Reducing the power consumption of household refrigerators through the integration of latent heat storage elements in wire-and-tube condensers

G. Sonnenrein [a], A. Elsner [a], E. Baumhögger [a], A. Morbach [b], K. Fieback [c], J. Vrabec [a,1]

[a] Thermodynamics and Energy Technology, University of Paderborn, Warburger Str. 100, 33098 Paderborn, Germany

[b] Miele & Cie. KG, Carl-Miele-Straße 29, 33332 Gütersloh, Germany

[c] Dr. Fieback PCM-innovativ GmbH, Am Fichtenberg 2, 14552 Michendorf, Germany

Highlights

- Heat storages may significantly decrease the condenser temperature of refrigerators.
- A lower condenser temperature decreases power consumption.
- Copolymer bound PCM can be dimensionally stable and leak proof.
- The thermal conductivity of the PCM copolymer compound was increased by adding graphite.
- A heat storage capacity of 180 kJ/kg was achieved.

Keywords

Household refrigerator, Power consumption, Condenser, Thermal storage, Phase change material, Polymer bound

Abstract

This study evaluates the influence of latent heat storage elements on the condenser temperature of a commercial household refrigerator. In order to determine the power consumption and the temperature distribution, a standard wire-and-tube condenser is equipped with different heat storage elements (containing water, paraffin or copolymer compound). The results indicate that particularly the application of phase change materials (PCM) lowers the condenser temperature, which leads to a significantly reduced power consumption.

[1] Corresponding author: jadran.vrabec@upb.de

1. Introduction

Although the power consumption of individual refrigerators seems to be low today, these home appliances still have a large potential for energy saving because of their vast number. They have an almost complete market penetration and they operate continuously throughout the year. The largest share of the electrical power consumption by private households in the OECD member states is caused by refrigeration (IEA, 2003). In Germany this share is about 20%, translating to about 7% of the total national electric power consumption (Barthel et al., 2005). In recent years, the power consumption of household refrigerators has been reduced considerably by the manufacturers, who responded to market pressure due to the bold labelling of energy efficiency that is prescribed in many countries. Nowadays, energy efficiency has become the decisive criterion for the consumer upon appliance replacement decisions (Faberi et al., 2007). For a further reduction of power consumption, both cooling load and the conversion of electric energy to cooling capacity can be optimized. The according technical developments can be divided into three categories:

1) *Improvement of casing and door:* By using polyurethane foam, which has long become standard, instead of polystyrene insulation, which has been common up into the 1980s, the cooling load was reduced by about 30%. Similar additional progress can be achieved through the application of e.g. vacuum insulated panels, but they are hardly used due to their high production cost in this price sensitive segment (Philipp, 2002). However, a simple increase of the polyurethane insulation thickness is mostly not effective because of the reduced net storage volume.
2) *Improvement of compressor efficiency:* The application of variable speed compressors enables for a transition from their common intermittent operation by on/off control towards a continuous and variably controlled operation. Less friction losses, a higher evaporation and a lower condensation temperature as well as a reduction of losses associated with the pressure equalization during compressor off times can be achieved. These effects may lead to a reduction of power consumption by up to 30% (Binneberg et al., 2002). However, variable speed compressors are usually not used in simple household refrigerators because of their substantially higher costs.
3) *Improvement of heat transfer performance of evaporator or condenser:* The maximum efficiency of cooling processes is determined by the difference between evaporator and condenser temperature. Reducing the condenser temperature resp. raising the evaporator temperature by 1 °C typically leads to a

power consumption that is reduced by about 2-4%. E.g., enlarging the effective heat transfer surface area of condenser or evaporator by approximately 50% reduces the power consumption by 6% or 10%, respectively (DKV, 1985). Another option is to use ventilators for the improvement of the convective heat transfer. However, the power consumption of such ventilators themselves must be put in relation to the overall performance gain (Roth, 2008).

The use of thermal heat storages, which is discussed in the present study, falls into the third category. Phase change materials (PCM) can absorb large quantities of heat at almost constant temperature. Thereby, temperature fluctuations can be reduced, which is interesting for numerous applications. PCM have already been successfully implemented in construction technology, transport boxes for sensible goods like medication or in heat sinks for electronic components (Mehling and Cabeza, 2008).

