Improving the performance of household refrigerating appliances through the integration of phase change materials in the context of the new global refrigerator standard IEC 62552:2015

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Highlights

- Copolymer-bound PCM are integrated in different refrigerating appliances.
- The impact on cooling capacity and temperature rise in the fresh-food compartments and power consumption is analyzed.
- Cooling capacity and temperature rise time are significantly increased.
- The developed polymer-bound PCM are dimensionally stable and leak proof.

Keywords

Household refrigerator, Thermal storage, Phase change material, Cooling capacity, Temperature rise

Abstract

This study presents the results of an experimental investigation of the influence of latent heat storage elements on the cooling performance and the temperature rise time of household refrigerating appliances in the context of the “new global refrigerator standard” IEC 62552:2015 (IEC 62552:2015, 2015). In addition to the daily energy consumption, this international standardization introduced performance tests for cooling capacity and temperature rise time. While the cooling capacity has long been anchored in various test procedures of consumer organizations, the temperature rise time, which only has been tested on freezers so far, will be a decisive factor in the future. Moreover, the need for so-called "smart appliances" that meet the growing demand for balancing power consumption to stabilize the power grid to compensate growing volatile renewable energies is increasing. Against this background, eight

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commercial household refrigerators and refrigerator-freezers are equipped with polymer-bound phase change materials (PCM) and their performance is determined under the new standard test conditions. The results show that the application of PCM increases the cooling capacity by up to 33 % and also increases the temperature rise time by up to 145 %, without affecting power consumption.

Nomenclature

h	specific enthalpy (kJ kg^{-1})
T	temperature (°C)
TMP_i	temperature measurement point
T_{ama}	time averaged ambient temperature (°C)
T_i	instantaneous refrigerator compartment temperature (°C)
T_{ma}	time averaged refrigerator compartment temperature (°C)
T_{Mi}	instantaneous M-package temperature (°C)
$T_{M,a}$	arithmetic average of all instantaneous M-package temperatures (°C)
$T_{M,max}$	instantaneous temperature of the warmest M-package (°C)
$\mathrm{M_i}$	M-package number

1 Introduction

Although the power consumption of a single household refrigeration appliance appears to be low, the savings potential of the entire fleet is considerable due to the almost complete market penetration and typical continuous operation. In total, over 1.5 billion household refrigerators and freezers are in use worldwide, accounting for approximately 4% of global electricity consumption (Coloumb et al., 2015), annually causing 480 million tons of CO2 equivalent (Barthel and Götz, 2012). As a result test standards with sometimes striking energy labels were developed in many countries from as early as the 1990s. Meanwhile, energy efficiency has become a decisive purchase criterion for consumers (Faberi et al., 2007). However, these often very different standards and regulations require specific tests for the regional distribution of these products, which in turn entails considerable efforts in time and money. For this reason, e.g. Bansal (2003) called for the creation of a single, consolidated testing standard. The development of this so-called "global standard" already began in 2006 and led to the new IEC 62552:2015 "Household refrigerating appliances – characteristics and test methods", which is currently being adapted into national standards in many countries and regions. In addition to the standardization of power consumption measurement, performance tests for cooling capacity and temperature rise time were now introduced. Table 1 provides an overview of the different test conditions for the daily energy consumption measurements of some of the most important international standards.

Table 1 - Overview of different test conditions for energy consumption measurements.

