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Cold storage using phase change material in refrigerated display cabinets: experimental investigation

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ABSTRACT

Refrigerated display cabinets are the main energy consumers in supermarkets. Cold thermal energy storage (CTES) using phase change materials (PCM) can significantly reduce temperature variations in a display cabinet during loading of warm items, defrost cycles or power outages. This contributes to reduced loss in product quality and less food being wasted. With an increasing share of intermittent renewables in the power grid, PCM-enhanced systems benefit from low-cost electricity during periods with low demand. Stored excess cooling can be later used during periods with high demand. A CTES prototype was developed using water as PCM integrated in an evaporator. This system was experimentally compared to a reference case not using the PCM capabilities. The results show the potential for PCM-CTES to consistently keep the cabinet air temperature low, thus prolonging shelf life and product quality. Charged PCM-CTES systems provide cooling for several hours after the main evaporator is deactivated.

Keywords: Refrigerated Display Cabinet, Thermal Energy Storage, Cold Storage, Phase Change Material, Supermarket Refrigeration, Defrost Cycle.

1. INTRODUCTION

1.1. Background

Due to the increased awareness on the overall energy consumption of refrigeration technologies, interests arise towards the application of thermal energy storage in the refrigeration sector. The International Institute of Refrigeration (IIR) estimates that the refrigeration sector consumes approximately 17 % of the overall electricity used worldwide (Coulomb, et al., 2015). Especially in supermarkets, refrigerated display cabinets and cold rooms for food storage require 45 % of the overall electricity demand. Refrigerated display cabinets and freezers are among the most energy-demanding devices due to their continuous operation in supermarkets (Elarem, et al., 2017). Therefore, even minor performance enhancements may yield major energy savings.

The management of overall energy utilization can be improved by supplying additional cold energy during peak demand hours in a cost-effective way. The combination of a refrigeration unit with a CTES enables mitigating peak energy demands and handling large variable thermal loads for a limited cost (Jokiel, et al., 2019) (Sevault, et al., 2018). In addition, an. CTES systems with high heat transfer rates enable to benefit from intermediate cheap electricity for refrigeration and from the increasing share of intermittent renewables in the power grid. Stored excess cold from low demand periods can be later reutilized during high demand periods.

Decentralized TES systems integrated in supermarket refrigeration units can operate as short-term thermal batteries for smart grids, which enable using excess power from either local photovoltaic units or from the grid - in case of available low-cost power. CTES systems are an effective solution to decouple production of cold from immediate utilization, especially during temporal mismatches between energy production and demand.

In addition to reducing the maximum required effect of the refrigeration unit, this will enable more stable operation of the refrigeration unit and reduce operational costs (Gibb, 2018). In this case, the refrigeration unit can be dimensioned after the mean cooling demand, rather than after the peak demand, to further reduce

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investment costs. A more uniform supply of cooling to the system despite the, e.g., periodic defrost cycles, may also enable downsizing the evaporator units and the compressor, since maximum cooling peaks are decreased. The demand for refrigerant can similarly be reduced. Depending on the control strategies, the overall energy use can also be reduced in consequence.

However, the potential of CTES is still hardly exploited in the refrigeration industry, particularly in the supermarket sector, which often experiences large temperature fluctuations and varying thermal loads in the refrigerated display cabinets. Cabinets are continuously opened and closed, and after restocking of fresh goods, additional cooling or freezing is required. Large temperature fluctuations may affect both product lifetime and quality. Retailers claim that inefficient food storage or blackout situations due to power cuts account for 13 % of the total food waste in Norway, leading to both financial losses (2.76 billion NOK per year in 2017) and increased carbon footprints (ca. 150 ktons of $CO_{2,eq.}$ in 2017) (Stensgård, et al., 2018). The integration of cost-effective CTES into refrigerated display cabinets may yield significantly reduced amounts of food waste.

