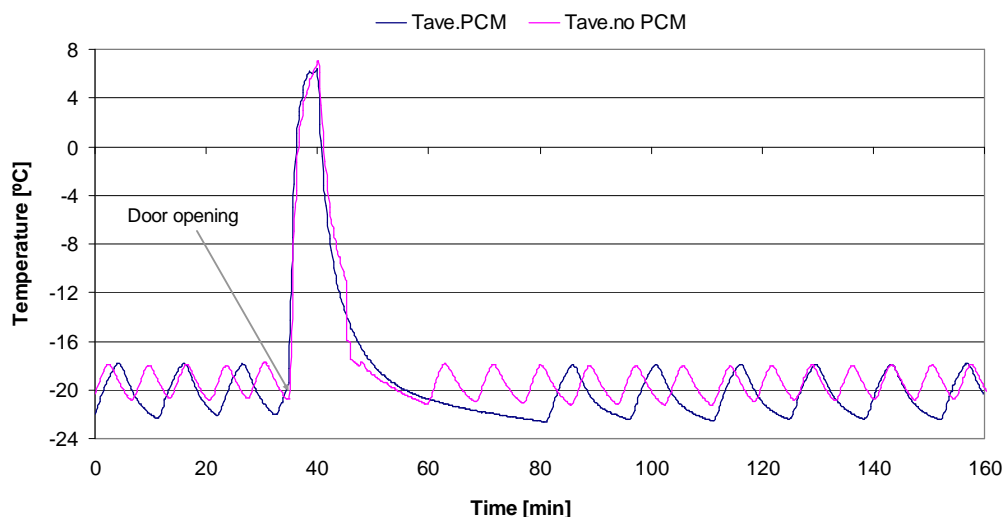


Fig. 97. Average air temperature during test 1d without M-pack.

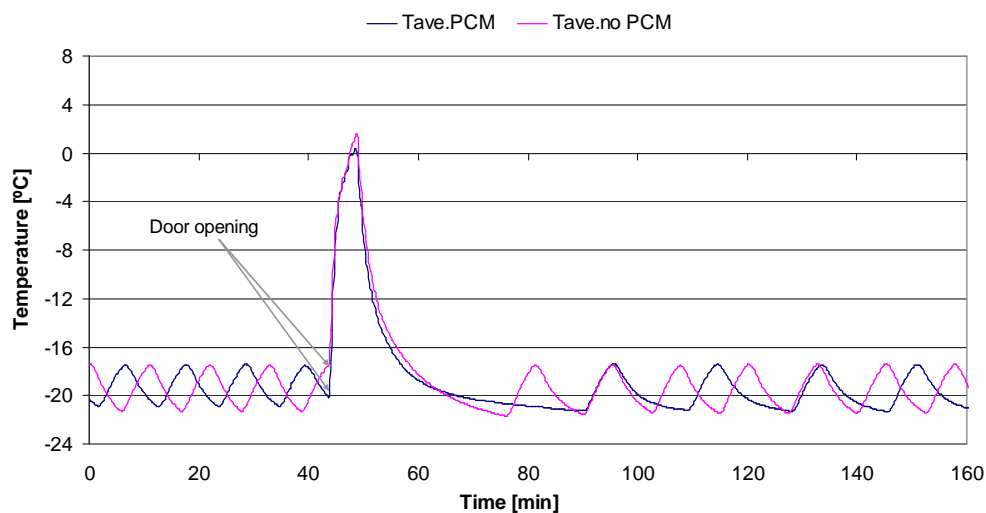


Fig. 98. Average air temperature during test 1d with M-pack.

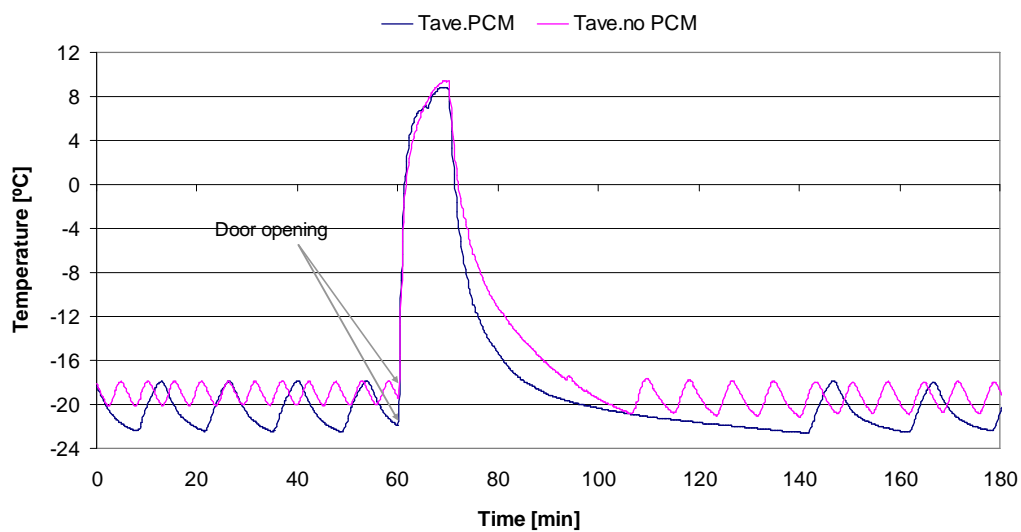


Fig. 99. Average air temperature during test 1e without M-pack.

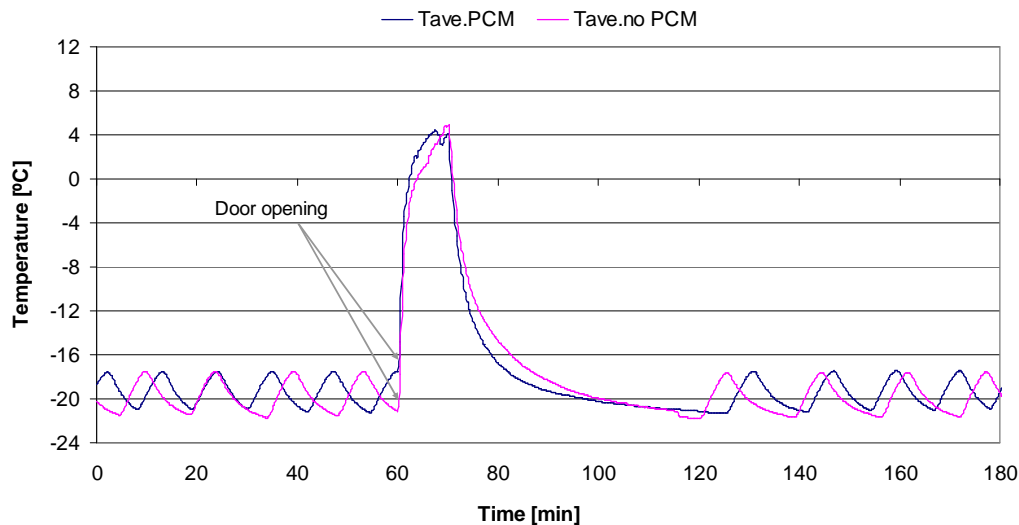


Fig. 100. Average air temperature during test 1e with M-pack.

2.2.2 Air temperature response to electrical power failure

A series of electrical power failure were done with the freezers loaded and unloaded with the M-packs with and without PCM under the same boundary conditions. In order to study the behaviour of both freezers five different tests were performed.

Here there were no problems with the data acquisition system since the duration of these experiments were much longer than the experimentation carried on in test 1.

Table 10 shows the difference of the air temperature inside the freezer before and after the electrical power failure and the temperature gradient in each experiment done. Huge difference between the freezer loaded and unloaded of M-packs was detected. Furthermore, the addition of these M-packs increased the thermal mass of the system and the values of the air temperature were higher if no M-packs were inside the freezer. In all the cases studied, the introduction of PCM in the freezers had good benefits in the drop air temperature doing these values lowers at each experiment. Note that when no M-packs were inside the freezer (less thermal mass) high values of temperature are measured in both freezers.

	Test 2.a	Test 2.b	Test 2.c	Test 2.d	Test 2.e
Freezer without M-pack					
Without PCM	7	8	18	20	24
With PCM	6	5	10	10	8
Delta T [°C]	1	3	8	10	16
Freezer with M-pack					
Without PCM	5	7	10	11	10
With PCM	3.5	5	6	7	6
Delta T [°C]	1.5	2	4	4	4

Table 10. Temperature difference in the air temperature due to electrical power failure.

In all the cases, the temperature reached inside the cabinet was lower when PCM was used. Therefore, the benefit of PCM is demonstrated in terms of air temperature and product quality.

As happened in other experiments, the freezer with PCM reached the storage temperature quicker than the freezer without PCM. Moreover, during a while the temperature was almost constant; this fact has benefit due to no fluctuations on the air temperature during this period. This effect happens due to the fact that when no M-pack were inside the freezer, all the mass was at low temperature while in the M-pack case, more mass (addition of M-packs) was at lower temperature and when the power is switched on again, the temperature difference was obviously lower.

Fig. 101 and Fig. 102 show the average air temperature during a electrical power failure of 15 minutes (test 2a) in the freezer (PCM and no PCM) unloaded and loaded with M-

packs, respectively. The freezer without PCM reached higher air temperatures in both experiments; being 1 °C higher than the unloaded freezer with PCM and 1.5 °C when the freezer was loaded with M-packs.

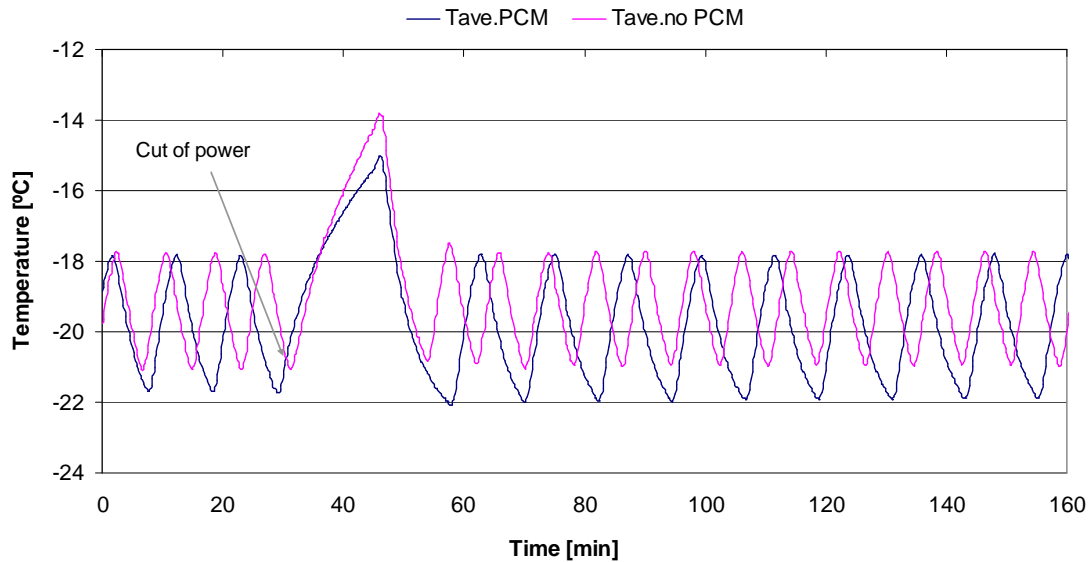


Fig. 101. Average air temperature during test 2a without M-pack.

