

Copolymer-bound phase change materials for household refrigerating appliances: Reduction of power consumption and demand side management

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Abstract

This study evaluates the influence of latent thermal heat storage elements on the evaporator and condenser temperatures as well as the energy performance of commercial household refrigerators. Two evaporator types and a standard wire-and-tube condenser are equipped with copolymer-bound phase change materials (PCM) and temperature distributions as well as power consumption are determined under standard conditions. The results show that the use of PCM increases the evaporator temperature and considerably decreases the condenser temperature such that power consumption is significantly reduced. Furthermore, refrigerating appliances equipped with PCM can be optimized through modifications of the control strategy to achieve two other targets: a) Temperature fluctuations in the refrigerator's fresh-food compartment during the cooling cycle can be reduced from 4°C to 0.5°C. b) The cooling cycle duration can be tripled without compromising the fresh-food compartment conditions. The latter may help to meet the growing demand for balancing power consumption to stabilize the power grid, e.g. if the share of highly fluctuating, sustainable energy supply is large.

Highlights

- Heat storage elements significantly increase evaporator and decrease condenser temperatures of refrigerators.
- Higher evaporator and lower condenser temperatures decrease power consumption.
- Reduced temperature fluctuation or demand side management may be achieved through modifications of the control strategy.

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- Copolymer-bound PCM for condenser and evaporator are dimensionally stable and leak proof.

Keywords

Household refrigerator, Power consumption, Thermal storage, Phase change material, Demand side management

Nomenclature

h	specific enthalpy (kJ kg^{-1})
T	Temperature (K)
λ	thermal conductivity ($\text{W m}^{-1} \text{K}^{-1}$)
ω	mass fraction (g g^{-1})

1. Introduction

Despite the fact that power consumption of a single household refrigerating appliance seems to be low, the energy saving potential of the entire fleet is significant due to its almost complete market penetration and its typical all-year runtime. On average, 13.4% of the power consumption of private households in the OECD member states is caused by cooling and freezing of food (IEA, 2003). In Germany, that share is 20%, which corresponds to about 7% of the overall national power consumption (Barthel et al., 2005). In recent years, the power consumption of household refrigerators and freezers was substantially reduced, where the major driver was the labelling of energy efficiency that became mandatory in many countries. Power efficiency has thus become a decisive criterion for consumers when purchasing new household equipment (Faber et al., 2007). Lower power consumption can be achieved by reducing the refrigeration load or by optimizing the refrigeration process. The according technical measures can be summarized in three categories:

- 1) *Enhanced insulation*: By replacing polystyrene, which was a common insulation well into the 1980ies, with polyurethane foam, which has become standard today, the refrigeration load was reduced by about 30%. However, increasing the insulation thickness is not an option due to the resulting reduction of cooling volume capacity, given that standards for equipment dimensions are defined. A further significant reduction of the refrigeration load can be achieved through the extensive use of vacuum insulated panels (VIP).

However, their high costs are an argument against the introduction of VIP in this price-sensitive segment (Philipp, 2002).

- 2) *Speed-controlled compressors*: Household refrigerators and freezers are usually operating intermittently through a simple on/off-control. The application of speed-controlled compressors would enable for a transition to a sustained operation. This would decrease friction and throttling losses in the compressor, increase the evaporator temperature and decrease the condenser temperature, avoid shifting of the refrigerant due to pressure equilibration during standstill and result in a reduction of power consumption by up to 30% (Binneberg et al., 2002). However, also in this case, substantially higher costs impede the use of speed-controlled compressors in simple household refrigerators.
- 3) *Optimized heat transfer at evaporator and condenser*: The maximum efficiency of refrigeration processes is determined by the temperature of evaporator and condenser. Increasing the evaporator temperature by 1 °C typically leads to a reduction of power consumption of 3-4%, decreasing the condenser temperature by 1°C reduces power consumption by 2-3% (Dalkilic and Wongwises, 2010). In the most basic case, this can be achieved by larger condenser and evaporator surface areas. E.g., surfaces that are enlarged by 50% reduce power consumption by about 10% and 6%, respectively (DKV, 1985). Ventilators also enhance convective heat transfer, however, their own power consumption must be taken into account (Roth, 2008).