1.2. Objectives

The aim of this work is to experimentally investigate the integration of a PCM-CTES evaporator to improve the thermal performance of a refrigerated display cabinet during defrost cycles, door openings or power outages. A prototype PCM-CTES evaporator was designed and tested in a refrigerated display cabinet in the laboratory. This study constitutes a major novelty in the field of TES, as the literature on experimental results from PCM-CTES systems is rather scarce.

1.3. Literature review

Thermal energy is most commonly stored in the form of either sensible or latent heat (Fleischer, 2015). In a sensible heat storage, heat is stored by heating a medium with high specific heat capacity. In the case of latent heat storage, the phase change of a material is utilized in the form of the specific latent heat of fusion (i.e., melting or solidification) to store or release heat. An advantage of latent heat storage is the high energy density in comparison to sensible heat storage, resulting in particularly smaller storage volumes. For a given temperature range, the high latent heat of fusion may enable PCM storages to store up to 5 – 14 times more heat per unit volume than common sensible storage materials such as liquid water or rock (Sharma, et al., 2009), due to the high amount of latent heat absorbed or released during the phase change. In addition, PCMs experience only a small specific volume change (5 – 15 %) during melting or solidification at operating temperatures, which limits the mechanical stress inflicted on the storage unit (Fleischer, 2015).

The most typical challenge with PCM-based TES systems is their limited heat transfer rate (Groulx, 2018). This can be addressed either by developing new advanced PCMs or by optimizing the design of the heat exchanger. An available solution relies on PCM encapsulated in plastic boxes, stacked in a large container flooded with the working fluid (Gschwander, 2018). However, such solutions are reported to still yield insufficient heat transfer rates and perform under expectations. Current CTES solutions based on ice banks have generally insufficient heat transfer rates, limiting the opportunities to match cooling peak demands. Therefore, there is a need for designing more effective heat exchangers using PCM to store cold energy. In this context, the consideration of both phase change processes and changing thermodynamic properties during the phase change is of great importance. Designing an effective TES system accounting for the changing thermodynamic properties and the low thermal conductivity of commercial PCMs is a complex task but would ultimately allow for more efficient PCM-based storage systems. Previous results (Sevault, et al., 2018) showed that a variation of a few millimeters in the distance between the air ducts and CO_2 coils while dimensioning a PCM accumulator yields considerably different PCM charging and discharging times.

PCM-CTES have been reported for various low-temperature applications, such as for protection of food and beverages (Oró, et al., 2012), air conditioning (Al-Abidi, et al., 2012) or industrial refrigeration (Li, et al., 2013) (Veerakumar & Sreekumar, 2016). PCM-CTES were seen to increase the production capacity, while supporting environmental challenges by increasing the utilization of intermittent renewable energy sources.

Energy savings resulting from PCM integration in refrigerated display cabinets were reported in various studies (Alzuwaid, et al., 2015). Food losses caused by inefficient storage capacity will be greatly reduced when PCM storages are applied. This may lead to lower retail prices since retailers would not need to increase listed prices to cover for such losses. A numerical study in (Lu, et al., 2010) showed that a PCM-CTES unit integrated in

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the evaporator of a refrigerated display cabinet reduced the temperature fluctuations during defrosting cycles by 1 – 3 K. The cooling of refrigerated cabinets is switched off several times a day to avoid the building of ice on the surface of the evaporators, which are needed to cool down the circulating air. These periods without cooling are called defrost cycles. To minimize heat gain or cabinet temperature fluctuations caused by defrost cycles and evaporator outage, the number of defrost cycles should be kept to a minimum. PCMs can be utilized to mitigate the effect of defrost cycles and power outages on the goods temperature by dampening the consequent temperature fluctuations.