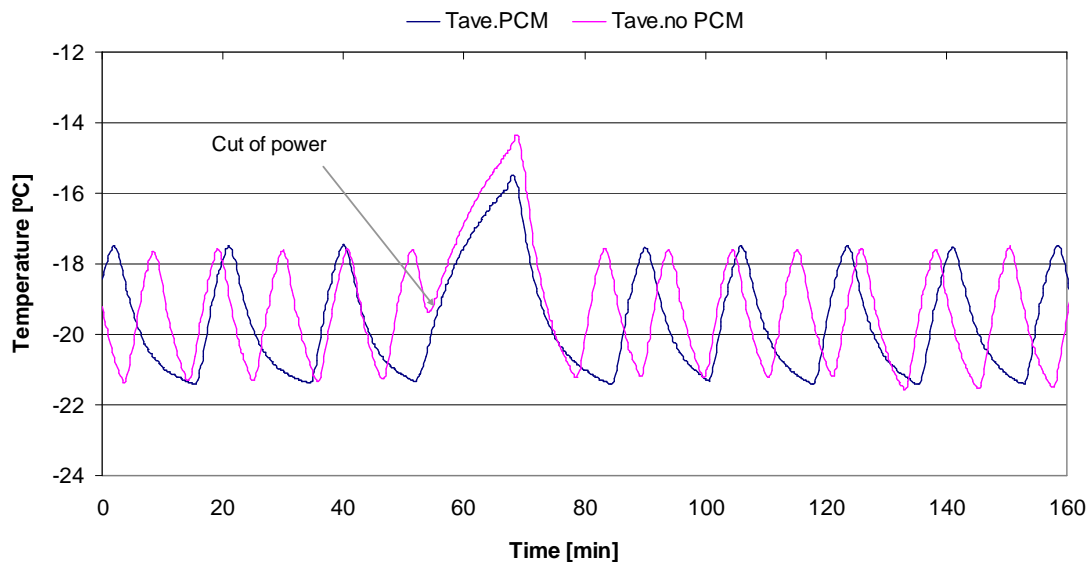


Fig. 102. Average air temperature during test 2a with M-pack.

Fig. 103 and Fig. 104 show the average air temperature during electrical power failure of 30 minutes (test 2b) in the freezer (PCM and no PCM) unloaded and loaded with the

M-packs, respectively. It can be seen that the air temperature of the freezer without PCM reached higher values in a shorter time. The average peak temperature of the unloaded freezer was 3 °C higher than the unloaded freezer with PCM, and 2 °C when the freezer was loaded with M-packs.

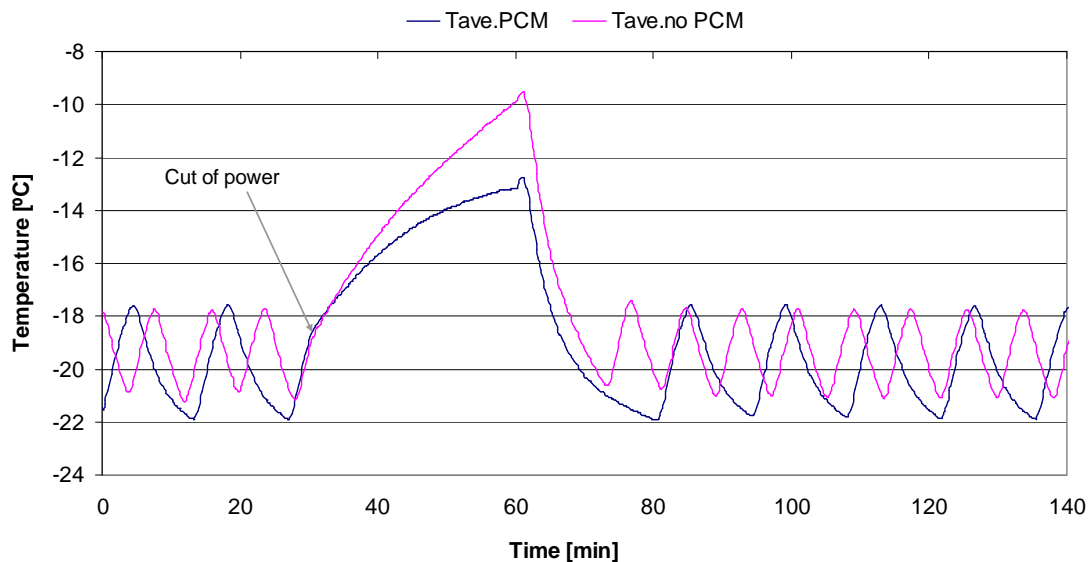


Fig. 103. Average air temperature during test 2b without M-pack.

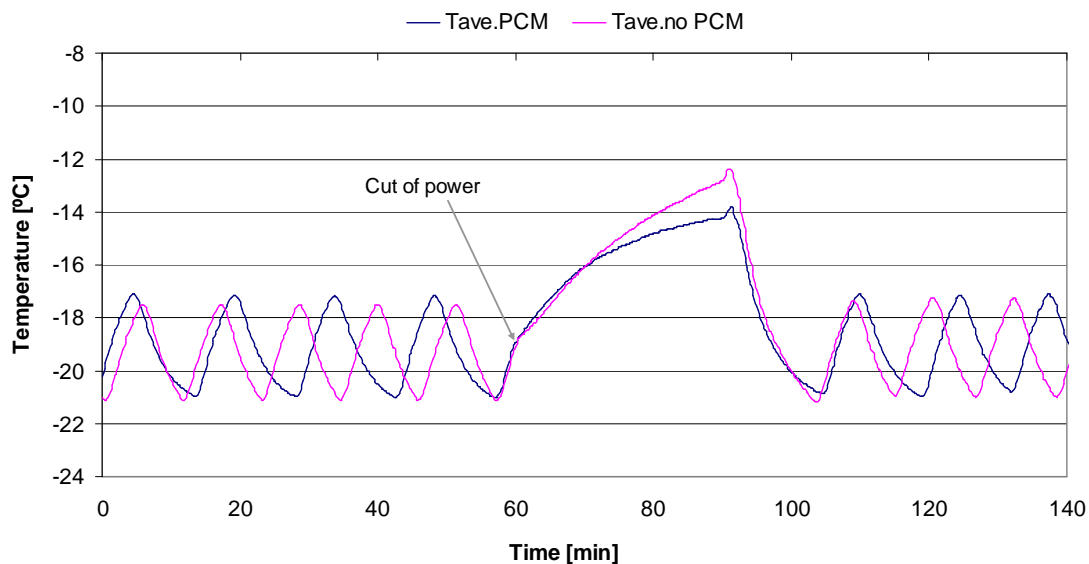


Fig. 104. Average air temperature during test 2b with M-pack.

Fig. 105 and Fig. 106 show the average air temperature during a electrical power failure of 1 hour (test 1c) in the freezer (PCM and no PCM) unloaded and loaded with M-packs, respectively. The freezers without PCM reached higher air temperatures in both experiments; being 7 °C higher than the unloaded freezer with PCM and 4 °C when the freezer was loaded with M-packs. However, when the freezer with PCM was loaded with M-pack the behaviour of it was completely strange and the comparison with the freezer with no PCM was not possible to do.

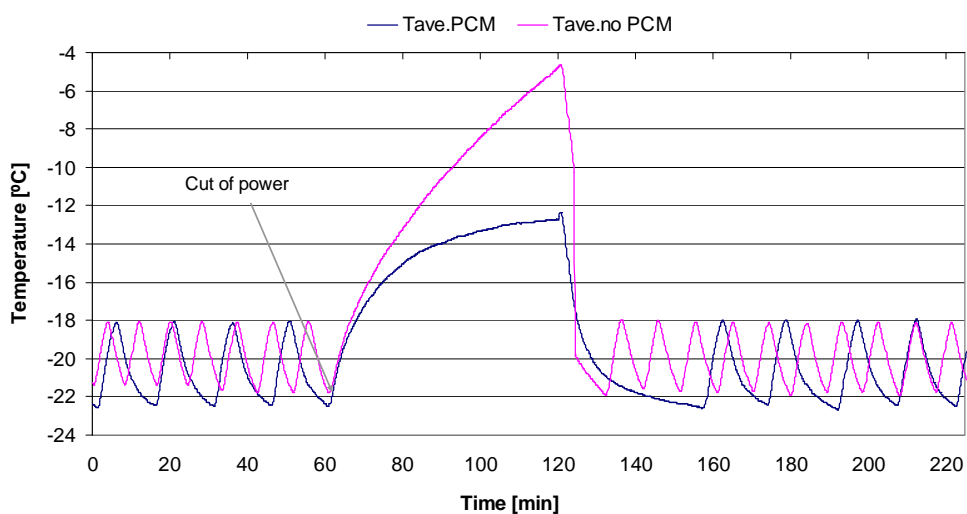


Fig. 105. Average air temperature during test 2c without M-pack.

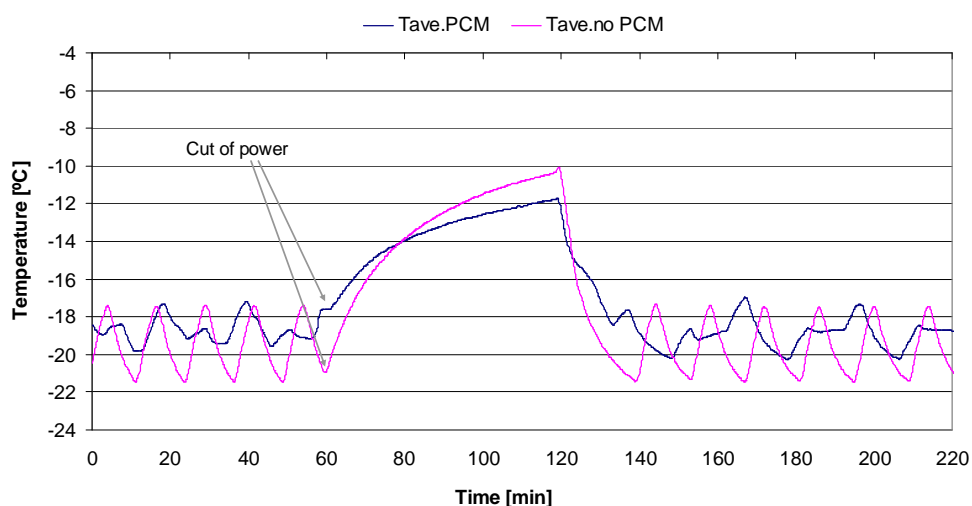


Fig. 106. Average air temperature during test 2c with M-pack.