The latent heat storage elements studied in this work belong to the third category. Phase change materials (PCM) can absorb large amounts of heat at almost constant temperature and are thus particularly well suited for heat storage. By implementing PCM, temperature fluctuations were reduced successfully in a variety of applications, e.g. transport boxes for sensitive goods or heat sinks for electronic devices (Mehling and Cabeza, 2008). The integration of PCM in cooling devices has been a matter of scientific analysis for many years now. In 1989, Onyejekwe (1989) installed a simple latent heat accumulator based on an eutectic NaCl/H₂O mixture in a cooling device. Wang et al. (2007a,b,c) examined the influence of PCM at various locations in the cooling system, i.e. between the compressor and condenser, and were able to raise their prototype's efficiency by 6-8%. A direct connection of a PCM-layer to the evaporator of a household refrigerating appliance allowed Azzouz et al. (2008, 2009) to achieve a 10 to 15% increase of the coefficient of performance (COP) through a higher evaporator temperature and a considerable reduction of the on/off switch control frequency. In addition to the increase of energy efficiency via encapsulated PCM in an industrial device, Cheralathan et al. (2007) were able to prove the

potential of charge shifting into cost-effective power night-rates. Through the integration of PCM panels into a household freezer, [Gin and Farid \(2010\)](#) found an improved storage quality due to the temperature stabilization and a lower power consumption during defrosting cycles and door openings ([Gin et al., 2010](#)).

Refrigeration devices with latent heat storages are well suited for future Demand Side Management (DSM) concepts, because their compressor off-time can be considerably longer and also can be varied. DSM in general refers to the specific control of power use in order to meet a fluctuating power supply, which is crucial when the share of renewable energy is growing ([Kohler et al., 2010](#)). E.g., [Bagriyanik and Zehir \(2012\)](#) demonstrated even for customary refrigerators that a large fraction of their power demand can be displaced in time, where this effect can be boosted significantly with the use of PCM.

The heat discharge to the environment via the condenser of most household refrigerating appliances is based on free convection and radiation, which results in a moderate heat flux. Their intermittent operational mode with a typical on/off-relation of about 1:2 thus results in comparatively high condenser temperatures during compressor runtime. Lowering the temperature of the condenser during the runtime of the compressor and a partial shift of the heat discharge into the downtime of the compressor has the potential for considerable improvement. For this purpose, [Marchi Neto et al. \(2009\)](#) experimentally studied a liquid water storage with a volume of 122 l, which is hardly feasible in practice.

In the past, refrigerator manufacturers also attempted to integrate PCM into their appliances. However, problems like volume expansion upon temperature variation and particularly PCM leakage protection were impeding practical implementation. Recent successes in producing dimensionally stable, polymer-bound PCM seem to be promising for solving these problems. [Chen et al. \(2011\)](#) were able to reduce the power consumption of a refrigerator/freezer combination with a paraffin-polyethylene compound on their integrated, i.e. foamed, condenser by almost 12%. However, in Europe and Asia mainly wire-and-tube or plate-and-tube condensers are employed, which allow for a considerably better heat transfer because of their larger surface area even under installation conditions ([Bansal und Chin, 2003](#)). Due to the direct access to the condenser on the backside of the appliance, leakage protection of the PCM elements is of vital importance in the long term.

In a previous study ([Sonnenrein et al., 2015](#)), we were able to reduce the power consumption by about 10% through an installation of a newly developed copolymer-

bound PCM into a standard wire-and-tube condenser. It was shown that power consumption can be reduced in a defined manner by variation of condenser's PCM loading. The present study presents the results of experimental work with copolymer-bound PCM attached to different evaporator types to investigate the power consumption and the temperature distribution in the fresh-food compartment with respect to their potential for future DSM concepts.

2. Methodology

All manufacturers must specify the power consumption of household refrigerators and freezers since the directive 94/2/EG came into force. Since 2014 in European countries, the respective power consumption measurements are regulated by the norm DIN EN 62552, according to which the present study was carried out. Details on the test methods and conditions are given in DIN EN 62552, which are mostly congruent with the preceding norm DIN EN ISO 153 in accordance with DIN EN ISO 15502.

3. Test setup

3.1. Refrigerating appliances

The present work is based on a free-standing refrigerator of type Miele K-12020S-1 with a volume capacity of 163 l and a power consumption of 123 kWh/a (energy efficiency class A+) and fully integrated built-in type Miele K-32122i with a volume capacity of 151 l and a power consumption of 98 kWh/a (energy efficiency class A++). K-12020S-1 has a meander-shaped, foamed evaporator (see Fig. 1) and a plate-and-tube condenser. K-32122i has a free hanging rollbond evaporator and a wire-and-tube condenser.