To counter the increase in temperature in refrigerated cabinets during defrost cycles or power outages, PCM-enhanced evaporators have been studied in Sevault et al. (2018) and Jokiel et al. (2019). The benefits of utilizing PCM were investigated using a dynamic modelling approach. It was shown that the defrosting process on the surface of a standard evaporator stands already as a CTES, even in systems without additional PCM storages. The application of additional PCM storages however helped to extend the CTES effect for longer periods. Similar results are reported in (Ben-Abdallah, et al., 2019), which evaluated the potential for load peak shifting using PCM storage in open display cabinets via experimental investigations. The experimental results showed significant potential for PCM to preserve a relatively low cabinet temperature during a compressor stop, damping the temperature rise for both cabinet air and food products.

In Coccia et al. (2019), a CTES is proposed to change the timing of end-use consumption from high electricity cost periods to low-cost periods. Cold thermal energy can be generated by electricity during off-peak times and is stored in the CTES. During peak-hours the stored cold is used to flatten the utility load profile. Results showed that, with an adequate application of demand side management, this application can lead to substantial economic savings. Taking advantage of the different electricity prices during peak and off-peak hours, results showed savings of up to 25 % of yearly electricity cost.

2. EXPERIMENTAL SETUP

A PCM-CTES evaporator prototype was manufactured at the laboratories of SINTEF Energy Research (Norway). The developed prototype is based on the preliminary concepts detailed in Sevault et al. (2018) and Jokiel et al. (2019). A commercially available refrigerated display cabinet was equipped with the PCM-CTES prototype. The cooling system keeps the food products' temperature within 2 – 4 °C using a controlled fan maintaining the air temperature below 2 °C and above 0 °C, to prevent freezing of the food products.

The PCM-CTES evaporator is integrated along the air circulation path of the refrigerated display cabinet, downstream from the standard evaporator (cf. Figure 11). To keep as much space as possible for the food products, the PCM-CTES evaporator should be sufficiently compact to be retrofitted in existing refrigerated displays, while offering high heat transfer rates with the circulating air.

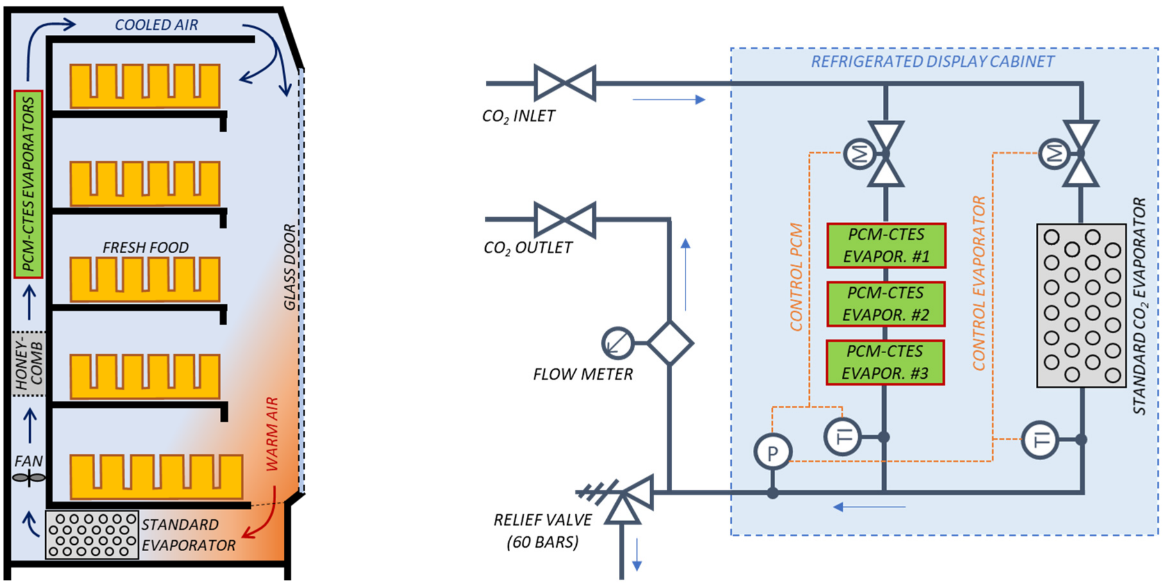

Figure 1: Schematic of a standard refrigerated display cabinet enhanced with a PCM-CTES evaporator (left) and corresponding CO_2 process diagram showing the three PCM cold storages in series (right)

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In addition to connecting the cabinet's standard evaporator to the main CO_2 cooling system, a parallel CO_2 connection for the newly implemented PCM-CTES prototype was set up, as depicted in **Error! Reference source not found.**1. The charge and discharge operations are controlled by the valves upstream from the standard evaporator and the PCM-CTES prototype made of three PCM-CTES evaporator units connected in series.