Fig. 107 and Fig. 108 show the average air temperature during a electrical power failure of 2 hours (test 1d) in the freezer (PCM and no PCM) unloaded and loaded with M-packs, respectively. The freezer without PCM reached higher air temperatures in both experiments; being 11 °C higher than the unloaded freezer with PCM and 4 °C when the freezer was loaded with M-packs.

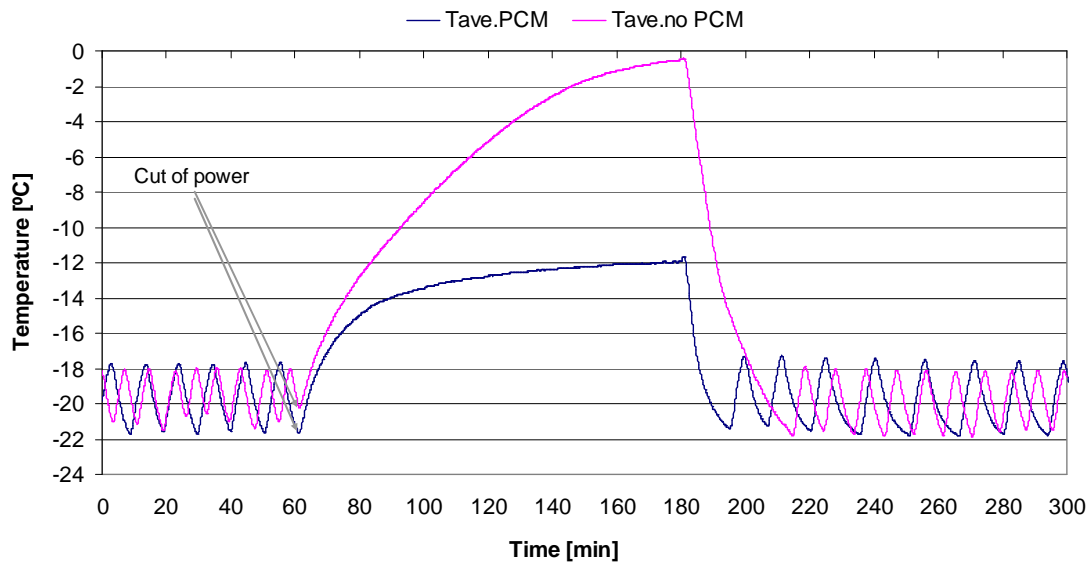


Fig. 107. Average air temperature during test 2d without M-pack.

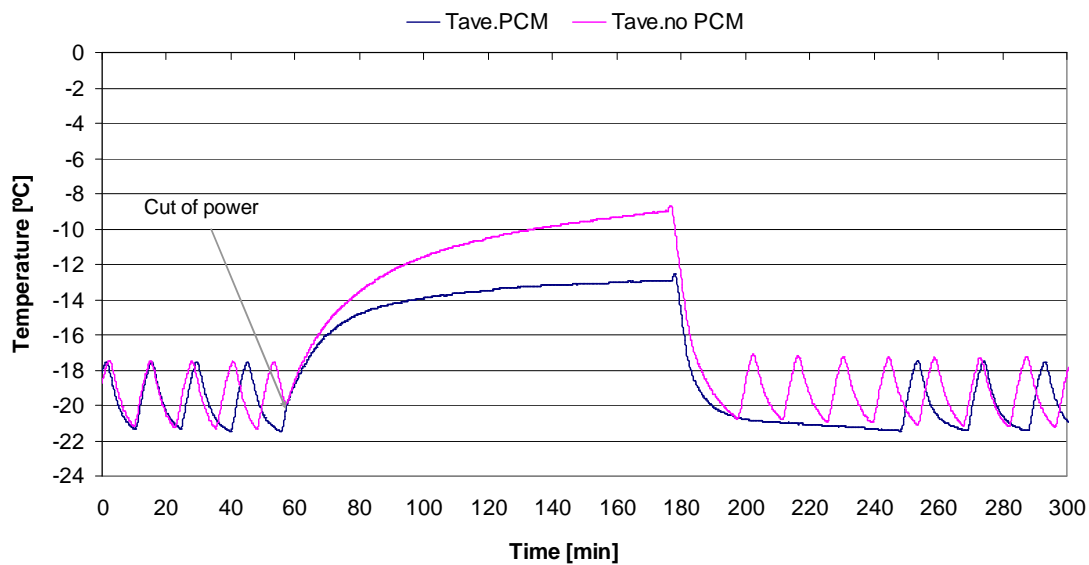


Fig. 108. Average air temperature during test 2d with M-pack.

Fig. 109 and Fig. 110 show the average air temperature during a electrical power failure of 3 hours (test 2e) in the freezer (PCM and no PCM) unloaded and loaded with M-packs, respectively. The freezer without PCM reached higher air temperatures in both experiments; being 16 °C higher than the unloaded freezer with PCM and 4 °C when the freezer was loaded with M-packs.

In addition, the freezer with PCM reached much faster working air temperature values after the switched on than the freezer without PCM. The results clearly show the benefit of using PCM even loaded or unloaded with M-pack.

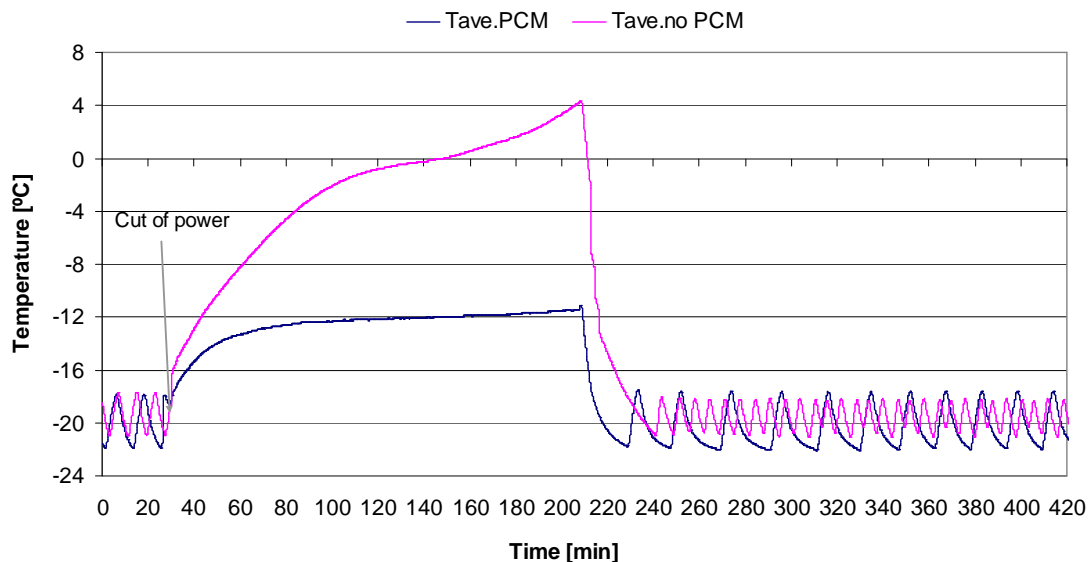


Fig. 109. Average air temperature during test 2e without M-pack.

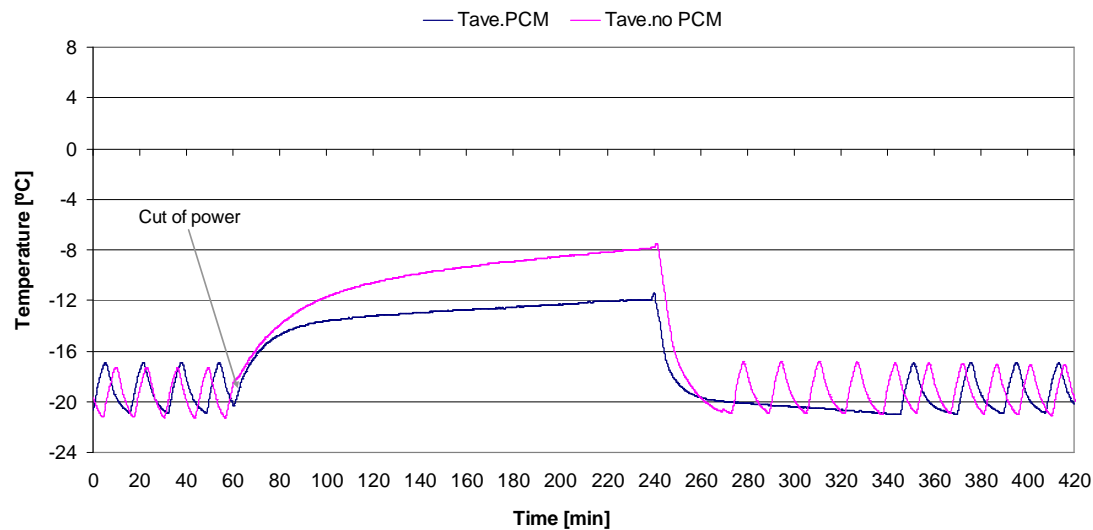


Fig. 110. Average air temperature during test 2e with M-pack.

2.2.3 M-pack response

It is well known that the size of ice crystals in ice cream grow larger when the ice cream is stored under fluctuating conditions. For that reason it is very important evaluate the M-pack response under different experiments. Following ISO standard ISO 15502:2005/AC:2008, only the hottest M-pack temperature has to be taken into account in each freezer. Therefore, only the hottest M-pack is showed in the results commented below.

As it was expected, the hottest M-pack was always the M-pack situated at a higher position inside the freezer, which were the M-pack 4 and M-pack 8, respectively. Fig. 63 shows the hottest M-pack during the experimentation in the freezer with PCM.

Fig. 111 show the hottest M-pack temperature in test 1a and 1b when door opening occurs, respectively. The M-pack temperature was always higher when no PCM was inside the freezer.