Region	Europe	Australia / New Zealand	USA	USA	Japan	Global standard
Standard	EN 62552:2013	AS/NZS 4474.1:2007	ANSI/AHAM HRF-1(2007)	AHAM HRF-1(2008)	JIS C 9801 (2006)	IEC 62552:2015
Energy consumption test						
Ambient temperature	25 °C	32 °C	32.2 °C	32.2 °C	15 °C & 30 °C	16 °C & 32 °C
Fresh food compartment temperature	5 °C	3 °C	3.3 / 7.22 °C	3.9 °C	4 °C	4 °C
Frozen food compartment temperature	-18 °C	-15 °C	-15/ -17.8 °C	-17.8 °C	-18 °C	-18 °C
Loading of frozen food compartment	yes	no	no (No-frost) yes (static cooling)	no (No-frost) yes (static cooling)	no (No-frost) yes (static cooling)	no
Door openings and insertion of warm load	no	no	no	no	yes (No-frost)	no
Performance test at varying ambient temperatures						
Ambient temperature	10/16 to 32/38/43 °C	10/32/43 °C	12.8/21.1/ 32.2/43.3 °C	-	15/30 °C	10/16 to 32/38/43 °C
Fresh food compartment temperature	0 to 4 °C	0.5 to 6 °C	1.1 to 5 °C	-	0 to 4 °C	0 to 4 °C
Frozen food compartment temperature	≤-18 °C	≤-15 °C	≤-15/ -17.8 °C	-	≤-18 °C	≤-18 °C
Loading of frozen food compartment	Yes	yes	yes	-	yes	yes
Freezing test	yes	no	no	no	yes	yes
Temperature rise test	yes	no	yes (freezers only)	no	yes	yes
Pull-down test	no	yes	yes	no	yes	yes
Automatic ice-making test	yes	yes	yes	no	yes	yes

The positive influence of PCM, both on power consumption and temperature stability of household refrigeration appliances, has been known for a long time and has been the subject of scientific research in recent years. PCM can absorb large amounts of heat at almost constant temperature and are thus particularly well suited for heat and cold 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) provide a general overview.

Already Onyejekwe (1989) attached a simple latent heat accumulator based on an eutectic NaCl/H2O mixture to the evaporator to increase the coefficient of performance (COP) of a refrigerator. Wang et al. (2007a,b,c) examined the influence of PCM at various locations in the cooling system and were able to raise their prototype's efficiency by 6-8 %. Besides an increase of energy efficiency, Cheralathan et al. (2007) were able to prove the potential of load shifting into cost-effective power night-rates of an industrial cooling device. A direct connection of different PCM-layers to the evaporator of a household refrigerator allowed Azzouz et al. (2008, 2009) to achieve a 10 to 15 % increase of the COP through a higher evaporator temperature and simultaneously a considerable reduction of the on/off switch control frequency. Through PCM in contact with the refrigerator compartment evaporator of a domestic refrigerator/freezer appliance, Visek et al. (2014) showed an improvement of about 6 % in terms of energy consumption during the refrigeration cycle.

In a preceeding study (Sonnenrein et al., 2015), we were able to reduce the power consumption by up to 12 % through the integration of polymer-bound PCM into foamed as well as roll-bond evaporators. Yusuffoglu et al. (2015) achieved similar energy savings of about 10 % in their studies on the integration of different PCM in foamed evaporators. Niyai et al. (2017) located PCM in a roll-bond evaporator of a domestic refrigerator and were able to reduce its compressor running time significantly. Cofré-Toledo et al. (2018) studied the integration of two eutectic PCM and could also show an improved COP through an increase of the evaporator temperature, but the temperature of the refrigerator compartments was affected negatively. Investigations of Berdja et al. (2019) showed similar results. Maiorino et al. (2019) integrated water as a PCM in contact with the evaporator of a household refrigerator and showed a reduced switching frequency and lower temperature fluctuations in the refrigerator compartment. Ben-Abdallah et al. (2019) came to similar conclusions by integrating PCM into the evaporator of an open display cabinet. Although the most commonly studied PCM configuration is the integration into the evaporator, another possibility is the integration into the condenser. Cheng et al. (2011) were able to reduce the power consumption of a refrigerator/freezer combination by up to 12 % through the integration of a paraffin-polyethylene compound on the integrated, i.e. foamed, condenser. In another investigation (Sonnenrein et al., 2015), we studied different options of sensible and latent heat storage elements integrated into standard wire-and-tube condensers and were able to reduce the power consumption by about 10 % with a newly developed PCM polymer compound.

The third possibility is to integrate PCM inside the freezer or refrigerator to reduce temperature fluctuations or to slow down the temperature rise, e.g. in case of a power failure. Gin et al. (2010a, b) studied the temperature rise in a household freezer with integrated PCM panels during power loss, defrosting cycles as well as door openings and found an improved storage quality and a significantly decreased rate of temperature increase inside the freezer. Oró et al. (2012a) found consistent results for commercial freezers and also observed a significantly slower temperature rise in case of a refrigeration system failure (Oró et al., 2012b). Liu et al. (2017) placed a NaCl/H2O mixture in the freezer and water as a PCM in the air duct of the fresh food chamber of an air-cooled frost-free refrigerator and found a decreased temperature rise in the fresh food and freezing compartments, but noticed an increase of power consumption depending on the operating mode. More studies about the application of PCM in refrigerators/freezers can be found in the reviews of Mastani Joybari et al. (2015) or Bista et al. (2018).