3.2. Heat storage materials

High-capacitive, form-stable latent heat storage elements based on block copolymer-bound organic paraffin derivatives were developed in this study. They were integrated in evaporators and condensers and examined with respect to their influence on performance and power consumption. Fig. 2 shows the temperature dependence of the specific enthalpy h of the compound developed for the evaporator in comparison to a typical salt-water mixture based test-package composition according to DIN EN 62552. Measurements were done with Differential Scanning

Calorimetry (DSC, SETARAM TG-DSC 111) and also with a heat flow three-layer calorimeter (W&A, WOTKA), developed specifically for analyzing PCM. The latter allows for a considerably larger sample quantity than commercial DSC devices and therefore yields the phase change temperature more precisely. The specific enthalpy h of the compound in the temperature range of from -15 °C to 5 °C is approximately 200 kJ/kg and thus has only about $2/3$ to $3/4$ of the storage capacity of typical salt-water-based approaches. However, Fig. 2 demonstrates the main problem when integrating salt-water solutions, particularly on the evaporator: The sub-cooling necessary for initiating solidification, thus the difference between melting and freezing temperature, is typically between 5 and 10 °C . By comparison, the present paraffin derivative shows no significant sub-cooling. In this case, the temperature of the evaporator, where the PCM undergoes solidification, can be higher, which is crucial for performance increase. An additional advantage of polymerization is form-stability of the PCM elements. Moreover, it avoids leaking of the PCM in its “liquid” state so that macro-encapsulation is not necessary. Finally, the thermal conductivity of the PCM of $\lambda = 0.19\text{ W/(m K)}$ was increased by adding a specific graphite (THERMOPHIT GFG, SGL GROUP), depending on its mass fraction ω by up to a factor of 20 to $\lambda = 3.95\text{ W/(m K)}$ for $\omega \approx 0.3\text{ g/g}$. Details on the compound integrated in the condenser are given in our previous study ([Sonnenrein et al., 2015](#)).

3.3. Measurement of temperatures and power consumption

The test setup and all executed measurement procedures were in accordance with the norms DIN EN 153 and DIN EN ISO 15502 under standard conditions. Temperature sampling was performed by thermocouple differential measurements, each against a reference per measuring point in a mixture of ice and water. The utilized acquisition interface OMB-DAQ 55/56 (Omega Technologies) was combined with a pre-amplifier LTC1049 (Linear Technologies), which limits the offset conditioned by zero-point drift to $\pm 0.025\text{ K}$. The typical error of thermo-elements of $\pm 1\% \times \Delta T$ in other work was reduced to $\pm 0.5\% \times \Delta T$ by batch consistency and polynomial calibration. For determining the power consumption under standard conditions (average temperature of the fresh-food compartment $T_m = 5\text{ °C}$, ambient temperature $T_a = 25\text{ °C}$ and humidity 50%), energy meters type EZI 1 (Zimmer Electronic Systems) with 25 pulses/Wh were used, leading to a relative measurement error of about $<1\%$.

4. Results and discussion

Experimental tests with copolymer-bound PCM attached to two different evaporator types and a standard wire-and-tube condenser were carried out to investigate the power consumption and the temperature distribution in the fresh-food compartment. The aim of this work was to improve the energy efficiency as well as to study the potential for future DSM concepts without compromising the fresh-food compartment conditions.

4.1. Temperature distribution and power consumption

The influence of the latent heat storage elements integrated into the spaces of the meander-shaped, foamed evaporator of refrigerator K-12020S-1 (see Fig. 1, top) on the evaporator temperature (T_E) and the fresh-food compartment temperatures (standard temperature measurement positions T_1 , T_2 and T_3) is shown in Fig. 3. 600 g of PCM were sufficient to significantly increase the evaporator temperature, approximately triple the cooling cycle duration and lower the compressor's relative runtime from 27% to 21% under comparable fresh-food compartment and environment conditions. With the latent heat storage, the minimum temperature of the evaporator was increased by ~ 10 °C from -22.6 °C to -12.5 °C and averaged over compressor runtime by ~ 8 °C from -14.2 °C to -6.2 °C. Altogether, this leads to a reduction of power consumption of up to 12%.

Prior studies, e.g. by [Azzouz et al. \(2008, 2009\)](#), demonstrated that the cooling cycle duration can be increased with more PCM mass up to 10 h with average air temperatures between 0 °C and 10 °C in the fresh-food compartment. However, examined in more detail, as shown in Fig. 4, this results in a considerably larger temperature amplitude of chilled foodstuffs (measured in a modified 250 g M-package according to DIN EN 62552 in the geometric center of the fresh-food compartment, T_M) although the temperature amplitude in the fresh-food compartment (T_1 , T_3) remained the same, which adversely affects storage quality. Due to high expectations towards modern household refrigerating appliances, temperature fluctuations of the cooled goods in the fresh-food compartment are expected to have a maximum of ± 0.5 °C, and in chill compartments even only of ± 0.1 °C. Under these conditions the cooling cycle duration of refrigerators with a simple on/off-control and free convection is significantly limited, in case of K-12020S-1 to less than 4 h.