For many years, the integration of PCM in household refrigerators and freezers is a subject of scientific investigation. In 1989, Onyejekwe (1989) integrated a simple latent heat accumulator on the basis of an eutectic NaCl/H_2O mixture in a refrigerator. Wang et al. (2007a,b,c) developed a prototype, in which the influence of PCM at different places in the cooling system was studied, e.g. between compressor and condenser, and achieved a 6-8% improvement of efficiency. By connecting a layer of PCM directly onto the evaporator of a household cooling device, Azzouz et al. (2008, 2009) were able to demonstrate that the coefficient of performance (COP) can be increased by around 5-15% due to a higher evaporator temperature and a reduced number of on/off compressor cycles. Cheralathan et al. (2007) examined an industrial cooling system with encapsulated PCM and were able to show an increase of efficiency as well as the option to transfer power consumption, e.g., into cost-effective night tariffs. Gin and Farid (2010) found better storing quality for frozen goods because of stabilized temperatures due to the integration of PCM panels into a household freezing device. Moreover, they achieved lower power consumption during defrosting cycles and door openings (Gin et al., 2010). Oró et al. (2012) found consistent results for commercial freezers.

In most European household cooling devices, the heat transfer from the condenser to the environment is based on free convection and radiation only, which leads at the given temperatures to a low heat flux. Combined with the intermittent operational mode of these refrigerators, where the relation of on and off time is approximately 1:2, this leads to a fairly high condenser temperature during the compressor runtime. If a lower temperature of the condenser during the compressor runtime can be achieved by shifting a significant part of the heat transfer into the environment to the compressor off time, the COP can be improved. In an experimental study, Marchi Neto et al. (2009) therefore suggested a separate water reservoir by which the overall efficiency was increased. However, they used a volume of 122 liters which is not practical. Some appliance manufacturers already tried to integrate PCM into condensers. They encountered problems like volume extension during phase change and particularly the involved leak security contradicted a practical implementation so far. Only recent successes in producing dimensionally stable, polymer-bound PCM seem to open promising routes to the solution of these problems. E.g., Chen et al. (2011) achieved a power consumption reduction of almost 12% with the use of a paraffin-polyethylene compound in a cooling device with an integrated hot wall condenser. However, this strong effect can partly be traced back to the greater influence of the condenser temperature due to the higher heat flow into the refrigerant compartment, depending on the construction of this condenser type, and thereby lower efficiency. Therefore wire-and-tube or plate-and-tube condensers are predominantly used today in Europe and Asia. Because of their larger heat transfer surface area they provide a better heat transfer under typical installation conditions (Bansal und Chin, 2003). Due to the direct accessibility of the condenser at the back side of the appliance, leak security and dimensional stability of the deployed PCM are of greatest importance.

2. Methodology

Since directive 94/2/EG took effect in the European Union, manufacturers are obliged to indicate the power consumption of household cooling and freezing devices. In Europe, the determination of power consumption is controlled by DIN EN 153. All measurements and tests carried out in this study are in accordance with these guidelines. With respect to the detailed test methods und conditions we refer to the relevant paragraphs in DIN EN 153 of DIN EN ISO 15502.

3. Test setup

3.1. Cooling device

A completely integrated built-in off-the-shelf cooling device of type Miele K-9252i-1 with a storage volume of 152 liters and a power consumption of 98 kWh/year, corresponding to energy efficiency class A++, served as the basis for the present study. The heat discharge of this appliance was realized by a wire-and-tube condenser with an overall width of 455 mm and an overall height of 655 mm. To enlarge the heat transfer surface area, wires were welded vertically by a width of 400 mm and strength of 1 mm in a distance of 5 mm onto the horizontally passing tubes. So the tubes with an outer diameter of 4.75 mm are fixed at a distance of 40 mm from each other and the resulting space between them can be used for the integration of (latent) heat storage elements. Note that these features are all according to the off-the-shelf standard. Fig. 1 shows that condenser equipped with a taped bag and also equipped with a copolymer compound, which was developed in this work. In both cases, a heat storage mass of approximately 500 g was integrated into the standard wire-and-tube condenser in our lab subsequently to the production of the refrigerator.