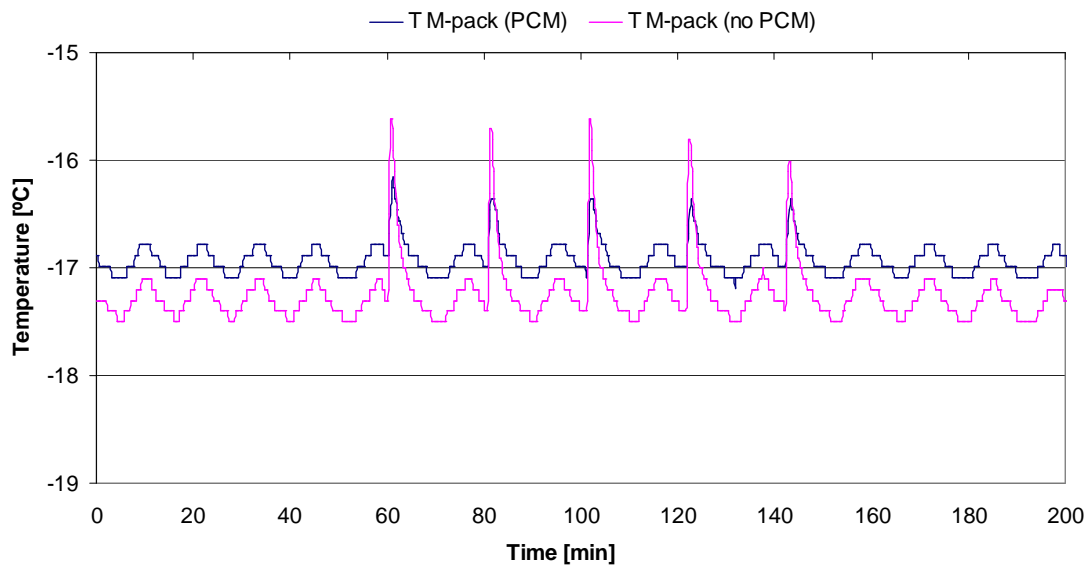


Fig. 111. Hottest M-pack temperatures during test 1b.

Fig. 112 shows the hottest M-pack temperature in test 1c when door opening occurs for a period of 1 minute. The behaviour of the M-pack temperature was the same for both cases, with and without PCM. Note that when PCM was inside the freezer, the product temperature after the door was closed was more constant. Therefore, the incorporation of PCM in the freezer was beneficial in terms of food quality.

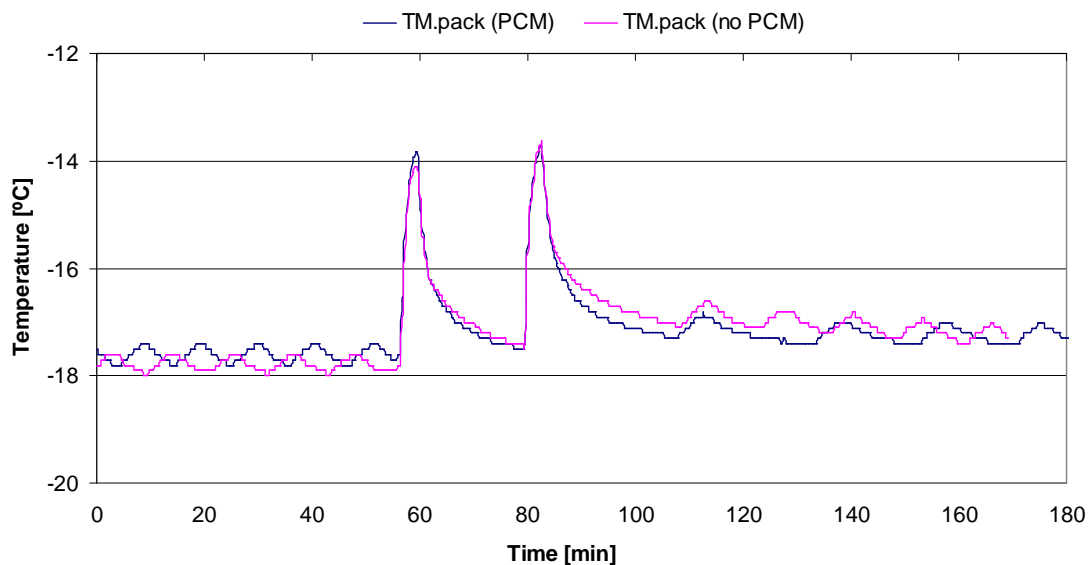


Fig. 112. Hottest M-pack temperatures during test 1c.

Fig. 113 shows the hottest M-pack temperature in test 1e when door opening occurs for a period 10 minutes.

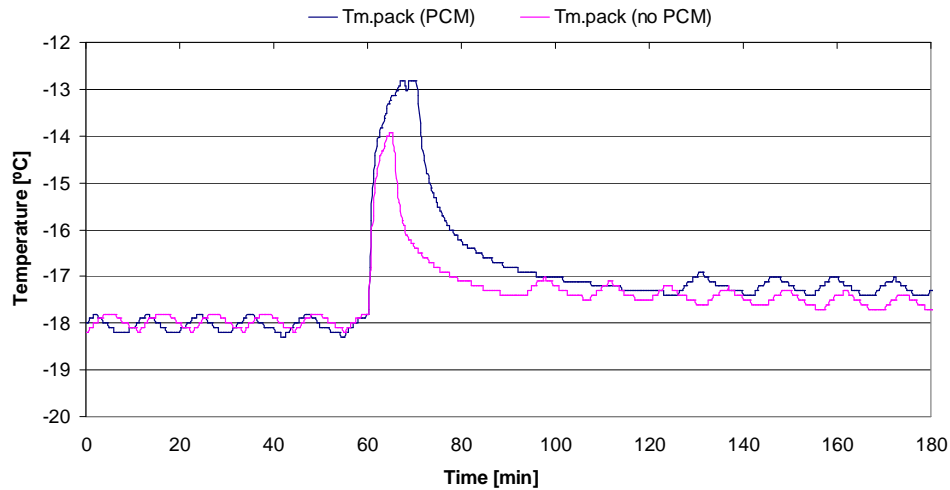


Fig. 113. Hottest M-pack temperatures during test 1e.

Fig. 114 and Fig. 115 show the hottest M-pack temperature in test 2a and 2b when electrical power failure occurs, respectively. Due to the shorter period of electrical power failure, the behaviour of the frozen product temperature was more or less the same in both experiments done.

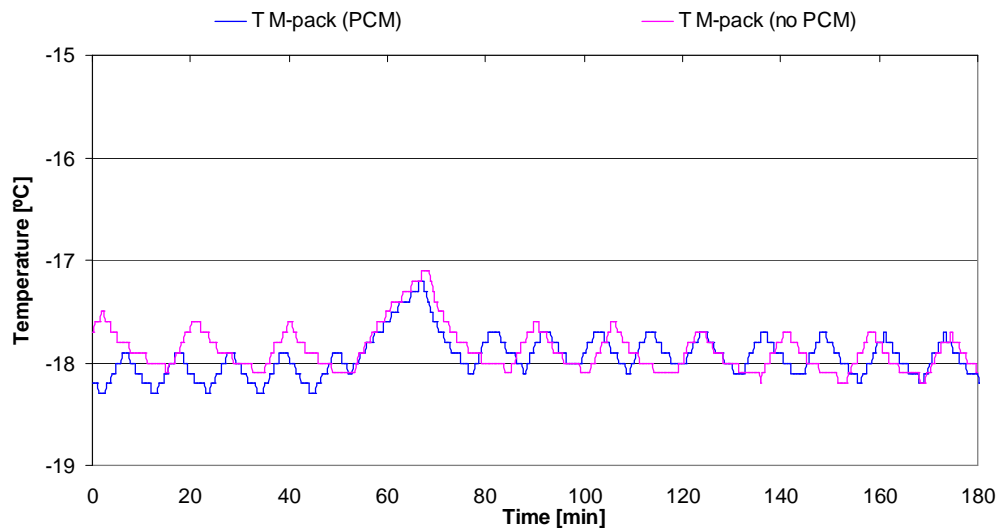


Fig. 114. Hottest M-pack temperatures during test 2a.

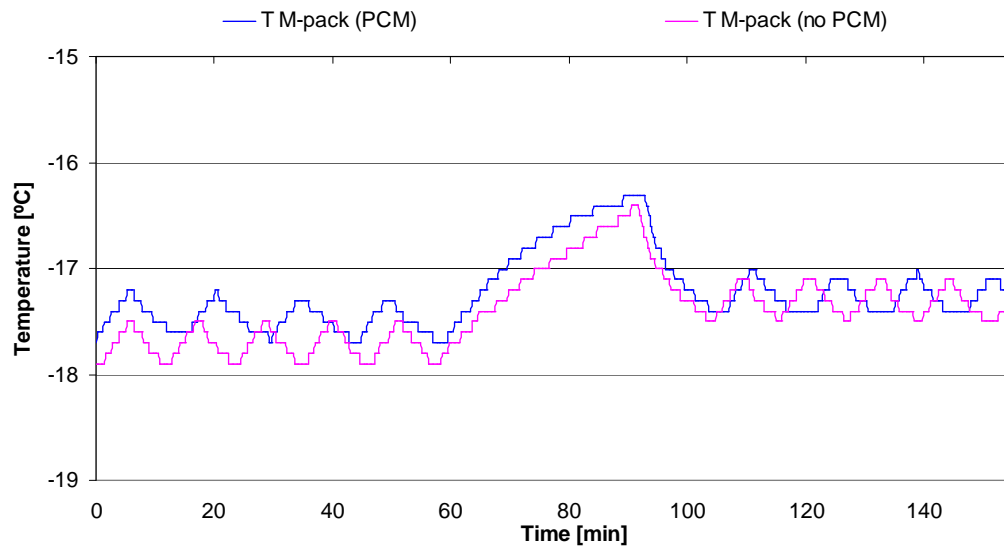


Fig. 115. Hottest M-pack temperatures during test 2b.

Fig. 116 and Fig. 117 show the hottest M-pack temperature in test 2d and 2e, when a electrical power failure of 2 and 3 hours occurs, respectively. The M-pack temperature was much higher when no PCM was inside the freezer even the temperature before the test 2d was not the exactly the same.

Results of test 2e (3 hours of electrical power failure) clearly show the efficiency of using PCM in order to improve the quality of the products stored and the efficiency of the freezers. The temperature before the test 2e started was the same for both M-pack and since the first instant the temperature in the M-pack inside the freezer without PCM was increasing more than the temperature in the other M-pack, reaching 2 °C more at the final of the electrical power failure. Once the freezers were switched on again, no temperature fluctuations were detected in the M-packs of the freezer with PCM; furthermore, 100 minutes after the temperature difference was still 1 °C.