In our preceding study, the integration of a copolymer-bound PCM into a standard wire-and-tube condenser was considered ([Sonnenrein et al., 2015](#)). Fig. 5 shows the

results for a combined integration of 150 g PCM foil into the evaporator and 500 g PCM elements into the spaces of the condenser of a commercial refrigerator, i.e. K-32122i (see Fig. 1, bottom). The construction of the refrigerator's free hanging rollbond evaporator leads to a higher evaporator temperature than in case of the foamed evaporator of K-12020S-1. Also here, the minimum evaporator temperature was increased with the integration of PCM by ~ 6 °C from about -16 °C to -10 °C and on average during the runtime of the compressor by ~ 6 °C from about -9.3 °C to -3.2 °C. The maximum condenser temperature T_C was reduced by ~ 8 °C from about 48 °C to 40 °C and on average during the runtime of the compressor by ~ 6 °C from 43.4 °C to 37.3 °C. The relative runtime of the compressor sinks from ca. 24% to 20%, altogether leading to a reduced power consumption of about 17%.

4.2. Control strategies

Through the modification of control parameters, e.g. the evaporator temperature around the phase change temperature of the latent heat elements, refrigerating appliances can be optimized with respect to the following target parameters:

- power consumption
- temperature fluctuations in the fresh-food compartment (and the cooled goods)
- DSM (increase/decrease power load)

Fig. 6 shows the temperature profiles of the fresh-food compartment of refrigerator K-12020S-1 with 600 g PCM under different control strategies for an average fresh-food compartment temperature T_m of about 5 °C. The reference refrigerator (without PCM) exhibits a temperature fluctuation in the fresh-food compartment of up to 4 °C over the cooling cycle duration (Fig. 6 a). By use of PCM, these fluctuations can be reduced to less than 0.5 °C with a comparable cooling cycle duration (Fig. 6 b). Fig. 6 c) shows the temperature profiles at an operating point of minimum power consumption with a cooling cycle duration of about 1.7 h that could serve as a basis for DSM. In this case, the refrigerator can be triggered to switch into an "increase load" mode in order to store for about 0.6 h energy during power oversupply, e.g. from renewable sources (Fig. 6 d). Conversely, during power shortage it can be decoupled from the electric network for up to 1.8 h in a "reduce load" mode (Fig. 6 e).

5. Conclusions

Evaporators as well as condensers of commercial household refrigerating appliances were equipped with latent heat storage elements, and their influence on power

consumption and performance was studied. The results show a considerable influence on evaporator and condenser temperature, directly impacting power consumption. Through the integration of the present block copolymer-bound PCM into the evaporator alone power consumption was reduced by 12%, and in a combined integration into evaporator and condenser even by 17%. The PCM-equipped refrigerators were further optimized through modifications of their control strategy, either minimizing temperature fluctuations in the fresh-food compartment or for the application of future DSM concepts. Given the leak proof and form stable characteristics of the developed copolymer compounds, their integration into household refrigerator production processes is much easier than encapsulated PCM from prior work.

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References

Azzouz, K., Leducq, D., Gobin, D., 2008. Performance enhancement of a household refrigerator by addition of latent heat storage. *Int. J. Refrigeration* 31, 892-901.

Azzouz, K., Leducq, D., Gobin, D., 2009. Enhancing the performance of household refrigerators with latent heat storage: an experimental investigation. *Int. J. Refrigeration* 32, 1634-1644.

Bagriyanik, M., Zehir, M. A., 2012. Demand Side Management by controlling refrigerators and its effects on consumers. *Energy Convers. Manag.* 64, 238-244.

Bansal, P. K., Chin, T., 2003. Heat Transfer Characteristics of Wire-and-Tube and Hot-Wall Condensers. *HVAC&R Research*, 9:3, 277-290.

Barthel, C., Hohmeyer, O., Irrek, W., Thomas, S., 2005. Energieeffiziente Kühl- und Gefriergeräte. (Energy efficient refrigerators and freezers). Endbericht, Wuppertal Institut für Klima, Umwelt und Energie. Available from: <http://www.wupperinst.org>.

Binneberg, P., Kraus, E., Quack, H., 2002. Reduction in Power Consumption of Household Refrigerators by using Variable Speed Compressors. *Int. Refrigeration*

and Air Conditioning Conference, Paper 615. Available from: <http://docs.lib.purdue.edu/iracc>.

Chen, W.-L., Mei, B.-J., Liu, Y.-N., Huang, Y.-H., Yuan, X.D., 2011. A novel household refrigerator with shape-stabilized PCM (Phase Change Material) heat storage condenser: An experimental investigation. *Energy* 36, 5797-5804.

Cheralathan, M., Velraj, R., Renganarayanan, S., 2007. Performance analysis on industrial refrigeration system integrated with encapsulated PCM-base cool thermal energy storage system. *Int. J. Energy Res.* 31, 1398-1413.

Dalkilic, A.S., Wongwises, S., 2010. A performance comparison of vapour compression refrigeration system using various alternative refrigerants, *International Communications in Heat and Mass Transfer* 37 (2010), 1340–1349.