The numerical modelling results from a pre-study (Jokiel, et al., 2019) were used to dimension to PCM-CTES prototype evaporators and estimate the required amount of PCM. Considering typical defrost cycle durations, heat losses through cabinet walls and doors, and ambient air infiltrations through the cabinet doors, Jokiel at al. (2019) concluded that ca. 30 kg of ice (water) per meter (width) of display cabinet would be sufficient to cover the cooling load during a typical defrost cycle. In addition, the cooling effect from melting the ice film on the standard evaporator during defrost, as well as any subcooling effect from the sensible heat of PCM, result in an additional cooling capacity.

The PCM-CTES prototype relies on three fluids: pure water as phase change material, CO_2 as refrigerant, and recirculated cabinet air. Water is selected as the PCM due to low cost, adequate thermal properties, chemical stability, durability, easy availability and non-toxicity. Water is best suited for such applications as both the heat absorption and release occur at a nearly-constant temperature of 0 °C. This proves beneficial for providing chilled air slightly above 0 °C with a desired product temperature in a temperature range of 2 – 4 °C.

The PCM-CTES evaporator consists of copper coils for the refrigerant, surrounded by PCM, fitted in a stainless-steel container. The air circulates both around the PCM-CTES containers and through an air duct in the middle (cf. Figure 22) thanks to the hollow geometry of the containers. The prototype geometry was chosen to enhance the heat transfer area given the available space. While charging, the heat transfer takes place from the PCM to the refrigerant through the copper tube walls. While discharging, the heat transfer occurs from the air to the PCM through the container's stainless-steel walls. The refrigerated cabinet is 3-m wide and divided into three sections. In this study, experiments are run only in the middle section, which is isolated from the two side-sections to keep control over the heat losses and circulating air during the tests (cf. Figure). Furthermore, a honeycomb structure was set up downstream from the air fan to homogenize the airflow before reaching the PCM-CTES evaporators. Three PCM-CTES containers were installed in the back of the middle section of the cabinet (cf. Figure), filled with approximately 11 liters of water per container. The geometry allows for water upward expansion during solidification, without risks for water leakages or damaging the containers.

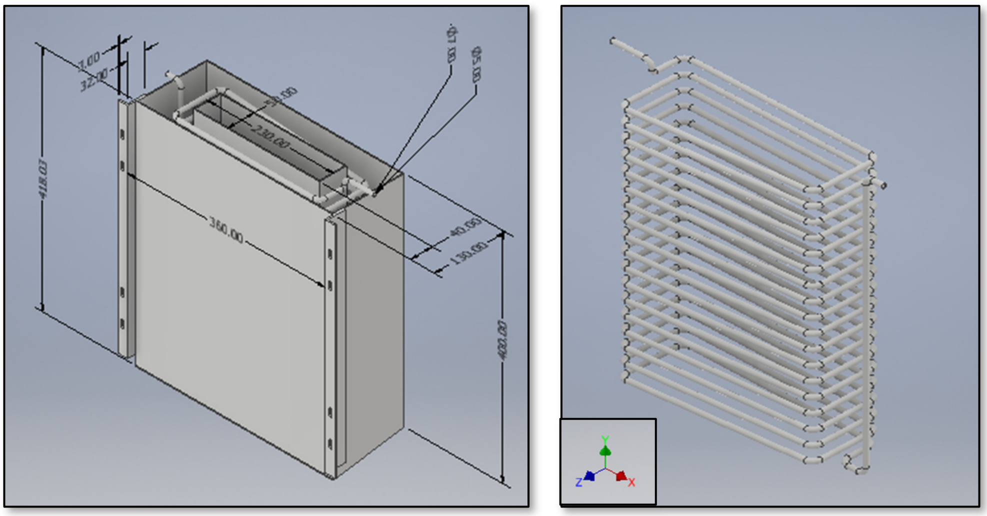

Figure 2: PCM-CTES evaporator prototype (left) and refrigerant coil without the container (right)