Together, these studies provide a good insight into the general advantages of PCM in refrigerators and freezers, such as the positive influence on COP, temperature fluctuations and on/off ratio. However, none examined the effects on the new standardized functional test procedures introduced internationally by the IEC 62552:2015. With this standard, cooling capacity and temperature rise time can now be quantified in the same way as the energy consumption and will thus play a comparable role in the future. Therefore, this paper studies the effect of a polymer-bound PCM on (1) the cooling capacity and (2) the energy consumption according the IEC 62552:2015 of eight commercially available household refrigerators. Moreover, the effects on the (3) temperature rise time in the refrigerator compartment were determined. For this purpose, a test procedure was developed that is analogous to the IEC test for freezer in order to examine the refrigerators' suitability as future smart appliances.

2 Test setup

2.1 Methodology

The tests in this study were performed according to IEC 62552:2015 (IEC 62552:2015, 2015). The cooling capacity test determines the time required to cool a specific load (4.5 kg per 100 l volume) from 25 °C down to 10 °C; details can be found in Part 2 of the IEC standard. The original temperature rise test in the IEC standard determines the time interval for the temperature of a specific load to increase by a certain amount. In the case of a three- or four-star freezer compartment, this would be from -18 °C to -9 °C, once the operation of the refrigeration system has been interrupted, details can be found in Part 2 of the IEC-standard. Analogously, in this study the time interval was determined during which the temperature of a specific load in the refrigerator compartment rises from 8 °C to 11 °C. Following Part 3 of the IEC standard, all power consumption tests were also performed at an ambient temperature of 25 °C. Although the standard mentions energy consumption tests at 16 and 32 °C ambient temperature and an interpolation of the measurements results to 25 °C, the method can in principle be applied at any other ambient temperature.

2.2 Measurement of temperatures and power consumption

The test setup and all executed measurement procedures were in accordance with the IEC standard mentioned above. Fig. 1 schematically shows the standard temperature measurement positions TMP_1, TMP_2 and TMP_3 as well as the filling and distribution of test packages and M-packages (M1 to M6) in a fresh-food compartment.