DKV, 1985. Möglichkeiten der Energieeinsparung bei Haushaltskühl- und Gefriergeräten. (Opportunities of energy savings for household refrigerators and freezers). Statusbericht 1, sec. ed., Deutscher Kälte- und Klimatechnischer Verein (DKV) e.V., Stuttgart.

Faberi, S., Esposito, R., Mebane, W., Presutto, M., Sciadoni, R., Stamminger, R., 2007. Preparatory Studies for Eco-design Requirements of EuPs: Final Report Domestic Refrigerators & Freezers. TREN/D1/40-2005.

Gin, B., Farid, M.M., 2010. The use of PCM panels to improve storage condition of frozen food. *J. Food Eng.* 100, 372-376.

Gin, B., Farid, M.M., Bansal, P.K., 2010. Effect of door opening and defrost cycle on a freezer with phase change panels. *Energy Convers. Manag.* 51, 2698-2706.

IEA, 2003. COOL APLIANCES: Policy Strategies for Energie Efficient Homes. Organisation for Economic Co-operation and Development, OECD.

Kohler, S., 2010. Integration of Renewable Energy Sources in the German Poer Supply System from 2015 – 2020 with an Outlook to 2025. dena Grid Study II, Deutsche Energie-Agentur. Available from: <http://www.dena.de/publikationen/energiesysteme/dena-netzstudie-ii.html>.

Marchi Neto, I., Padilha, A., Scalon, V.L., 2009. Refrigerator COP with thermal storage. *Appl. Therm. Eng.* 29, 2358-2364.

Mehling, H., Cabeza, L.F., 2008. *Heat and Cold Storage with PCM. An up to Date Introduction into Basics and Applications.* Springer-Verlag, Berlin, Heidelberg.

Onyejekwe, D., 1989. Cold storage using eutectic mixture of NaCl/H₂O: an application to photovoltaic compressor vapours freezers. *Sol. Wind Tech.* 6, 11-18.

Philipp, J., 2002. Optimierung von Haushaltskühlgeräten mittels numerischer Simulation. (Optimizing of household devices via numerical simulation). Forschungsbericht des DKV Nr. 65, Deutscher Kälte- und Klimatechnischer Verein (DKV) e.V., Stuttgart.

Roth, P., 2008. Energy saving on the high pressure side of a refrigerating plant. *KI* 03/2008, 30-35.

Sonnenrein, G., Elsner, A., Baumhögger, E., Morbach, A., Fieback, K., Vrabec, J., 2015. Reducing the power consumption of household refrigerators through the integration of latent heat storage elements in wire-and-tube condensers. *Int. J. Refrigeration* 51, 154–160.

Wang, F., Maidment, G., Missenden, J., Tozer, R., 2007a. The novel use of phase change materials in refrigeration plant. Part 1: experimental investigation. *Appl. Therm. Eng.* 27, 2893-2901.

Wang, F., Maidment, G., Missenden, J., Tozer, R., 2007b. The novel use of phase change materials in refrigeration plant. Part 2: dynamic simulation model for the combined system. *Appl. Therm. Eng.* 27, 2902-2910.

Wang, F., Maidment, G., Missenden, J., Tozer, R., 2007c. The novel use of phase change materials in refrigeration plant. Part 3: PCM for control and energy savings. *Appl. Therm. Eng.* 27, 2911-2918.



Fig. 1 Foamed evaporator of K-12020S-1 (top, left), equipped with PCM elements (top, right), rollbond evaporator of K-32122i equipped with PCM foil (bottom, left), condenser of K-32122i equipped with PCM elements (bottom, right)