3. EXPERIMENTAL RESULTS AND DISCUSSION

Experimental tests were carried out with an empty display cabinet (no food products, neither shelves), with a measured volume flow for air recirculation of 0.25 m^3/s, at a CO_2 evaporation pressure of 28 bar, resulting in a refrigeration CO_2 temperature of -8 °C. The measurements were conducted as a 24-h thermal response test

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to record the air temperature increase due to heat losses through the cabinet walls (i.e., mainly through the glass doors and the cabinet top plate). These measurements are then used as a rough estimate of the heat contribution through infiltration of warm ambient air and through heat losses of the light sources. The results can also contribute to feed or validate numerical simulations by observing the thermal response of the system.

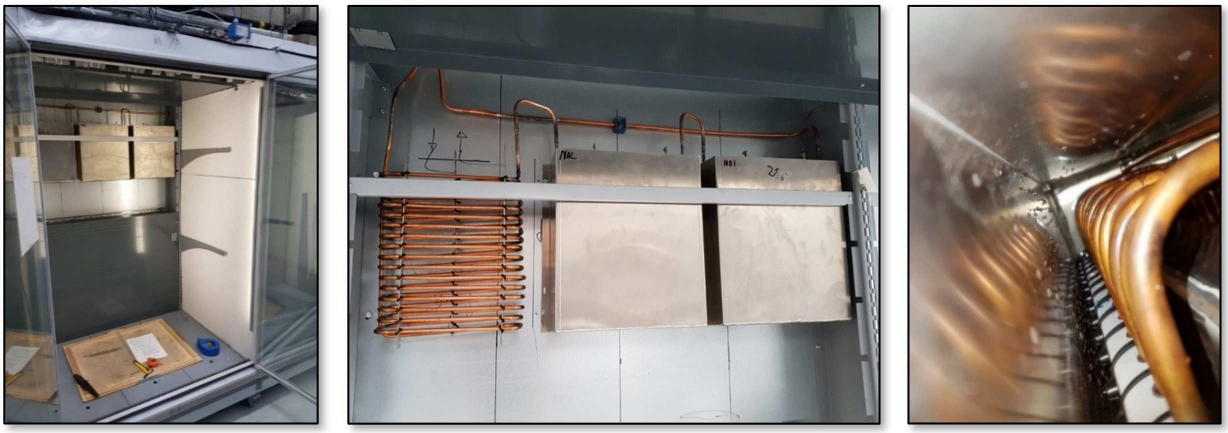

Figure 3: Isolated middle section of a standard supermarket refrigerated display cabinet with three PCM-CTES containers, without wall panel between PCM-CTES containers and shelves (left); build-up of the PCM-CTES evaporator prototype (center) and refrigerant coil inside the PCM-CTES container (right).

3.1. Cases "Reference" vs. "Active PCM-CTES evaporator"

In the first measurements series, two operation modes are compared with an ambient temperature of ca. 22 – 25 °C. For the "Reference" case, only the standard CO_2 evaporator, in the lower part of the cabinet, is used to cool down both the cabinet and the PCM through the circulating cold air. In this case, the added refrigerant coil in the PCM-CTES prototype is not used, and the PCM-CTES evaporator simply serves as a passive cold storage. For the case "Active PCM-CTES evaporator", both the standard CO_2 evaporator and the PCM-CTES evaporator in the back of the cabinet are actively used to cool down the cabinet and freeze the PCM.