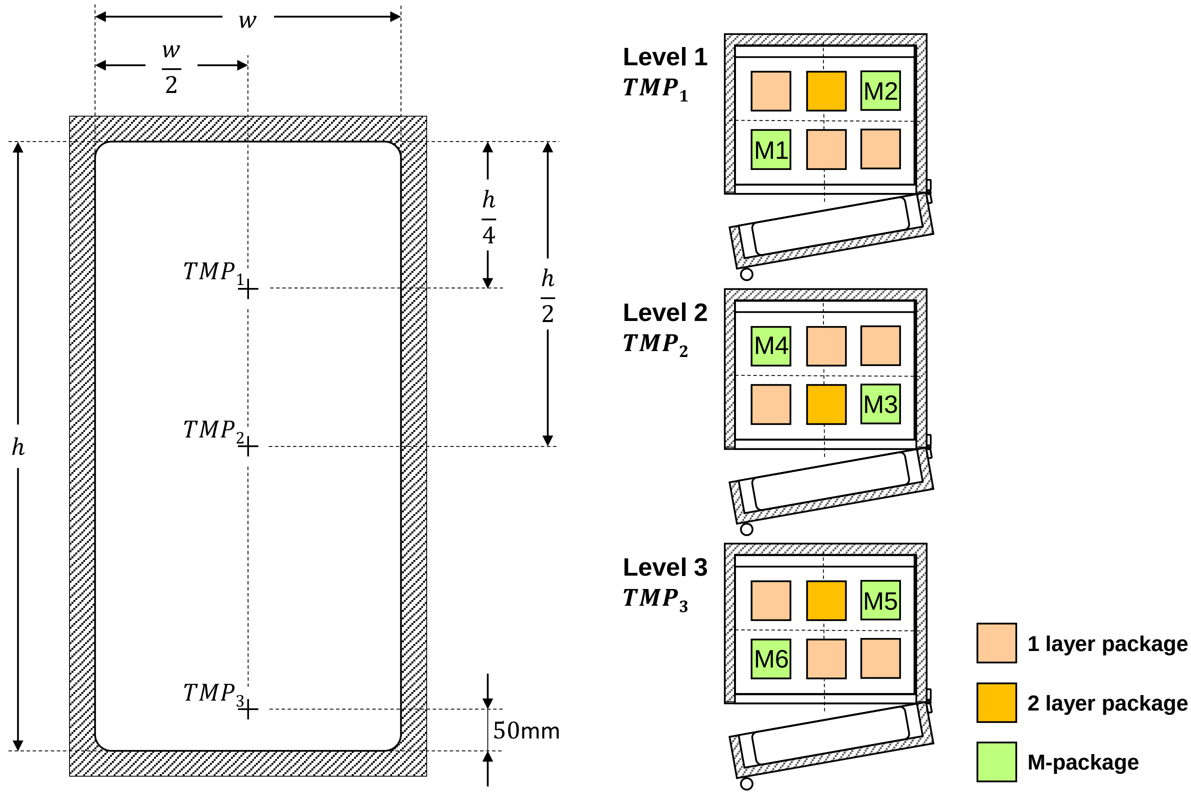

Fig. 1 Standard temperature measurement positions TMP_1, TMP_2 and TMP_3 (left) and the filling and distribution of test packages and M-packages in a fresh-food compartment (right).

Temperature sampling was carried out by thermocouple differential measurements, each measuring point with a reference junction in an ice water bath. The utilized acquisition interface OMB-DAQ 55/56 (Omega Technologies) was combined with a pre-amplifier LTC1050 (Linear Technologies), which limits the offset conditioned by zero-point drift to ±0.025 K. The typical error of thermo-elements of ±1% x ΔT in other work was reduced to ±0.5% x ΔT by batch consistency and polynomial calibration. For determining the power consumption under standard conditions (average temperature of the fresh-food compartment T_{ma} = 4 °C, ambient temperature T_{ama} = 25 °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 < 1%. Table 2 summarizes the measured quantities and their associated uncertainties.

Table 2 – Measured properties and their uncertainties.

Measured quantity	Measuring device	Uncertainty
Temperature	Thermocouples	±0.1 K
Power	Energy meters	±0.05 W
Time	Personal computer	±0.1 s/day

2.3 Refrigerating appliances

A total of eight commercially available refrigerators and refrigerator-freezers with volume capacities of the fresh food compartment between 158 l and 320 l were analyzed. Power consumption, cooling capacity and temperature rise tests were first performed with the appliances in their original state and subsequently with PCM. Table 3 summarizes the essential technical data of the examined appliances. Fig. 2 shows the setup of a fresh-food compartment equipped with PCM and M-Packages.

Table 3 - Technical data of the examined refrigerating appliances.

Test device	R1	R2	R3	R4	C1	C2	C3	C4
Combined refrigerator-freezer	no	no	no	no	yes	yes	yes	yes
Refrigerator model	K9252i-1	K12020 S-1	KRIE 2183	K37272 iD	CUPesf 3503	KD12622 S edt/cs	KG39 EAI40	BCD-185TNG
Manu-facturer	Miele	Miele	Bau-knecht	Miele	Liebherr	Miele	Siemens	Haier
Dimensions (HxBxT) [mm]	872 x 540 x 550	850 x 628 x 601	1770 x 535 x 540	1772 x 560 x 550	1817 x 631 x 600	1623 x 637 x 600	2010 x 650 x 600	1900 x 700 x 680
Fridge storage volume [l]	158	167	320	216	232	199	247	185
Total storage volume [l]	158	167	320	216	323	253	339	243
Refrigerant	35 g R600a	22 g R600a	55 g R600a	60 g R600a	90 g R600a	48 g R600a	78 g R600a	42 g R600a
Energy label	A++	A+	A++	A++	A++	A++	A+++	A++