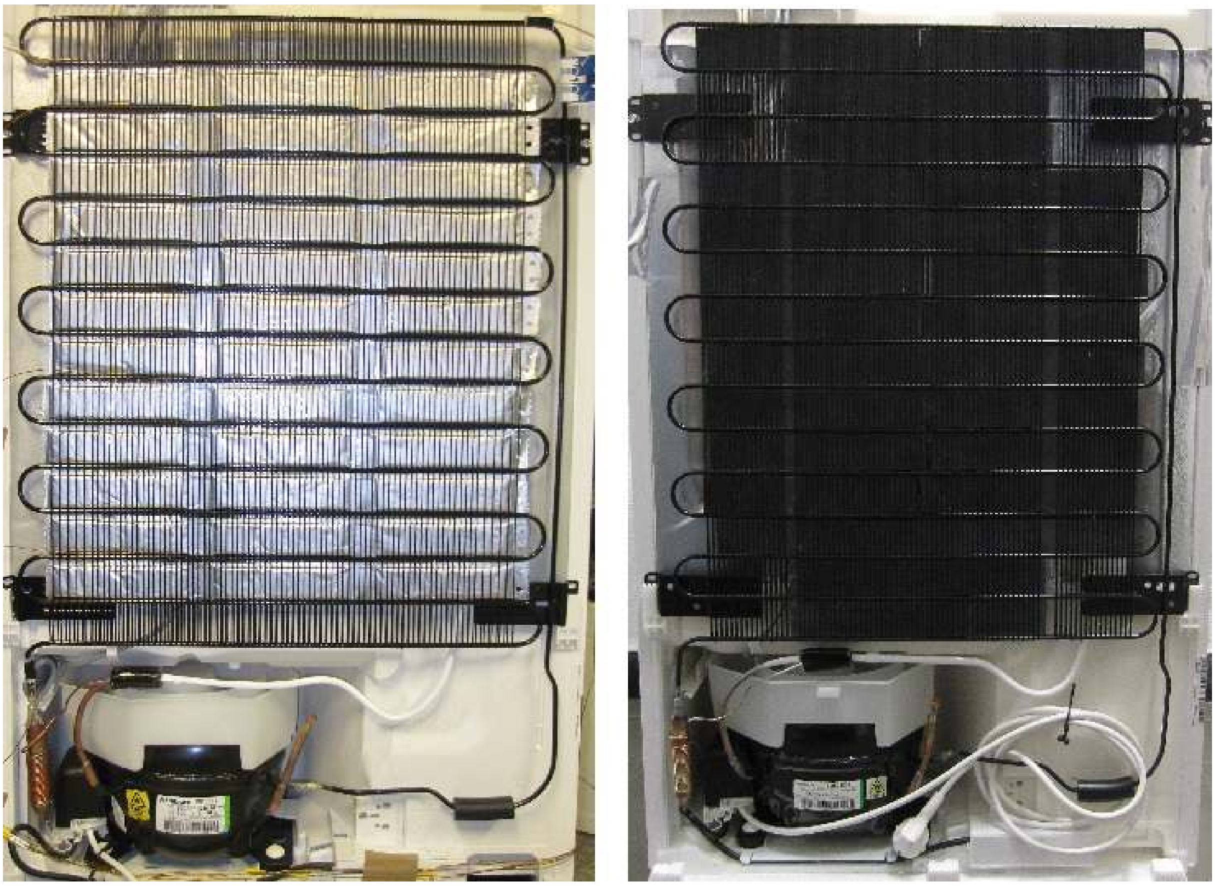

Fig. 1 – Wire-and-tube condenser, equipped with taped bags out of aluminum-composite film (left) or copolymer compound (right)

3.2. Storage materials

Different heat storage materials (water, paraffin and copolymer-bound PCM) as well as different macro-encapsulations (PE-HD foil and aluminum-composite film) were considered with respect to their influence on power consumption. Tab. 1 provides an overview. In addition to the standard heat storage components (water and paraffin as well as PE-HD foil and aluminum-compound film), a high-capacity, dimensionally stable PCM panel was developed on the basis of a block copolymer fixed organic paraffin derivative. The thermal conductivity of this copolymer compound itself of λ = 0.19 W/(m K) was increased by adding graphite (THERMOPHIT GFG, SGL GROUP). Upon addition of graphite to a mass fraction of $\omega \approx 0.3$ g/g, the thermal conductivity of the compounded material was higher by a factor of 20, i.e. λ = 3.95 W/(m K) was achieved.

Table 1 - Physical characteristics for different experimental heat storages

Characteristics	Heat storage type			
	Water [A]	PCM [B]	PCM [C]	Copolymer compound [D]
Mass [kg]	0.5	0.5	0.5	0.5
Density [kg l^{-1}]	1.0	0.76	0.76	0.89
Approx. phase change temperature [°C]	0	34	34	34
Storage capacity 25-40°C [kJ kg^{-1}]	63	251	251	182
Thermal conductivity [W m^{-1} K^{-1}]	0.6	0.19	0.19	0.64
Encapsulation	Al composite	PE-HD	Al composite	None

Due to constructional constraints given by the chosen refrigerator, the heat storage element thickness was limited to approximately 4 mm. Therefore a copolymer compound with a graphite mass fraction of $\omega \approx 0.1$ g/g and a thermal conductivity of 0.64 W/(m K) was chosen to achieve a higher heat storage capacity. In contrast to prior approaches, this compound material is dimensionally stable and in its “liquid” state it is secure against leakage and exudation. Therefore, encapsulation is not necessary. Another advantage of the developed heat storage element is the crucially lower installation effort during the production process, resulting in a cost-effective implementation of manufacturer requirements.