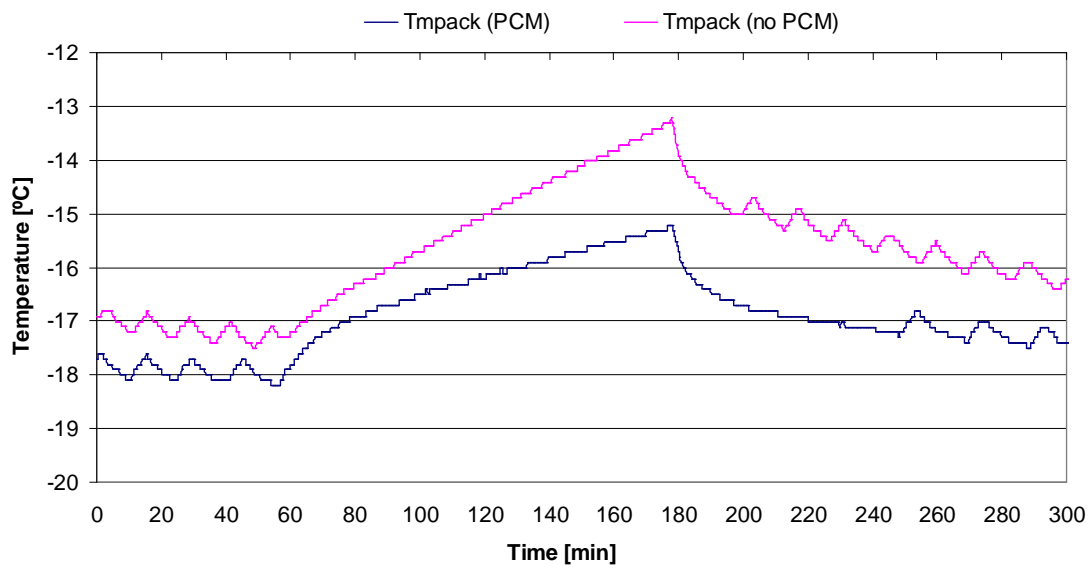


Fig. 116. Hottest M-pack temperatures during test 2d.

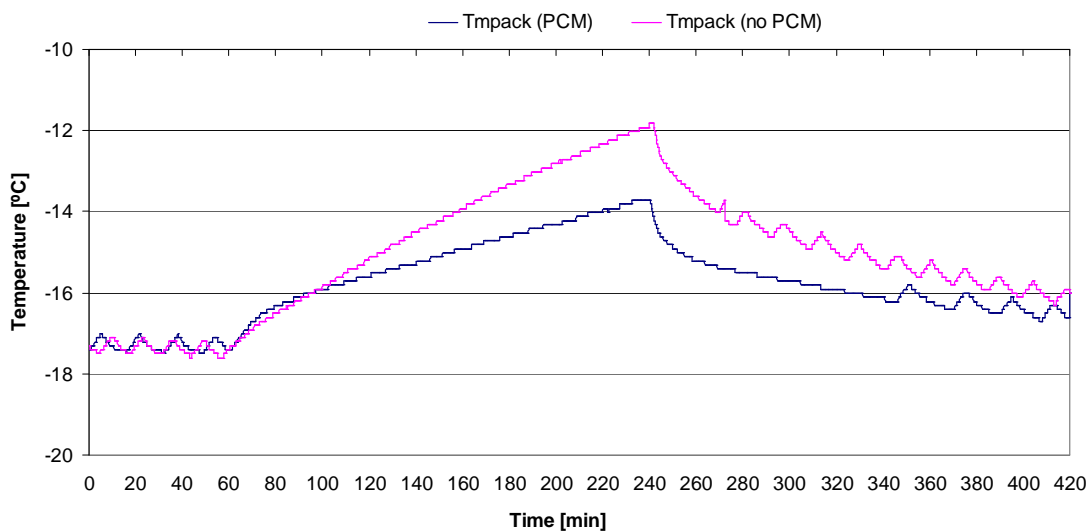


Fig. 117. Hottest M-pack temperatures during test 2e.

2.2.4 PCM response

It is important to evaluate the behaviour of the PCM during these experiments and insure that the PCM undergoes phase transition; otherwise it will act as sensible heat storage, which is small compared to latent heat storage. In some of the experiments done, only three temperature sensors were installed in order to measure the temperature

of the PCM.

In tests 1a, 1b, and 1c the temperature of the PCM after the door opening did not reach the temperature of the phase change which is -18°C . For that reason the effect of the PCM is not as latent heat but as sensible heat. In test 1d and 1e the temperature of the PCM reached lower values but the temperature graphs do not show any phase change transition. The results of those tests are shown from Fig. 118 to Fig. 127.

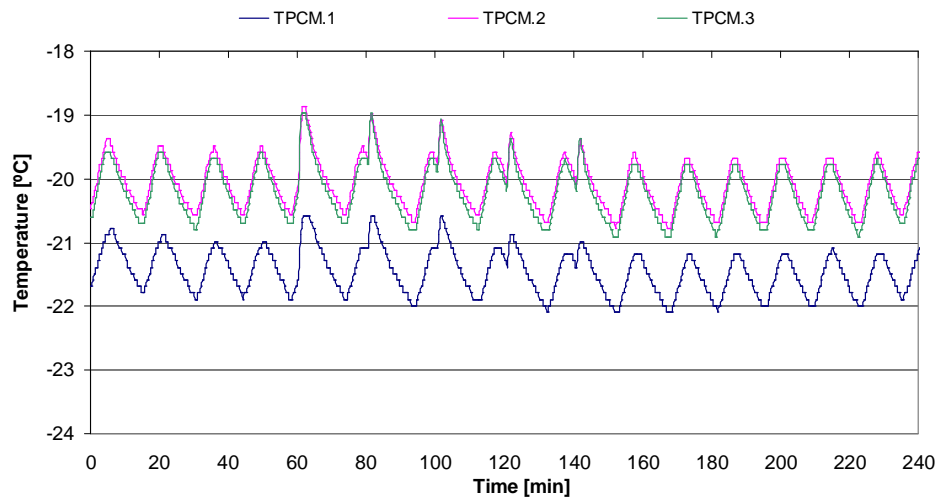


Fig. 118. PCM temperatures during test 1a without M-pack.

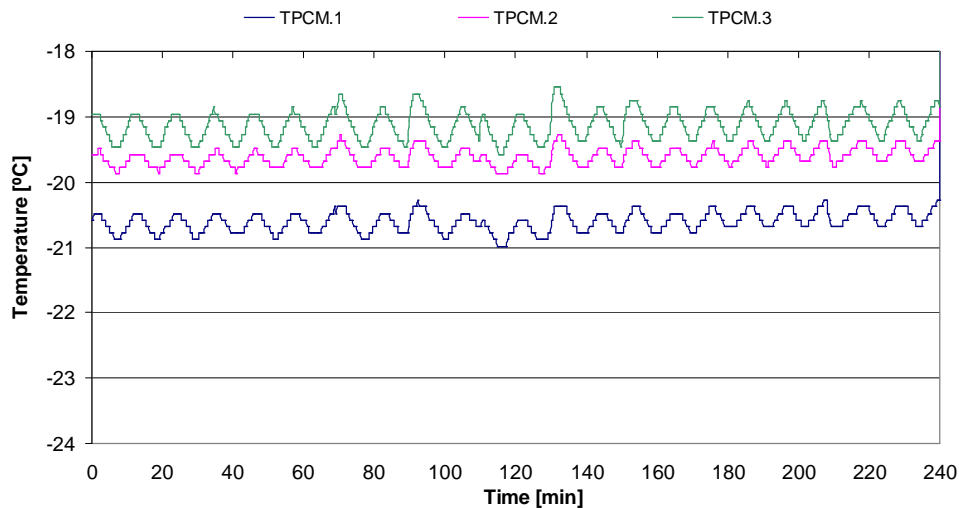


Fig. 119. PCM temperatures during test 1a with M-pack.

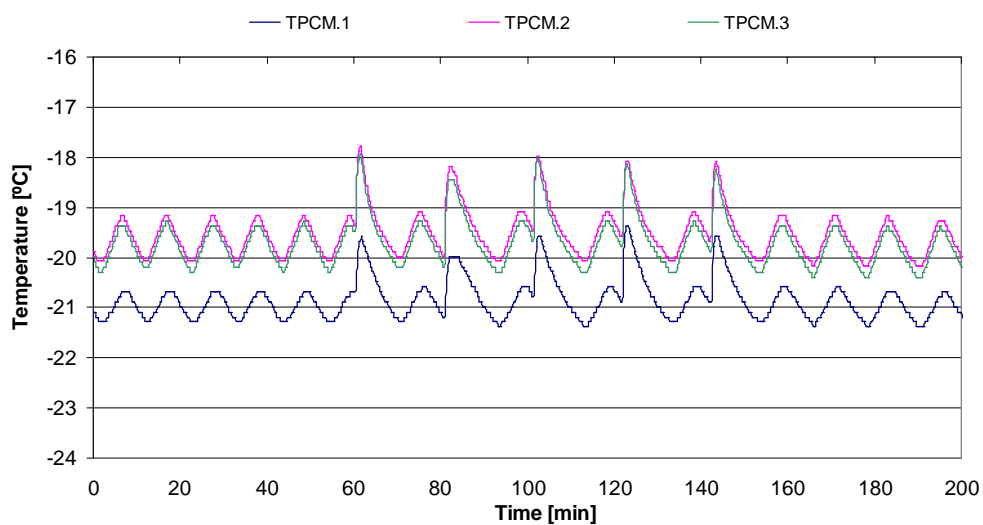


Fig. 120. PCM temperatures during test 1b without M-pack.

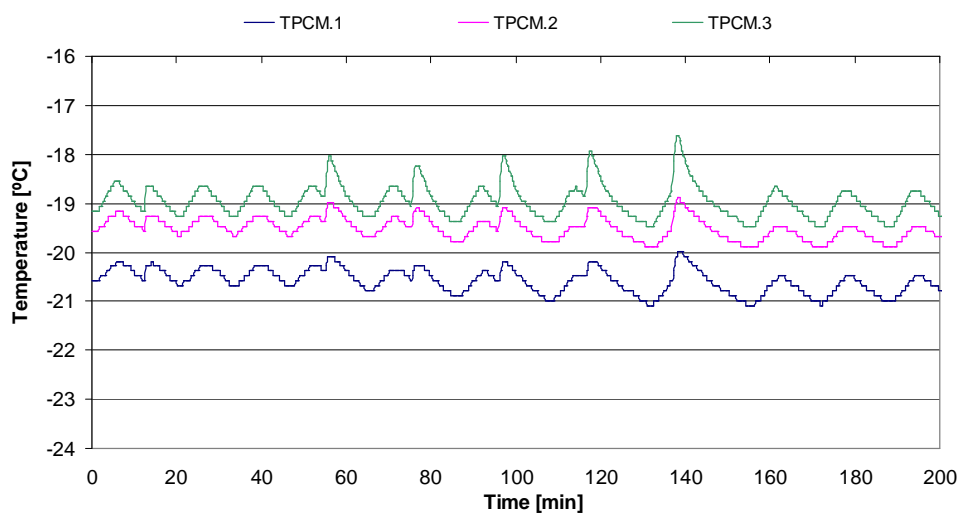


Fig. 121. PCM temperatures during test 1b with M-pack.