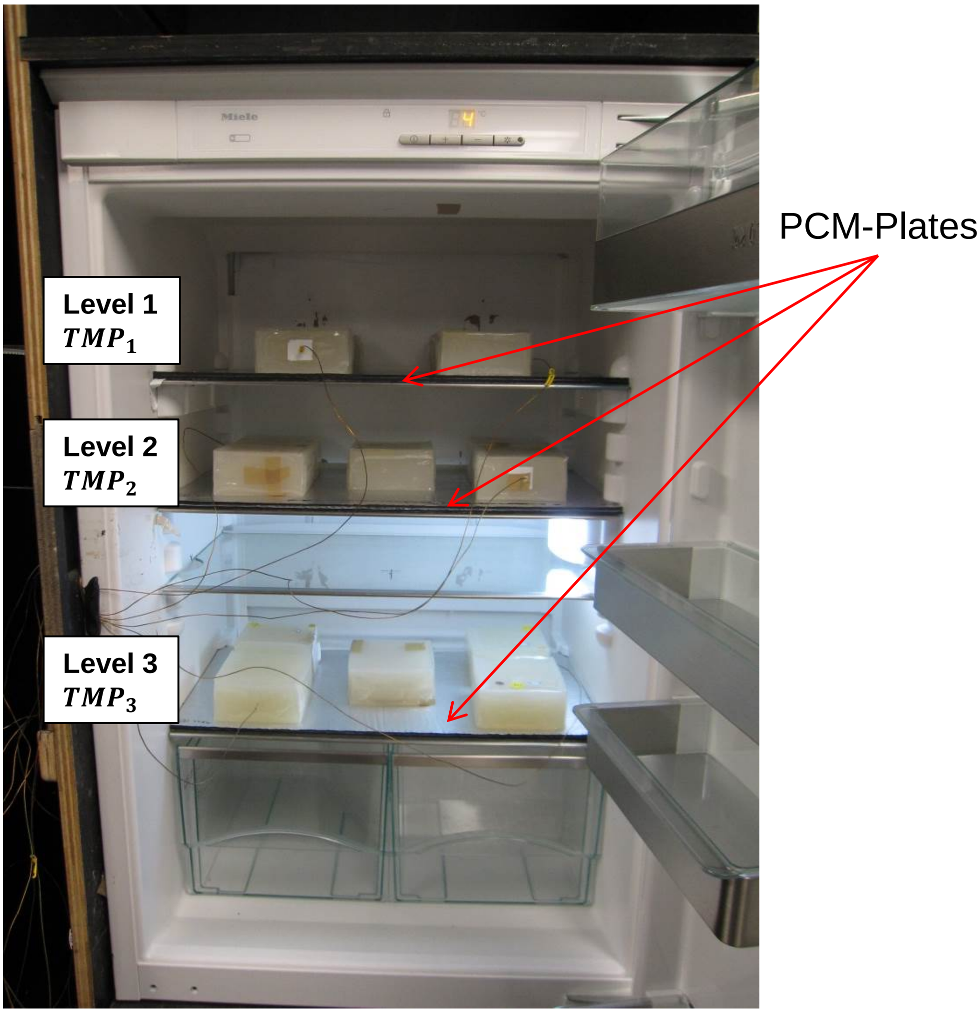

Fig. 2 Fresh-food compartment of a tested appliance equipped with PCM and M-packages.

2.4 Heat storage materials

High-capacitive, dimensionally stable latent heat storage elements based on polymer-bound organic paraffin derivatives were developed in this study. In contrast to prior approaches, this compound material is dimensionally stable and in its "liquid" state it is secure against leakage and exudation. Therefore, an elaborate encapsulation is not necessary and the PCM compound was processed into foil-laminated sheets and integrated on top of shelves of the refrigerating appliances, in order to examine their influence on performance and power consumption. Depending on the size of the fresh-food compartment and the number of shelves, between 1.79 and 2.96 kg of PCM were placed in the refrigerating appliances, corresponding to specific PCM densities of 0.72 to 1.41 kg per 100 l volume.

Fig. 3 shows the temperature dependence of the specific enthalpy *h* of the compound developed for the integration in fresh-food compartments of refrigerating appliances. 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 dimensionally stable polymer compound in the temperature range of from 0 °C to 15 °C is about 150 kJ/kg and the phase change temperature is around 9 °C.