The results in Figure 4 show the average PCM temperature for cases "Reference" and "Active PCM-CTES evaporator". The depicted PCM temperature was averaged from 34 thermocouples inside the PCM-CTES CO_2 evaporator. Figure 5 shows the corresponding PCM temperatures for each thermocouple. In the "Reference" case, only 3 thermocouples show PCM subcooling effects, while the remaining values stagnate around 0 °C, indicating that only partial freezing of the PCM occurred during the tests.

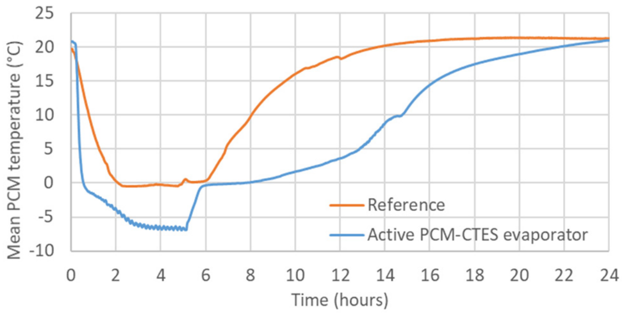

Figure 4: Averaged PCM temperature from 34 thermocouples inside the PCM-CTES evaporator

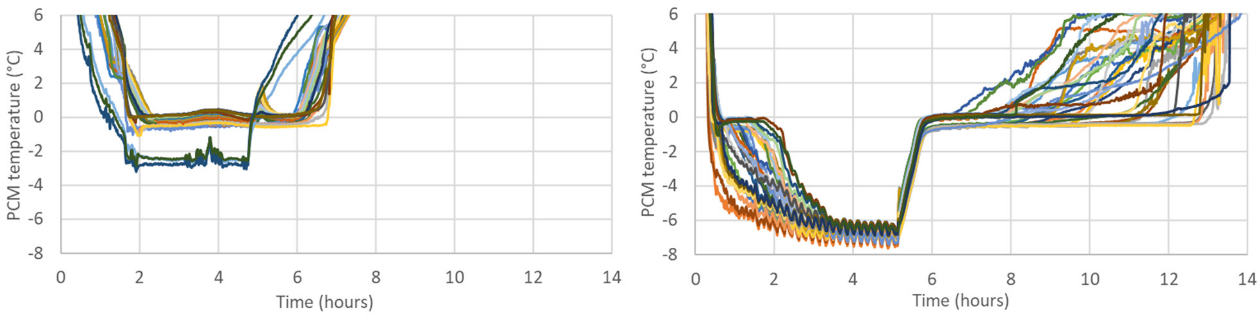

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Figure 5: Measured PCM temperature in the PCM-CTES evaporator (34 thermocouples) for the "Reference" case (left) and case "Active PCM-CTES evaporator" (right); cut-off in cooling duty after 5 h

It is shown in both Figure 4 and Figure 5 that the usage of the second CO_2 evaporator in the back of the cabinet enables a quicker and more thorough freezing and subcooling of the PCM. As a result, an implementation of a PCM storage that lacks an additional coil for refrigerant flow would lead to greatly increased freezing time, which compromises the overall dynamic storage capabilities for the PCM-CTES solution. The integration of PCM into a CO_2 evaporator is therefore concluded as the optimal solution for the best performance and flexibility, especially during highly dynamic operations of the refrigerated display cabinet.

3.2. Impact on the cabinet air temperature

Figure 6 shows the measured increase in cabinet air temperature after the cut-off in cooling duty and compares a reference case with the PCM-CTES only cooled by the standard evaporator (PCM not fully frozen), with a case with a fully charged PCM-CTES. The steady-state temperature for the cabinet air in the measurements was lower than in actual supermarkets: -3.5 °C instead of 2 – 4 °C). This is due to (1) the cooling duty which was regulated with a simple on/off-operation mode for the CO_2-valves to greatly speed up the PCM charging process; (2) the fan was also constantly "on", instead of being regulated to hold the air temperature between 2 and 4 °C in the cabinet; (3) if the cabinet was not empty, the thermal mass of the food products would help keep the air temperature higher over a longer time. Due to the CO_2 temperature of - 8 °C, the resulted steady-state temperature for the air in the empty cabinet was below zero, as visible at $t = 0$ s in Figure **6**.