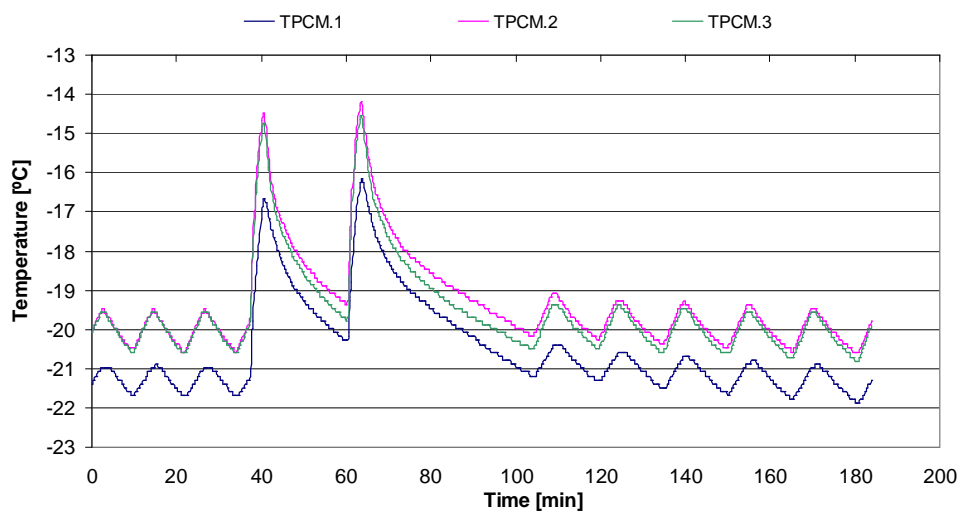


Fig. 122. PCM temperatures during test 1c without M-pack.

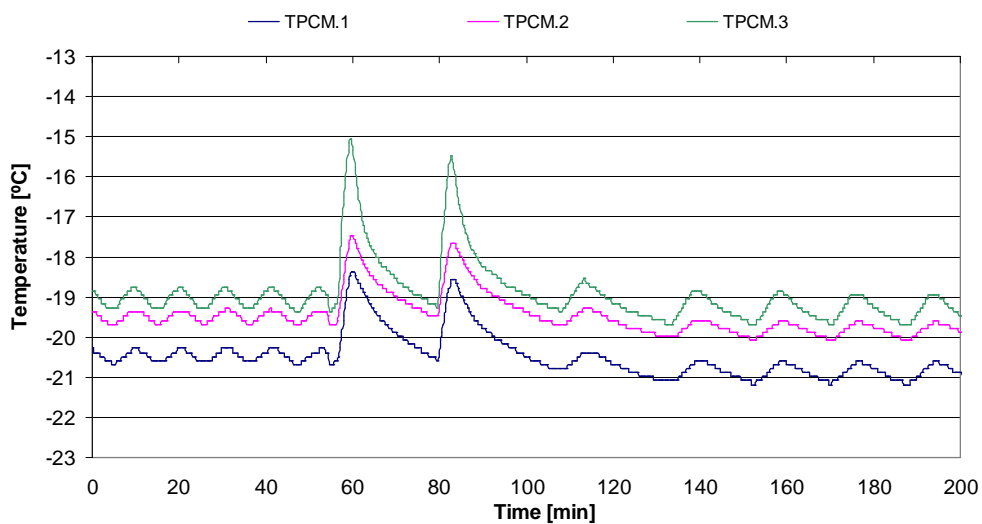


Fig. 123. PCM temperatures during test 1c with M-pack.

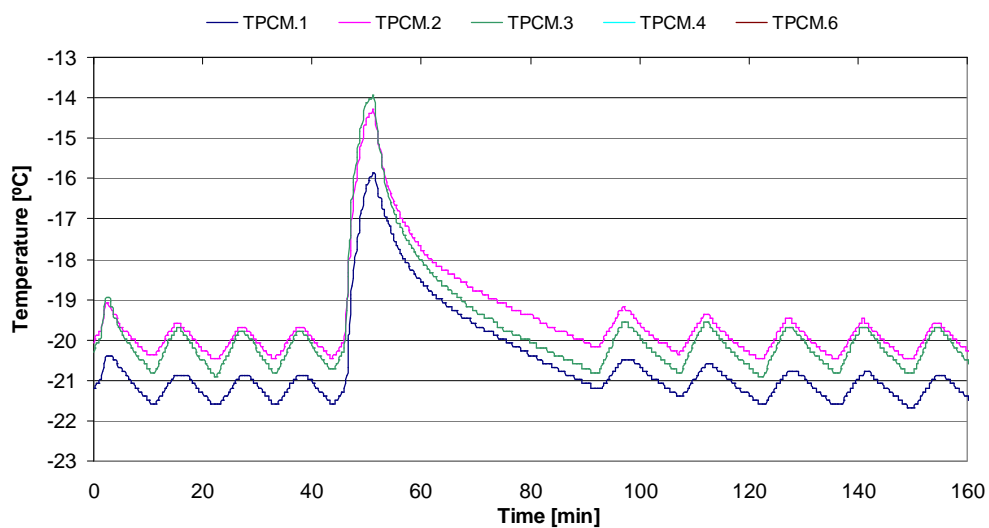


Fig. 124. PCM temperatures during test 1d without M-pack.

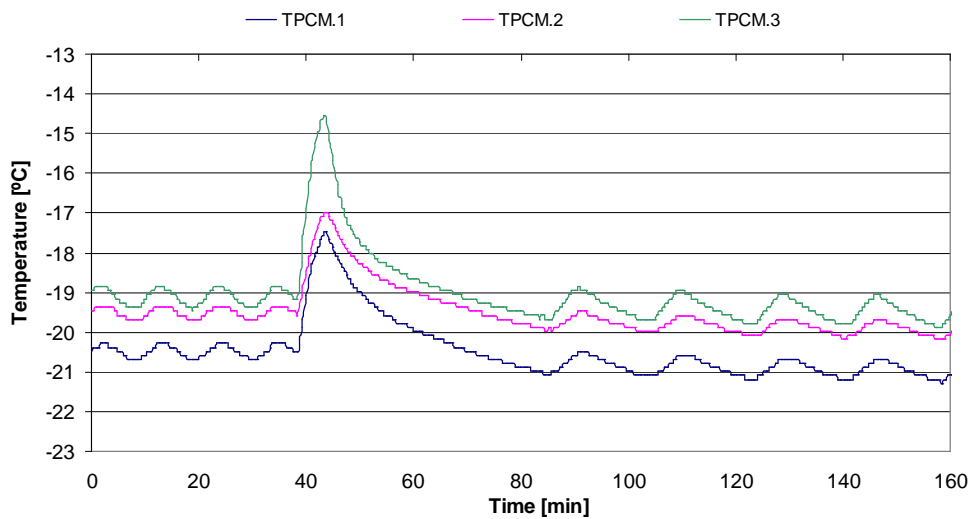


Fig. 125. PCM temperatures during test 1d with M-pack.

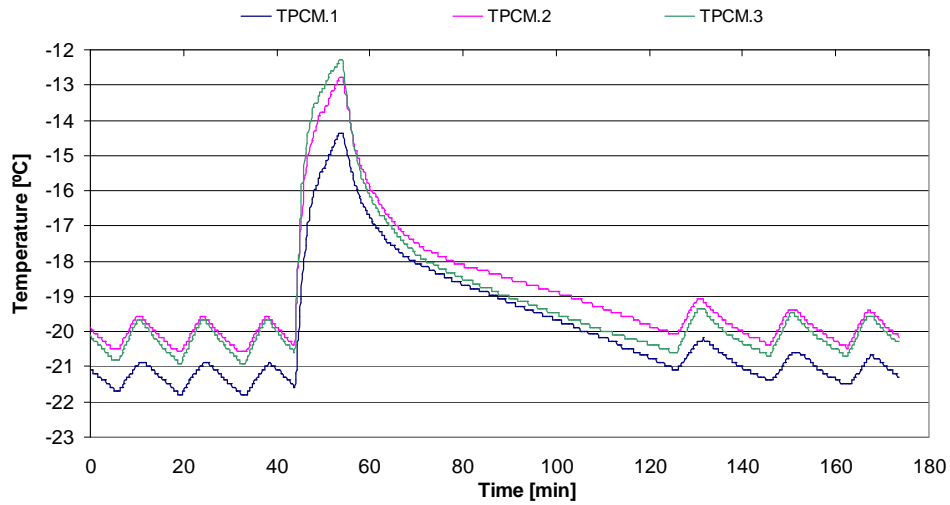


Fig. 126. PCM temperatures during test 1e without M-pack.

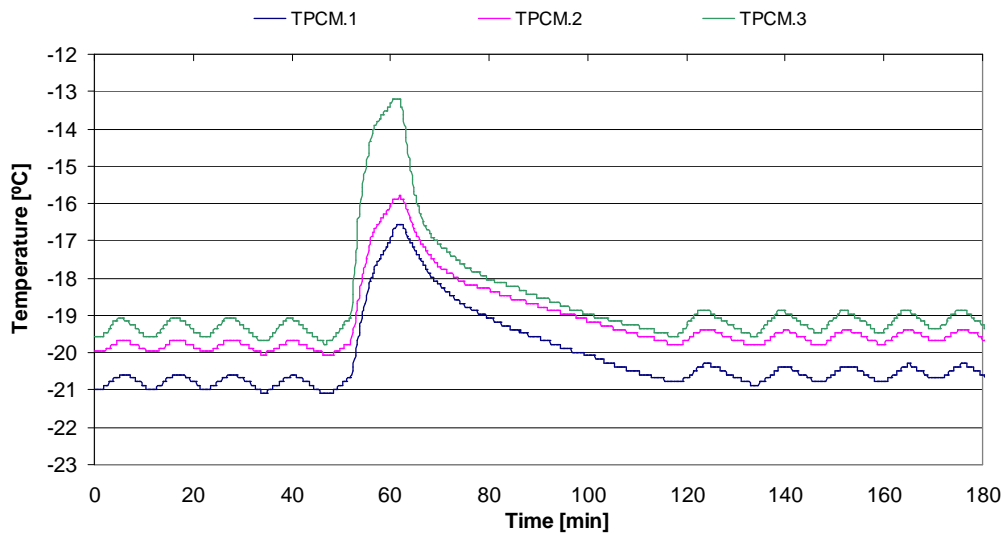


Fig. 127. PCM temperatures during test 1e with M-pack.

From Fig. 128 to Fig. 137 the PCM temperatures for all the experiments related to electrical power failure are shown. In tests 2a, 2b, and 2c the temperature of the PCM did not reach values of solidification temperatures. However, it is noticed that the temperature profile in all the cases changed; therefore solidification process started even the temperature of the PCM did not reach less than -18°C .