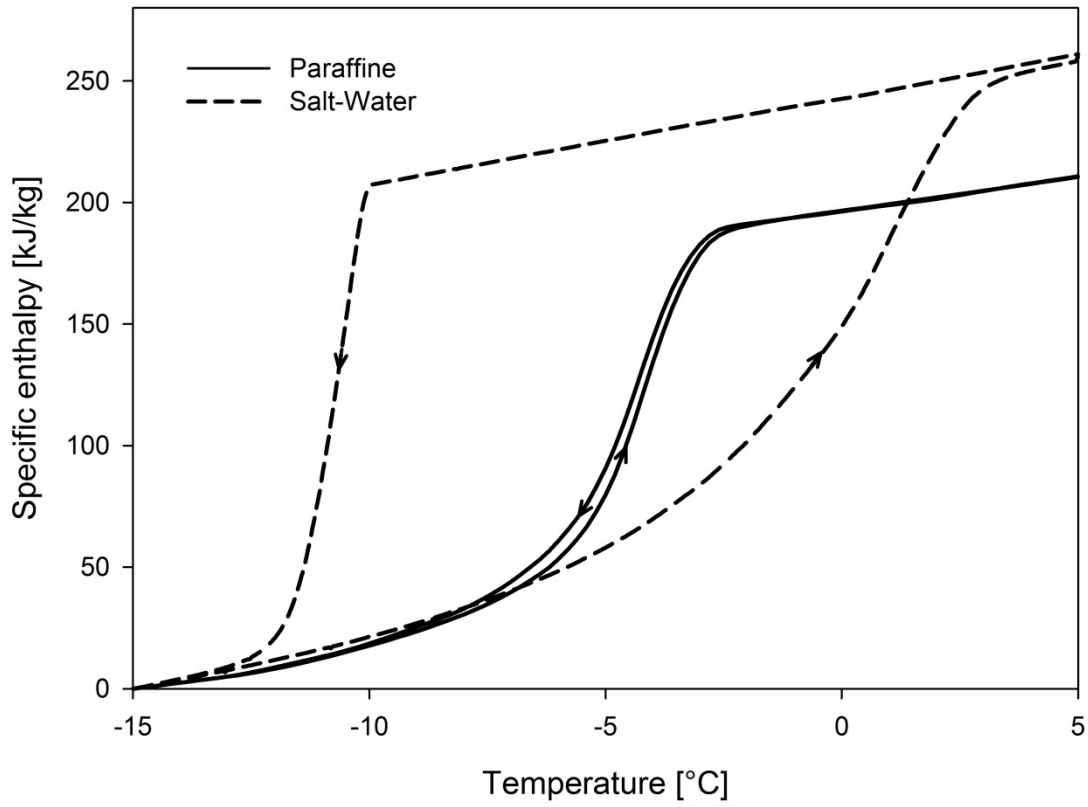


Fig. 2 Specific enthalpy as a function of temperature of the paraffin derivative (solid lines) compared to a salt-water mixture according to DIN EN 62552 (dashed lines)

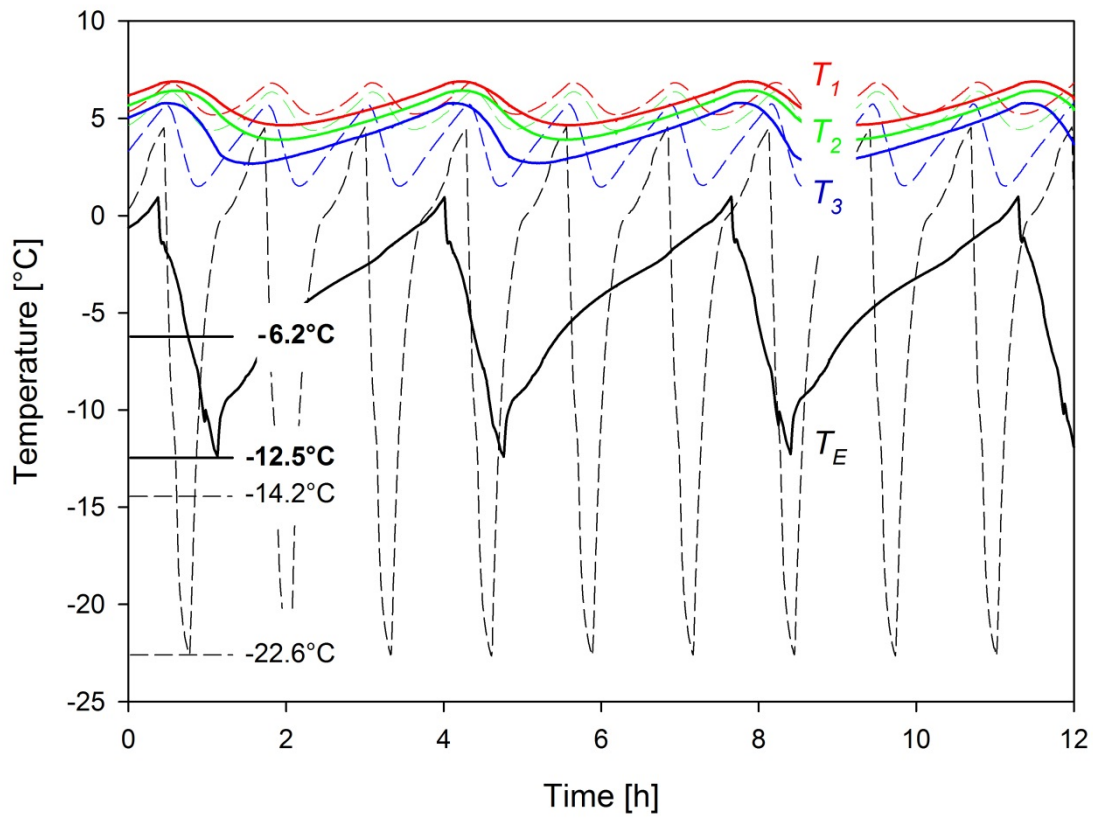


Fig. 3 Temperature of the fresh-food compartment of K-12020S-1 (T_1 , T_2 , T_3) and of the (foamed) evaporator (T_E) without (dashed lines) and with PCM (solid lines); numerical values indicate minimum and average evaporator temperatures during compressor runtime