In the "Reference" case, the air temperature quickly increases after the cut-off of cooling duty at $t = 0$ s (cf. Figure **6**6), due to a limited heat transfer from the PCM latent heat to the circulating air. Based on the gradient of temperature increase in the "Reference" case, the heat loss for the cabinet with a ca. 2-m^3 compartment volume was estimated to be up to 5 kW, especially within the first 2 h after the cut-off in cooling duty.

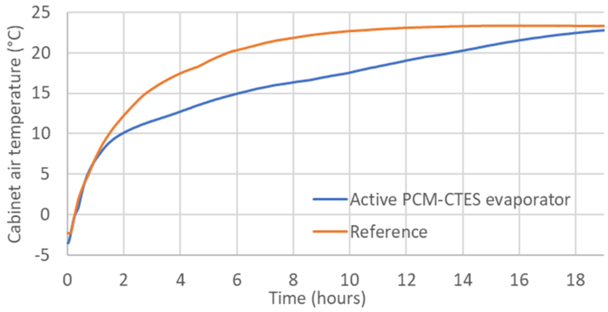

Figure 6: Cabinet air temperature measured in the middle of the cabinet after the cooling duty cut-off at *t* = 0 s

On the other hand, in case "Active PCM-CTES evaporator", the PCM successfully helps maintain a lower cabinet air temperature. For the "Reference" case, a temperature as high as 20 °C is already reached after 5.5 h, though not before 13.5 h in the case "Active PCM-CTES evaporator". The cabinet air temperature reached 15 °C in the case "Active PCM-CTES evaporator", instead of 2.5 h in the "Reference" case. However, the increase in temperature for the first hour was rather similar for both cases, whereas mitigating that sudden increase in temperature be the most needed effect during defrost cycles or power cut-offscase "Active PCM-CTES evaporator" the PCM-CTES prototype provides an increased cooling effect for the cabinet in comparison to the "Reference" case. However, it is rather underperforming with regards to keeping the cabinet air temperature under the crucial threshold of 4 °C to ensure a sustainable storage of food products. The effect of released latent heat is not visible in the initial phase after the cut-off in cooling duty. This could be explained by the limited heat transfer rates: even though frozen PCM is still available up to 8 h after the cooling duty cut-off (as seen in Figure 5 - right), the limited heat transfer area between PCM and cabinet air, as well as the low thermal conductivity of the PCM, hinders a higher cooling potential for the cabinet air. The design of the PCM-CTES prototype can be substantially improved to face these challenges.

3.3. Case: " Door Openings"

Figure 7 shows the temperature measurements for the case "Door Openings". During the first 5 h, the refrigerated display cabinet was chilled, only using the standard CO_2 evaporator, while the PCM-CTES evaporator prototype was not actively in use. After 2.5 Approximately 5 h after the start of the measurements, the cooling duty was completely cut off and the doors were opened again. After 5 min, the doors were closed

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and a quasi-steady state was reached with a cabinet air temperature of 7 °C. Then, only the PCM-CTES CO_2 evaporator was actively used to provide cooling to the cabinet. That way, the potential for quick-freezing the PCM without major feeding of sub-zero air into the cabinet could be investigated. However, a very similar effect in subcooling of the overall cabinet air can be observed both at 2 h and 5 h in Figure 7 for the two door-opening events. This illustrates the challenge to use a PCM cold storage with a freezing temperature of 0 °C, since there is a need for sub-zero refrigerant temperatures resulting in an increased risk for subfreezing the cabinet air as well.