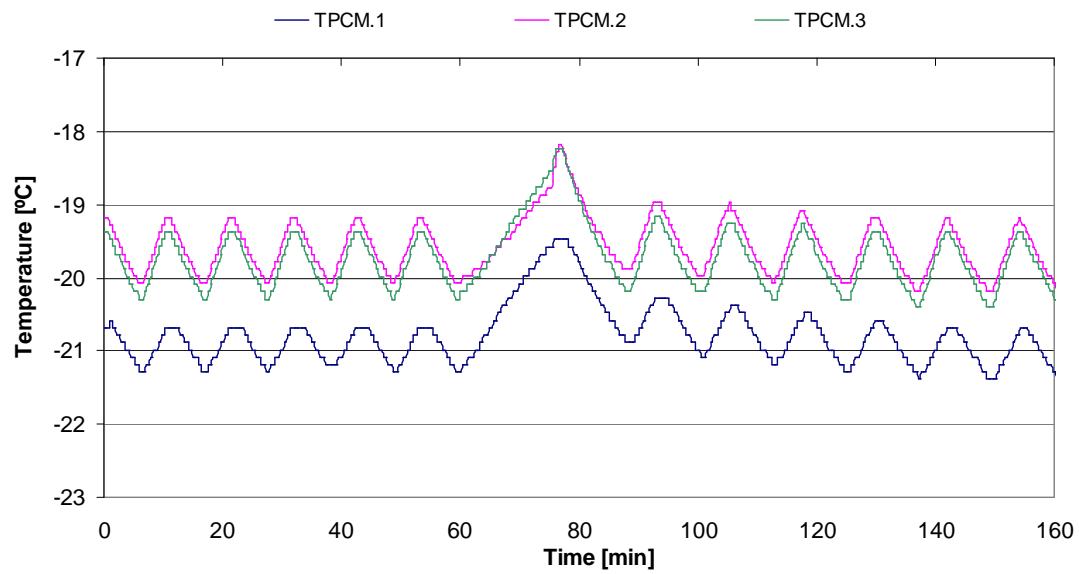


Fig. 128. PCM temperatures during test 2a without M-pack.

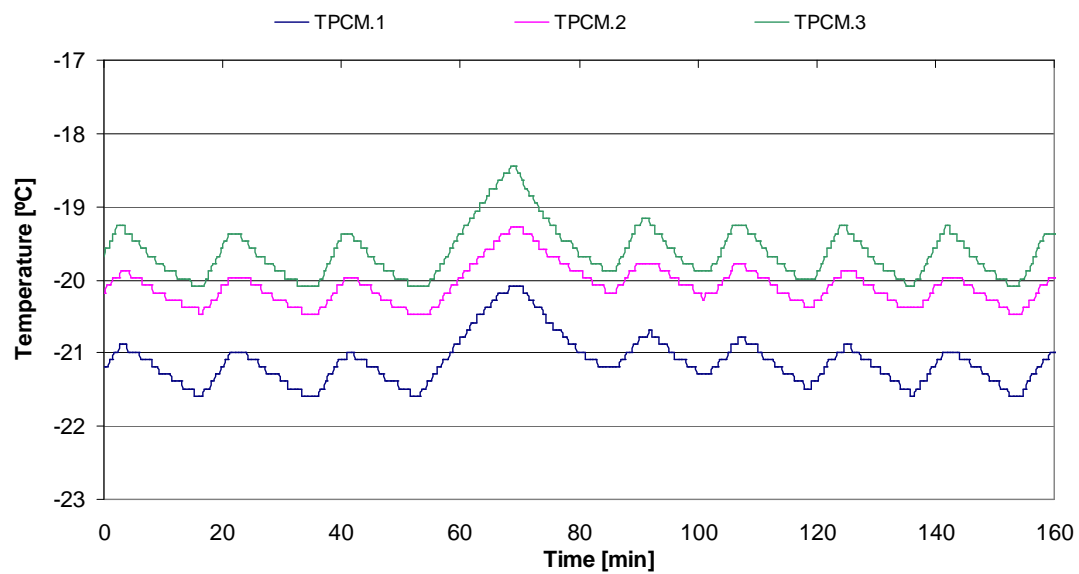


Fig. 129. PCM temperatures during test 2a with M-pack.

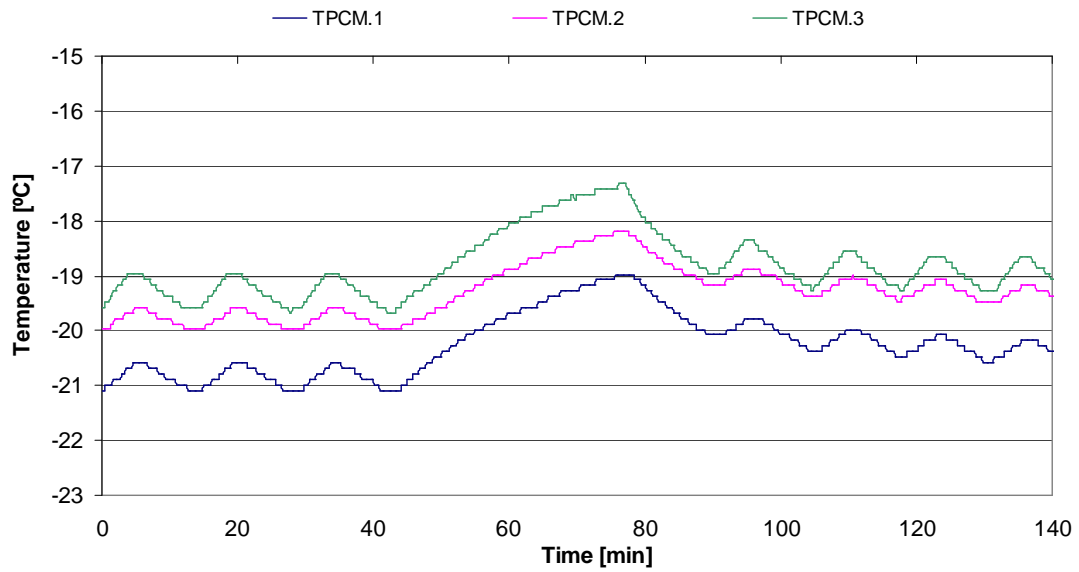


Fig. 130. PCM temperatures during test 2b without M-pack.

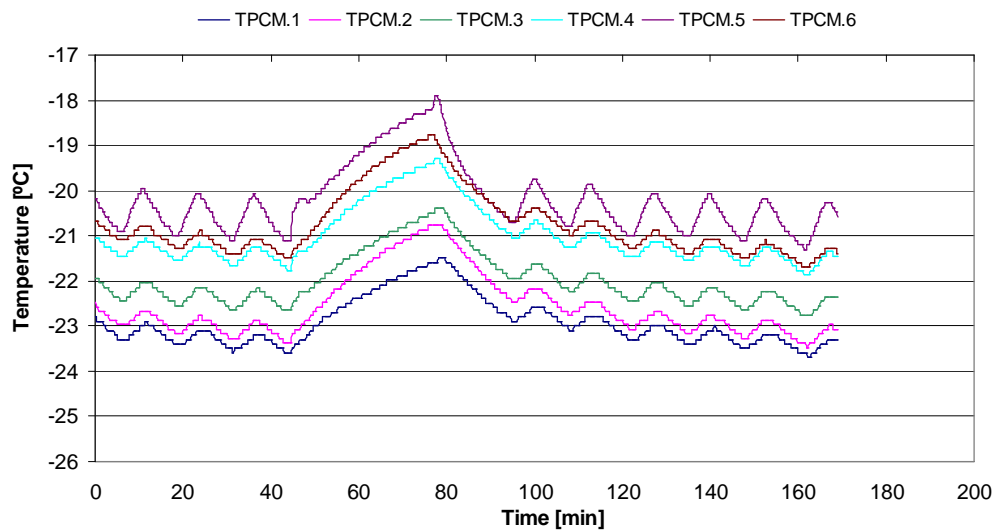


Fig. 131. PCM temperatures during test 2b with M-pack.

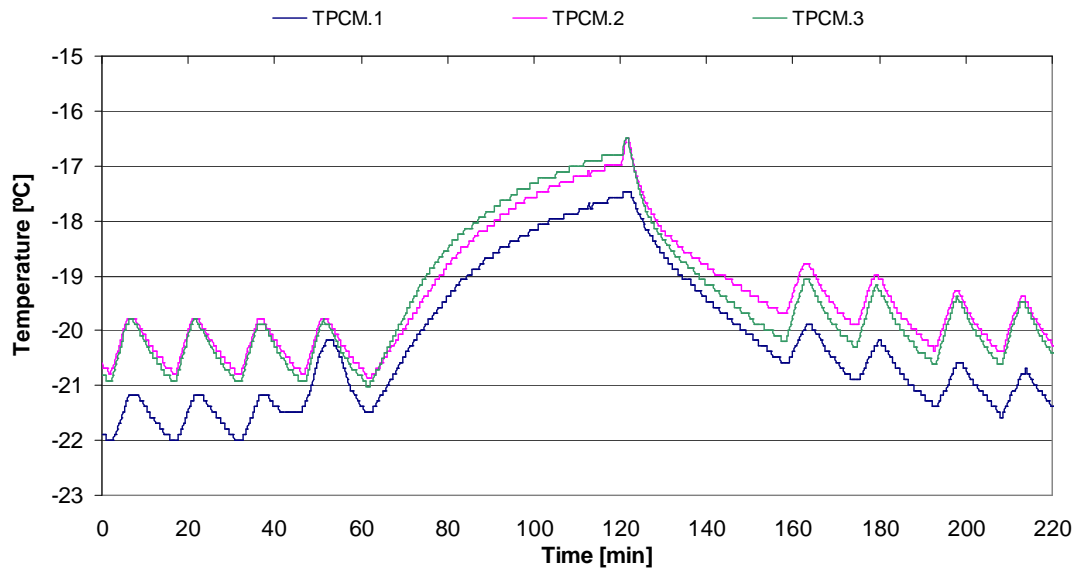


Fig. 132. PCM temperatures during test 2c without M-pack.

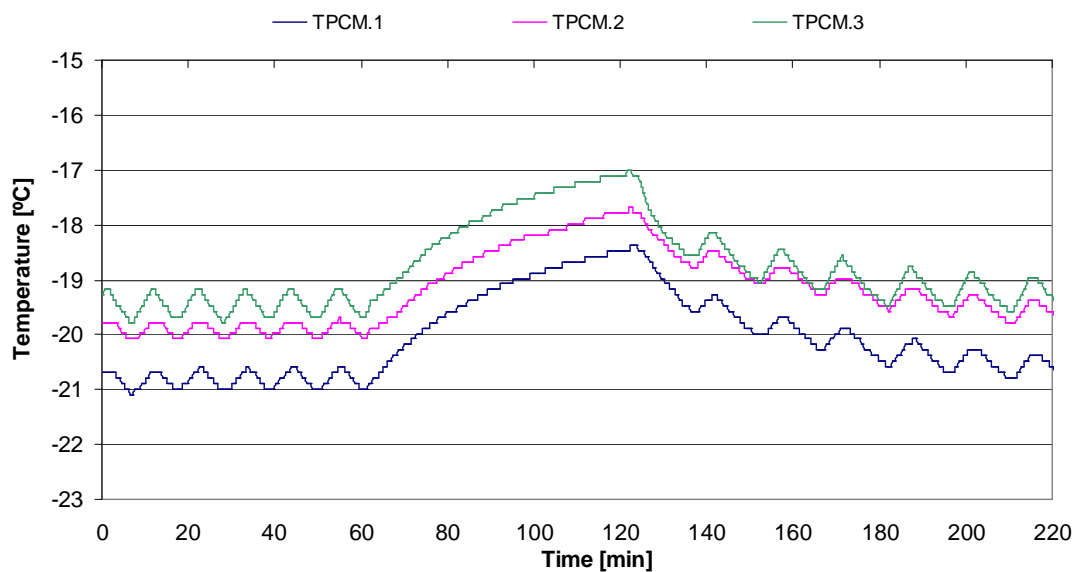


Fig. 133. PCM temperatures during test 2c with M-pack.