Fig. 2 shows the temperature dependence of the specific enthalpy of the developed copolymer compound ($\omega \approx 0.1$ g/g) in comparison with the pure PCM. The underlying measurements were carried out by Differential Scanning Calorimetry (DSC, SETARAM TG-DSC 111) and a heat flow 3-layer-calorimeter (W&A, WOTKA) specifically developed for the analysis of PCM. In comparison to common DSC devices, WOTKA allows much greater sample quantities up to 100 g to determine the phase change temperature. The heat storage capacity of the compounded material is lower than that of the pure PCM due to its significant graphite and copolymer content. Over the temperature range that is important for the condenser (from 25 °C to 40 °C) the heat storage capacity is reduced by approximately 25% from 250 kJ/kg to 180 kJ/kg (cf. Tab. 1). The melting temperature remains unaffected at approximately 34 °C. In comparison to the paraffin-polyethylene compound suggested by Chen et al. (2011), the present copolymer compound exhibits a storage capacity that is larger by a factor of six in the relevant temperature range.

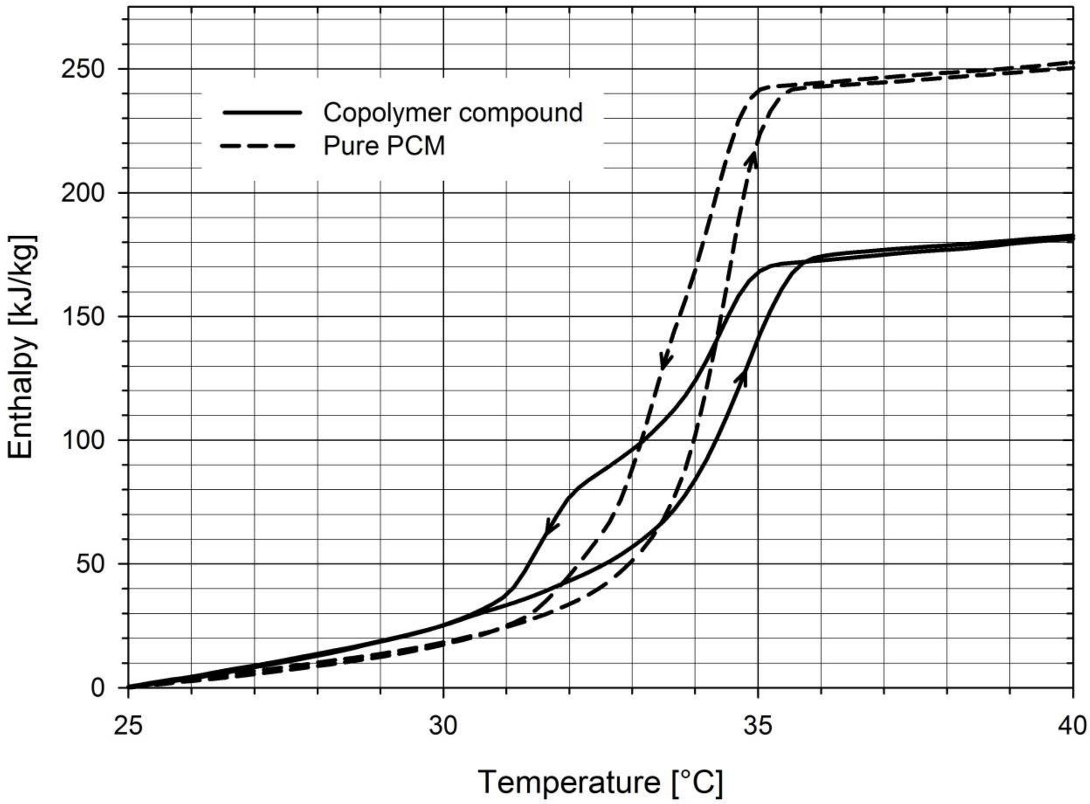

Fig. 2 – Specific enthalpy as a function of temperature of pure PCM (dashed lines) compared to the copolymer compound (solid lines)