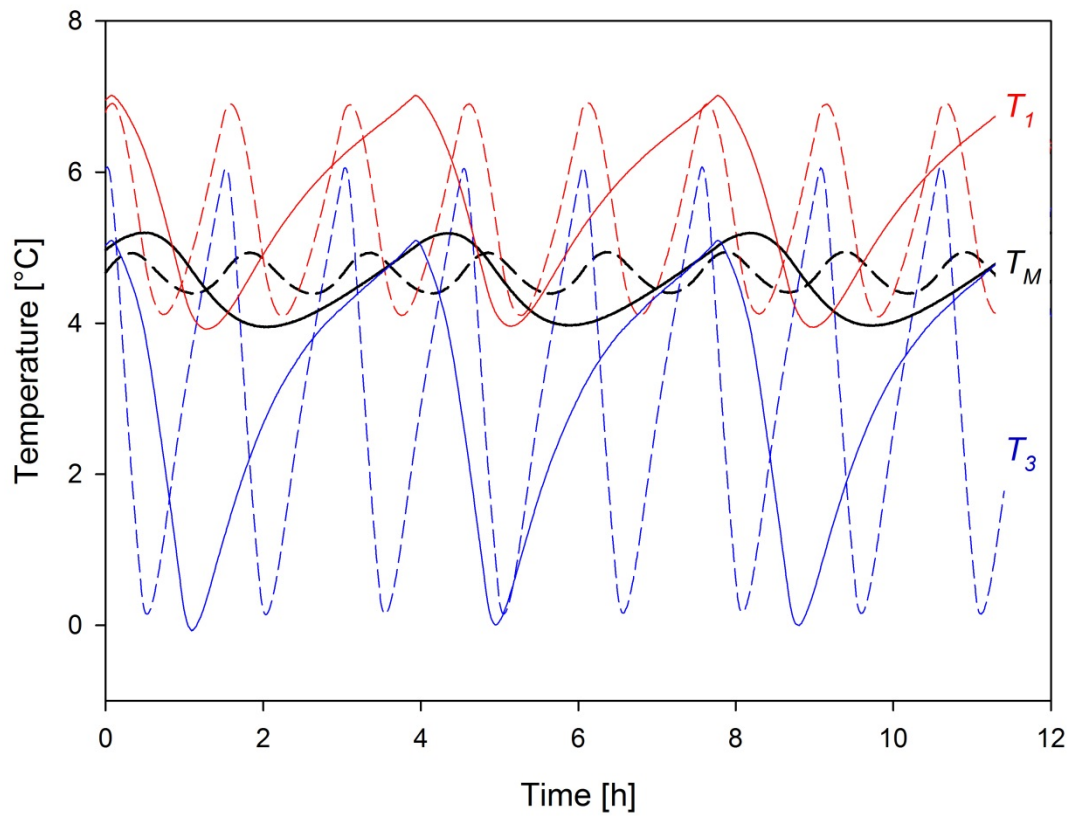


Fig. 4 Temperature of the fresh-food compartment of K-12020S-1 (T_1 , T_3) and the M-package (T_M) without (dashed lines) and with PCM (solid lines)