Fig. 134 and Fig. 135 show the temperature of the PCM during test 2d loaded and unloaded of M-pack respectively. In these tests, where 2 hours of electrical power failure occurs, it has detected initial phases of solidification. However there was not enough time to solidify the PCM.

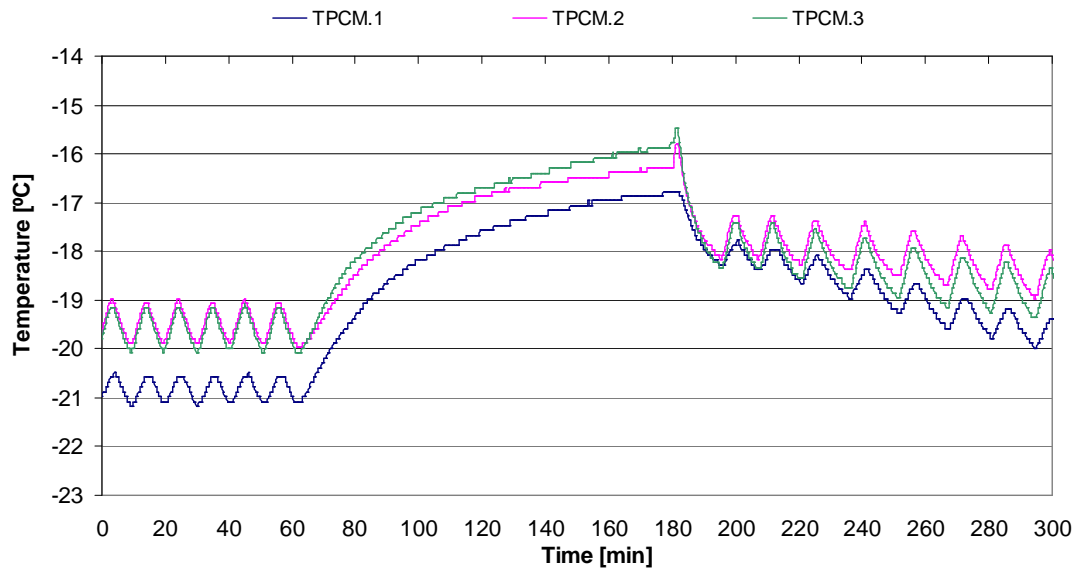


Fig. 134. PCM temperatures during test 2d without M-pack.

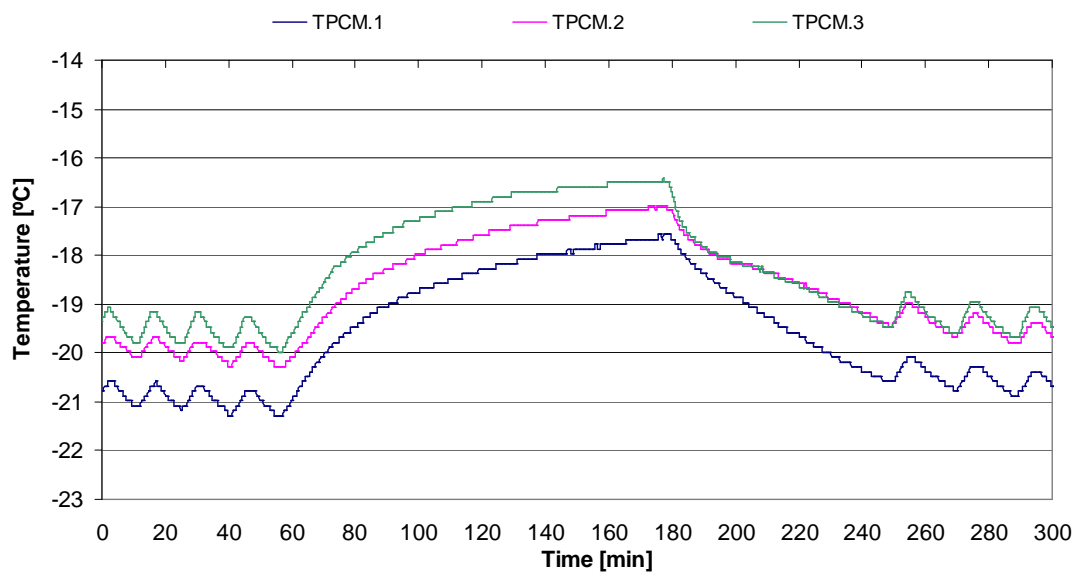


Fig. 135. PCM temperatures during test 2d with M-pack.

Fig. 136 and Fig. 137 show the temperature of the PCM during test 2e loaded and unloaded of M-pack respectively. The PCM during test 2e of unloaded M-pack started to melt but the PCM did not reach the melting temperature when the freezer was loaded with M-pack. The presence of M-pack (simulating food) add significant thermal mass that prevented solidification of the PCM, suggesting that a fully loaded freezer can

sustain for longer time a electrical power failure periods.

In test 2e without M-pack not all the PCM samples had the phase change at the same temperature. $T_{PCM.1}$, $T_{PCM.2}$, and $T_{PCM.3}$ had the phase change at the same temperature (near -18°C) but in $T_{PCM.4}$ and $T_{PCM.5}$ phase change occurred at -17.5°C , 1.5°C less than the others.

As there were no M-packs inside the freezer, these values can be taken as the real behaviour of the PCM due to the fact that the other values of the PCM temperature were influenced by the M-pack. Notice that when there was time available for the PCM to solidify (test 2d) the behaviour of the PCM was similar to this but there were no enough time. Therefore, the incorporation of M-pack inside the freezer influence in the PCM temperature due to the addition of thermal mass and preventing the solidification of the PCM.

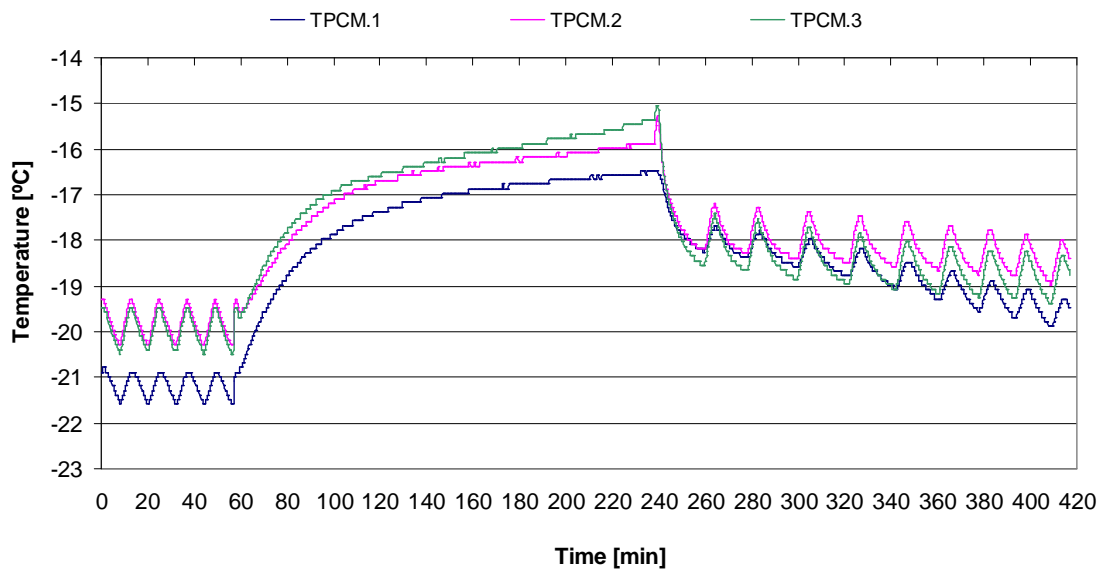


Fig. 136. PCM temperatures during test 2e without M-pack.

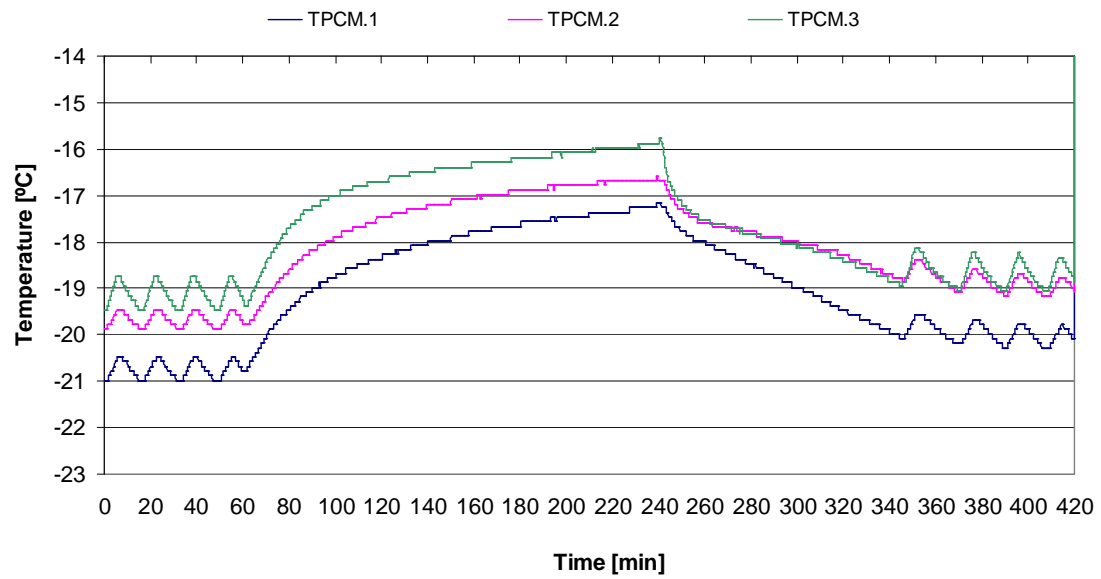


Fig. 137. PCM temperatures during test 2e with M-pack.