3.3. Measurement of temperature and power consumption

The present test setup and all procedures followed the norms DIN EN 153 resp. DIN EN ISO 15502. Temperature was sampled by thermocouple differential measurements, each against a reference thermo element per measuring point in a mixture of ice and water. The employed data acquisition module OMB-DAQ 55/56 (Omega Technologies) was complemented with the pre-amplifier LTC1049 (Linear

Technology), which limited the offset error caused by zero point drift to ±0.025 K. The typical error of thermocouples of ±1% x ΔT could thus be lowered to ±0.5% x ΔT by batch consistency of the deployed thermocouples and a polynomial calibration. The temperatures of the condenser were measured under standard conditions (average cold storage temperature 5 °C, environment temperature 25 °C and humidity 50%). For the measurement of the power consumption, energy counters of type EZI 1 (Zimmer Electronic Systems) with a resolution of 25 impulses per Wh were used. The relative measurement error of the considered standard power consumption was approximately 1%. For the visualization of the temperature distribution of the condenser, a thermographic camera of type MIDAS 320L (DIAS Infrared) with a resolution of 320 x 240 pixels was employed for the long-wave infra-red spectral range from 8 to 14 µm.

4. Results and discussion

4.1. Condenser temperature

The influence of a heat storage on the condenser temperature of the refrigerator is shown in Fig. 3. The condenser temperature was significantly reduced in all its sections during the entire runtime of the compressor. Therefore, a large part of the heat discharge was taking place during the compressor off time.

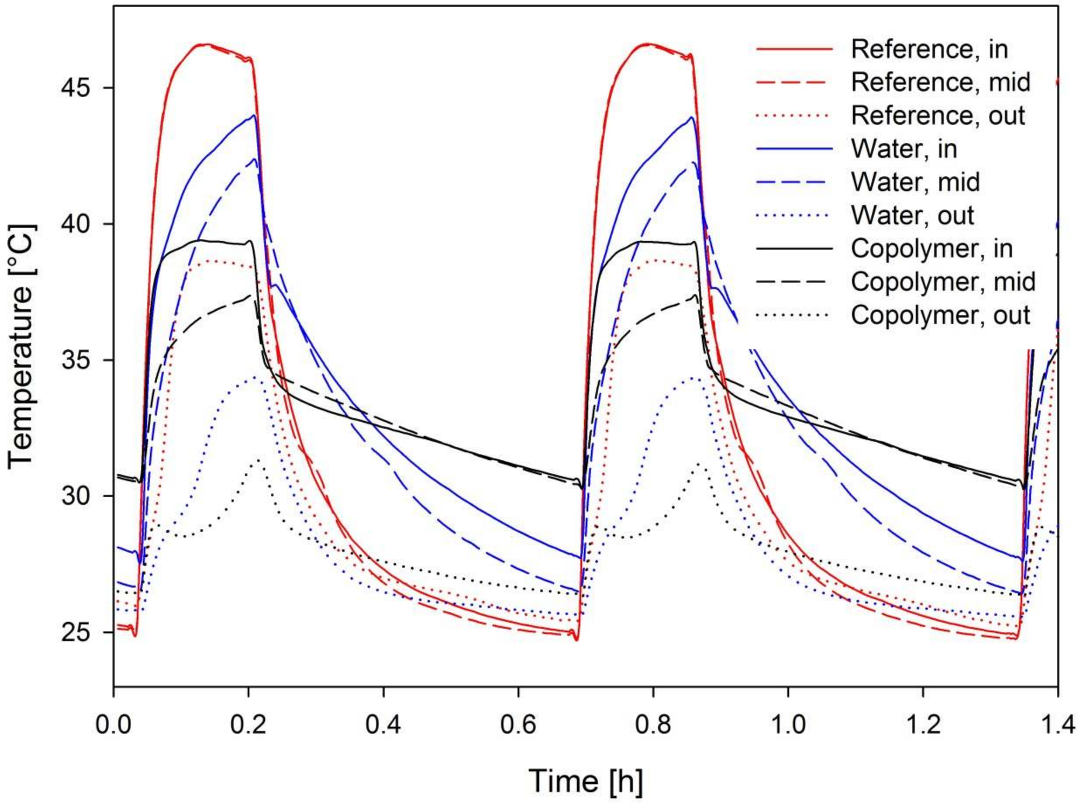

Fig. 3 – Temperature of the condenser over time at the entry (in), its geometric center (mid) and its exit (out) of the reference refrigerator, with sensible heat storage (water) and with latent heat storage (copolymer compound)

With a sensible heat storage (water), the maximum temperature was reduced at the entry of the condenser towards the end of the compressor runtime by ~3 °C from approximately 47 °C to 44 °C, with the latent (copolymer compound) heat storage even by ~8 °C to approximately 39 °C. In the geometric center of the condenser, the temperature was reduced by the sensible heat storage by ~5 °C and with the latent heat storage even by ~10 °C to just 37 °C. The condenser outlet temperature was reduced from 39 °C to 34 °C (water) or 31 °C (copolymer compound). This decrease of the condenser temperature, together with the associated lower refrigerant pressure, leads to an increase of the refrigerator's COP. The compressor runtime is thus shorter under otherwise constant conditions. As a result, the duration of the complete operating cycle was also somewhat shorter, because the compressor off time remained constant.