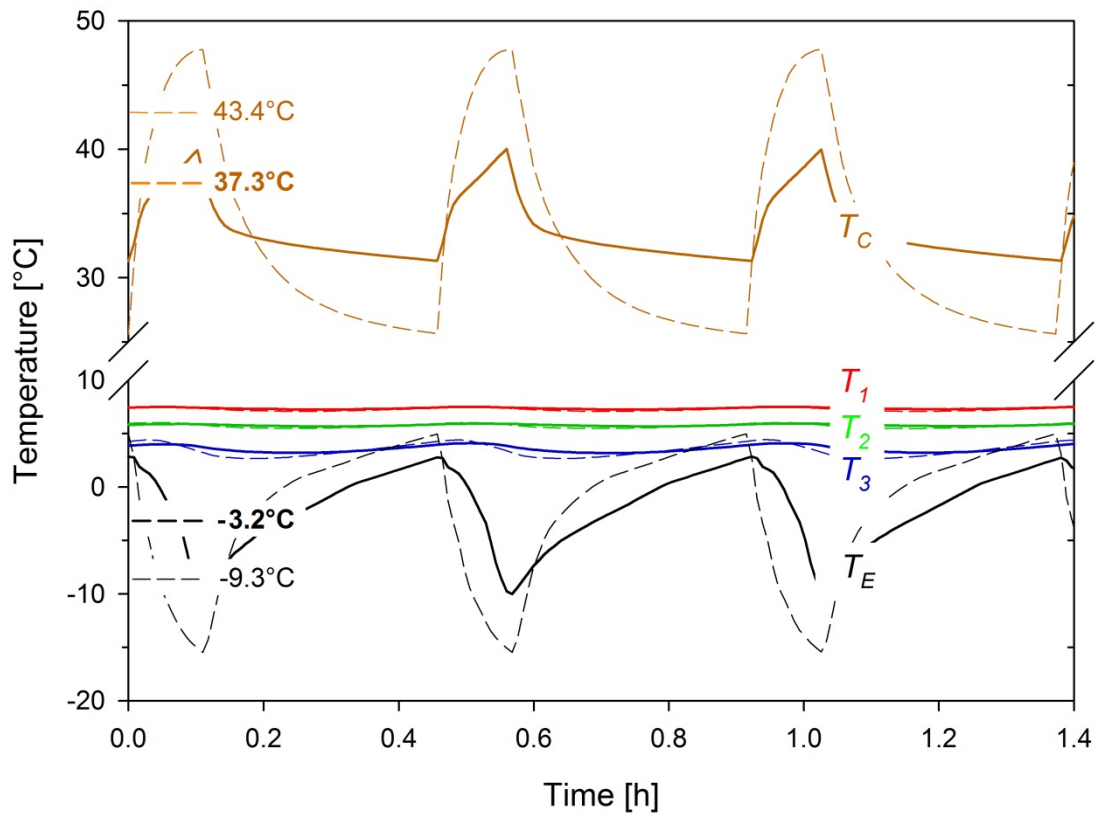


Fig. 5 Temperature of the fresh-food compartment of K-32122i (T_1 , T_2 , T_3), of the rollbond evaporator (T_E) and of the condenser (T_C) without (dashed lines) and with PCM on evaporator and condenser (solid lines); numerical values indicate average evaporator and condenser temperatures during compressor runtime

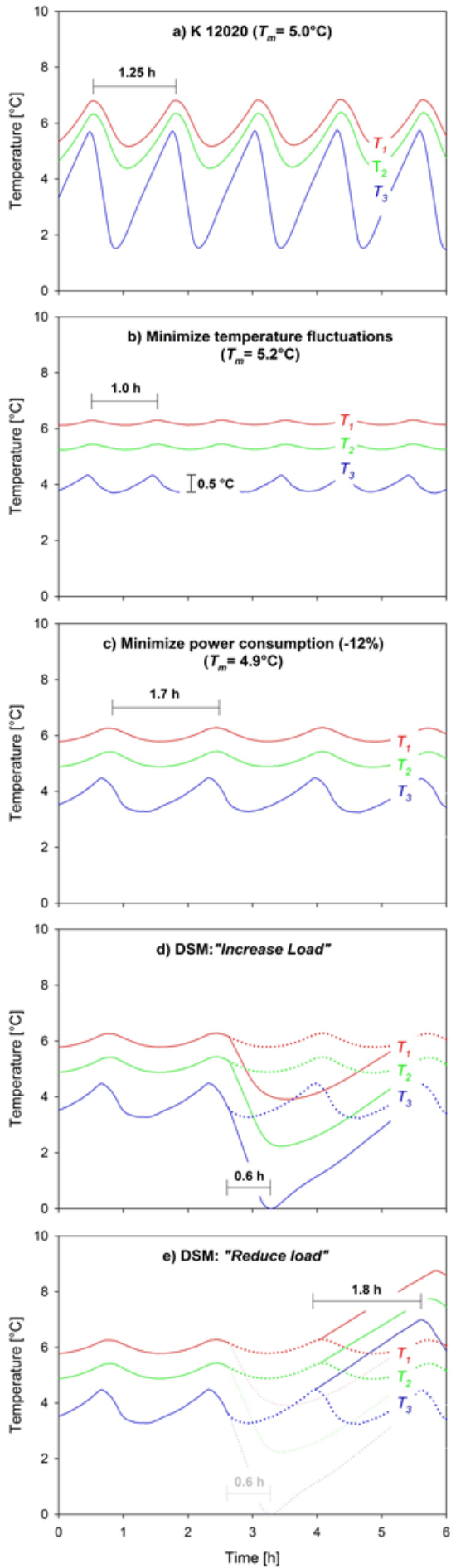


Fig. 6 Temperature of the fresh-food compartment of K-12020S-1 for different control strategies: a) without PCM, standard control, b) with PCM, minimizing temperature fluctuations, c) with PCM, minimizing power consumption d) with PCM, increasing load, e) with PCM, reducing load