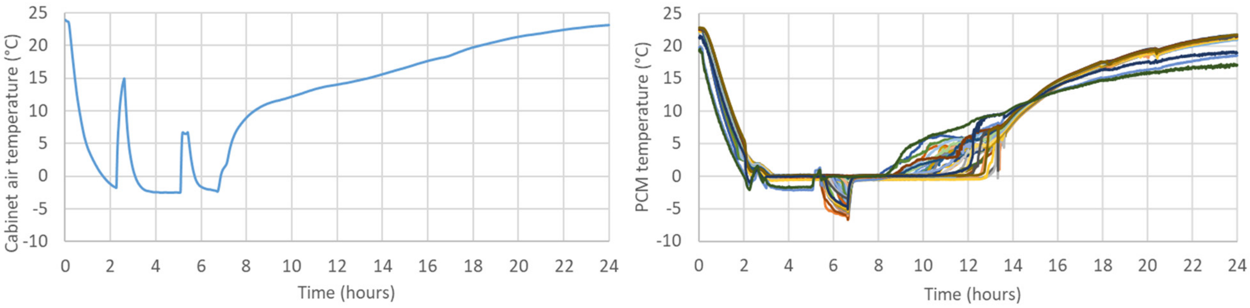

Figure 7: Cabinet air temperature and PCM temperature for case "Door Openings": the cabinet door was opened for 10 and 5 min, both after ~2 h, respectively, after the start of measurement recording

4. CONCLUSIONS

An experimental prototype of CO_2 evaporator was designed to implement affordable and effectively integrated CTES technologies based on PCM in refrigerated cabinets. PCM-CTES yields a more uniform cooling supply and helps counter temperature increases in the cabinet during door openings, defrost cycles or power outages. They would allow for downsizing standard evaporators and compressors, since maximum cooling peaks are decreased, and thus reduce both operational and investment costs, enabling a more sustainable supermarkets.

display cabinet equipped with PCM-CTES was able to provide an increased cooling effect for the cabinet during cooling cut-offs, in comparison to standard display cabinets without active PCM-CTES. However, the display cabinet with active PCM-CTES was rather underperforming with regard of keeping the cabinet air temperature sufficiently low over a long period to ensure a sustainable storage of refrigerated goods. The effect of released latent heat was not visible in the initial phase after the cut-off in cooling duty, leading to a decreased potential for efficient food storage for the current PCM-CTES setup, even though frozen PCM was still available up to 8 h after the cut-off in cooling duty. This is due to the limited heat transfer rates between the PCM and the circulating air, both because of the limited heat transfer area between PCM and cabinet air and the relatively low thermal conductivity of the PCM.

The measurement results led to two main conclusions for the current design of PCM-CTES prototype: (1) the current PCM-CTES CO_2 evaporator provides lower cooling effects from the frozen PCM than expected; (2) the process of freezing the PCM resulted in an increased risk for subcooling of cabinet air, therefore risking partial freezing of stored food products. Therefore, a refined PCM-CTES unit should consider improvements regarding increasedfor optimum utilization of the stored cold energy. The addition of metallic fins on both the storage interior and exterior walls would certainly increase the heat transfer rates from the melting PCM towards the cabinet air sooner after a cut-off in cooling duty.

Further research with the experimental setup will include the following considerations:

- Experimental tests should eventually be carried out with the display cabinet filled up with food products. The increased thermal mass in the cabinet can also mitigate the quick thermal response characteristics that were observed in the current experimental results with an empty display cabinet.
- A general increase in evaporator pressure from currently 28 bar (-8 °C) will, on the one hand, increase both the CO_2 supply temperature closer to 0 °C and, thus, the charging time for the PCM-CTES unit. On the other hand, it will significantly lower the risk for subcooling the cabinet air and, thus, prevent potential damage of the stored goods.
- Another PCM providing a freezing point at around 2 °C might be an alternative solution to reduce the risk

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of subcooling stored goods while charging the PCM-CTES unit.

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