Fig. 4 shows infrared images of the condenser, indicating its temperature distribution at different stages of the cooling cycle: immediately before the start of the compressor, at the end of the compressor runtime when the maximum temperature is reached, and 15 min. after the end of the compressor runtime during the cool down phase. In comparison with the reference device without heat storage, all studied heat storage types lead to a significantly lower maximum condenser temperature. During the compressor off time the condenser temperature is higher due to the thermal storage mass. Before the start of the compressor the difference between sensible and latent heat storage can be seen most clearly, i.e. the condenser with sensible heat storage cooled off much more. Latent heat storage exhibits higher temperature during the entire cool down phase of the condenser, thus utilizing the compressor off time substantially more for heat discharge to the environment. In addition, the maximum temperature during compressor runtime is lower than in case of sensible heat storage.

Comparing PCM elements in PE-HD encapsulation with the PCM elements in aluminum-compound film highlights the influence of thermal conductivity. The aluminum-compound encapsulation exhibits a more homogeneous temperature distribution during all stages of the cooling processes. However, the most homogeneous temperature distribution, and therefore the lowest maximum temperature, was achieved by the copolymer compound developed in this work.

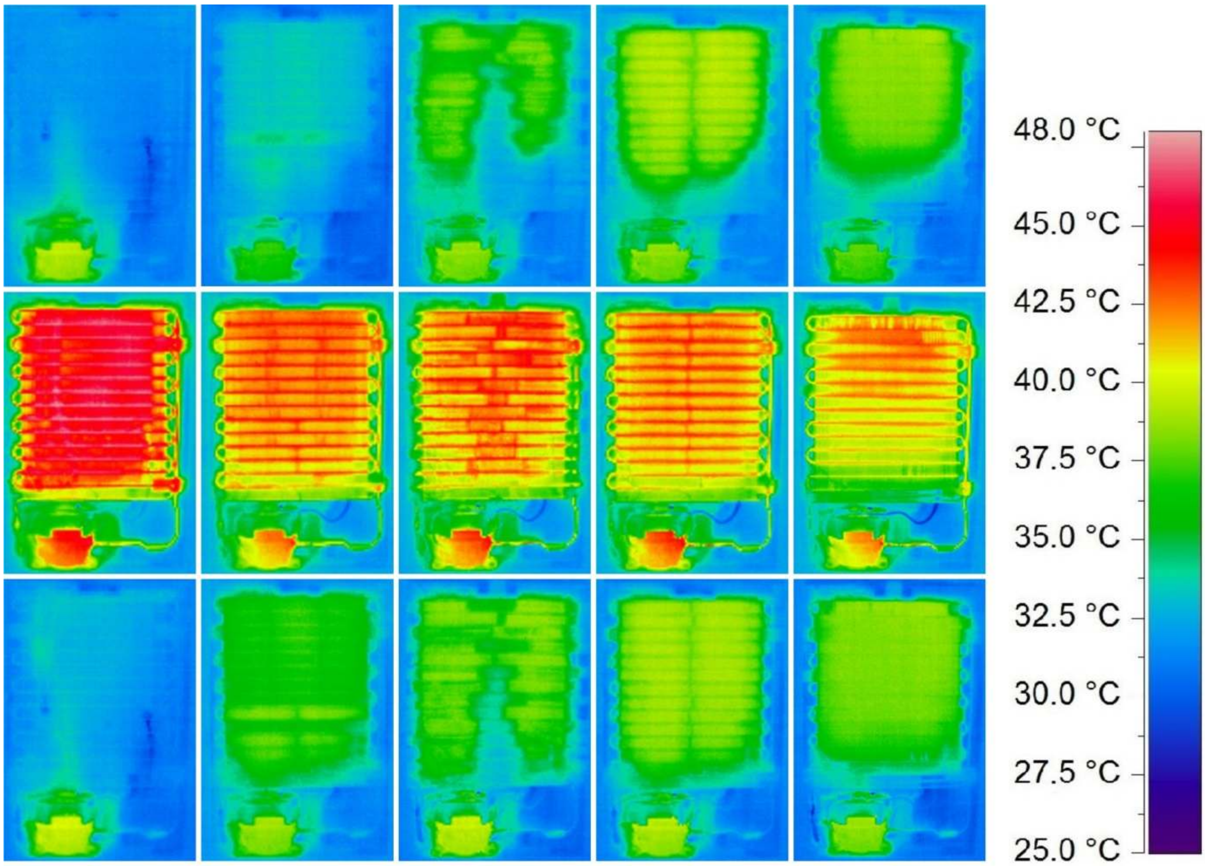

Fig. 4 – Temperature distribution of the condenser; top: immediately before compressor runtime, center: at the end of compressor runtime, bottom: 15 min. after the end of compressor runtime; column 1: without heat storage (reference), column 2: with sensible heat storage (water), column 3: with PCM in PE-HD foil, column 4: with PCM in aluminum-composite film, column 5: with copolymer compound

4.2. Power consumption

The measured temperature distributions are reflected in the power consumption, cf. Fig. 5. The use of a sensible heat storage in a common wire-and-tube condenser compared with the reference device lead to a reduction of the energy input of ~3%. With the straightforward form of a latent heat storage, depending on the encapsulation, ~5% (PE-HD-foil) or ~7% (aluminum-compound film) was saved. Employing the copolymer compound developed in this work, the power consumption was reduced by ~10%.

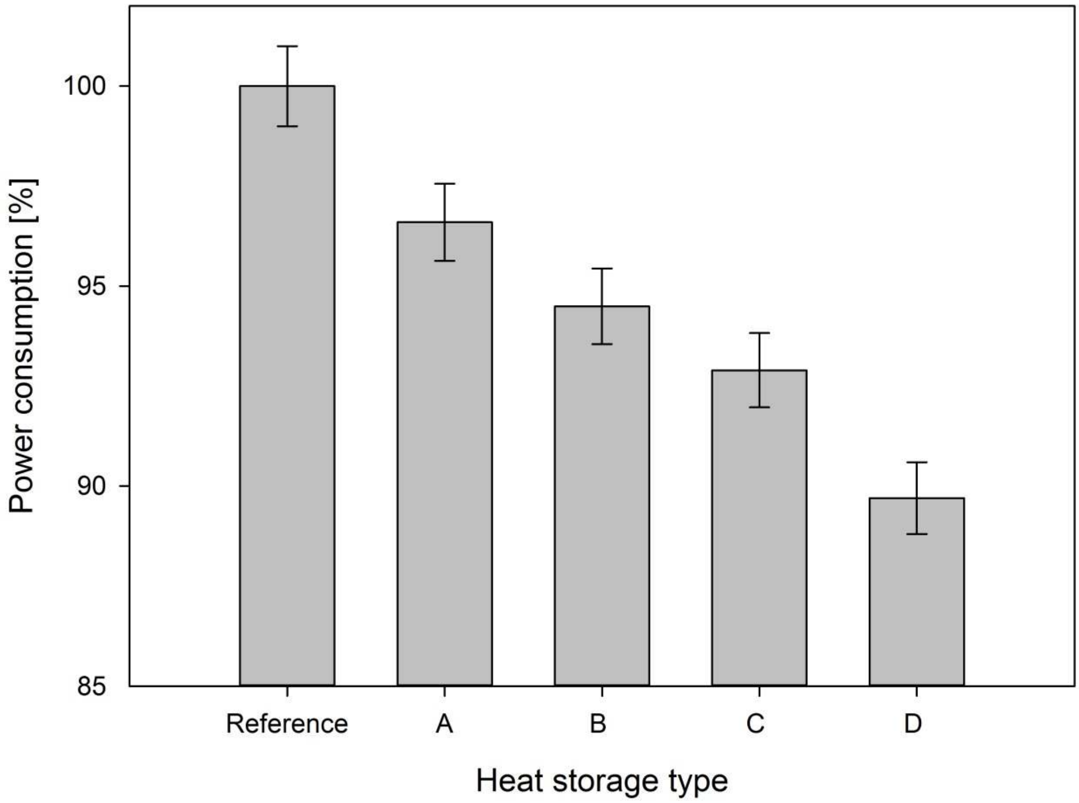

Fig. 5 – Power consumption relative to the reference refrigerator for different (latent) heat storages (A: sensible water heat storage, B: PCM and PE-HD foil, C: PCM and aluminum-composite film, D: copolymer compound); the vertical bars represent measurement uncertainties

An important advantage of the present PCM concept for manufacturers of household cooling and freezing devices is that by variation of the loading (i.e. number of heat storage elements per condenser) the reduction of the power consumption can be adjusted even at the end of product development. That may be of interest, e.g. if a defined power consumption reduction must be realized to achieve a higher energy efficiency class. Fig. 6 shows the influence of the loading on the power consumption. Loading only 25% of the condenser surface with copolymer compound lead to a reduction of ~4%, loading the entire condenser to ~10%.

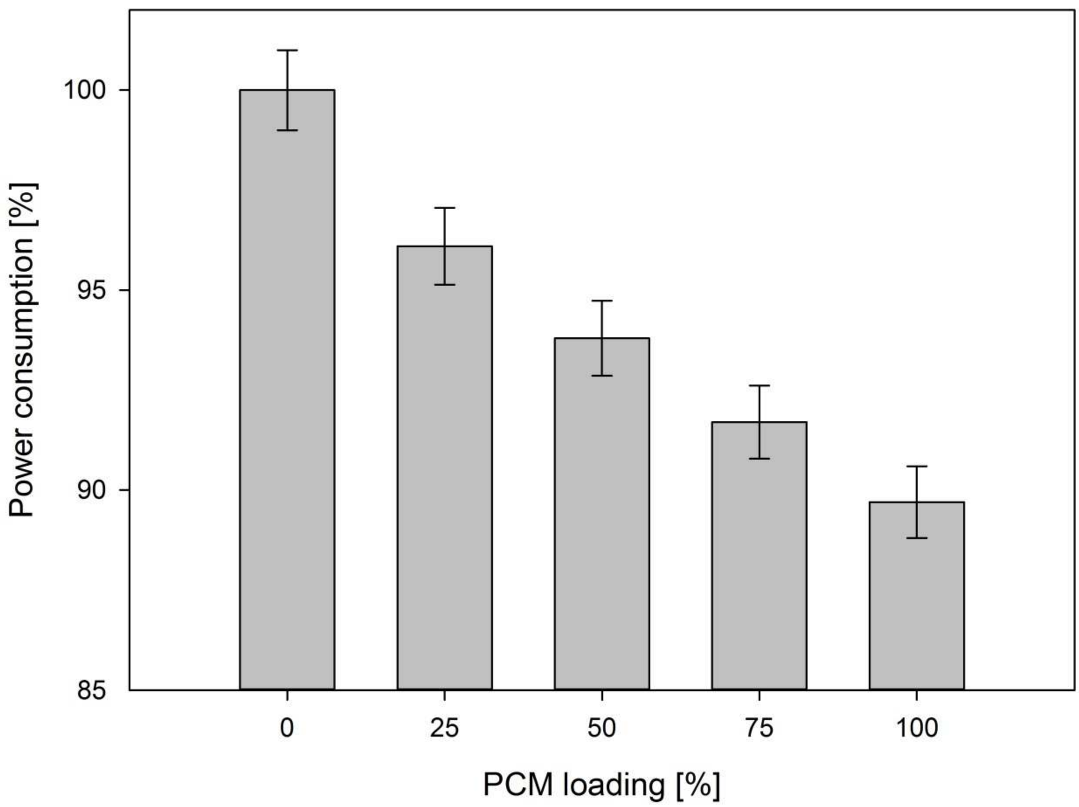

Fig. 6 – Power consumption depending on the loading of the condenser with copolymer compound elements; the vertical bars represent measurement uncertainties

5. Conclusion

In this experimental study, a standard wire-and-tube condenser was equipped with different sensible and latent heat storage elements and their impact on power consumption was compared to the corresponding off-the-shelf household refrigerator. The results show a significant impact of heat storage on the condenser temperature and consequently on power consumption. This effect is much more pronounced for latent than for sensible heat storage. By integrating a copolymer compound heat storage, power consumption was reduced by up to 10%. Up to this limit, a defined power consumption reduction can be achieved by customized loading of the condenser with PCM. Due to the leak and exudation security even in its "liquid" state, encapsulation of the copolymer compounded PCM is not necessary. Due to their stable spatial dimensions the heat storage elements developed in this work can be integrated with considerably less logistics and assembly effort into the production process than encapsulated ones. Because they have a large storage capacity of 180 kJ/kg, only little storage mass of about 0.5 kg is required for a significant effect. In summary, a cost-effective method of reducing the power consumption of household refrigerators was presented.

Acknowledgement

This work was supported by Deutsche Bundesstiftung Umwelt (DBU, AZ 28626).

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