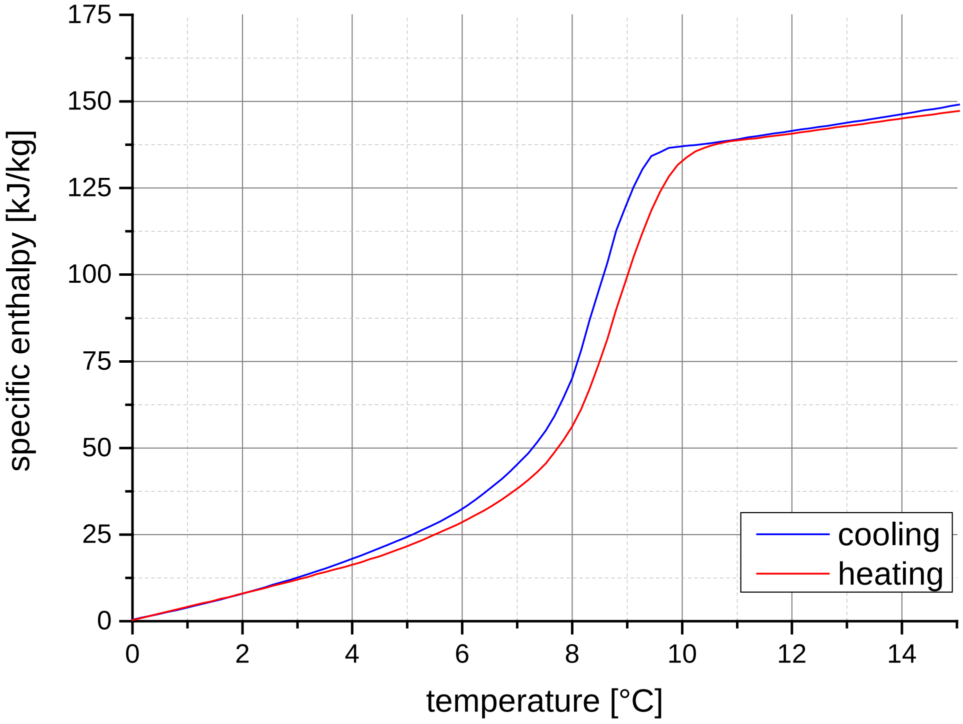

Fig. 3 Specific enthalpy as a function of temperature of the developed polymer compound.

Fig. 3 also shows a significant advantage of the present polymer compound compared to the salt-water or glycol solutions often used in other studies. The subcooling that is necessary for initiating solidification of these liquids, thus the difference between melting and freezing temperature, is typically between 5 and 15 K, whereas the present polymer compound does not undergo significant subcooling. This is crucial for the use in the fresh food compartment, where only very small temperature differences are available for solidification and melting of the PCM. A further advantage of the present polymer compound is its transparency (or milky transparency), which also enables simple integration into the (e.g. double-walled) shelves in later practice, cf. Fig. 4.

Fig. 4 Transparency of the present polymer compound from solid (up) to liquid (down).

3. Results and discussion

Experimental tests with eight commercially available household refrigerators and refrigerator-freezers, cf. Table 3, equipped with PCM polymer compound were carried out to investigate the effect on cooling capacity, temperature rise and daily energy consumption following the global standard IEC 62552:2015 (IEC 62552:2015, 2015).

3.1. Cooling capacity

The cooling capacity test according to IEC 62552:2015 (IEC 62552:2015, 2015) determines the time required to cool a specific load (4.5 kg per 100 l volume) from 25 °C down to 10 °C. For this purpose, the refrigerating appliances were each loaded with 4.5 kg per 100 l (fresh-food compartment) volume with defined test- and M-packages (IEC 62552:2015, Part 1, Annex C) according to a defined filling plan (IEC 62552:2015, Part 2, Chapter 7), cf. Fig. 1. Loading started when stable operating conditions with a mean temperature T_{ma} = + 4 °C ± 0,5 K have been attained. In order to achieve comparable and reproducible results, loading always took place exactly at the start of a compressor cycle. And as defined in the standard, if the appliance had a "quick cooling" function, this was activated at the moment when the load was inserted. Fig. 5 shows an exemplary temperature curve of such a cooling capacity test, where the cooling time was measured by determining the time between loading and when the arithmetic mean of the temperatures of all M-packages ($T_{M,a}$) has reached 10 °C.

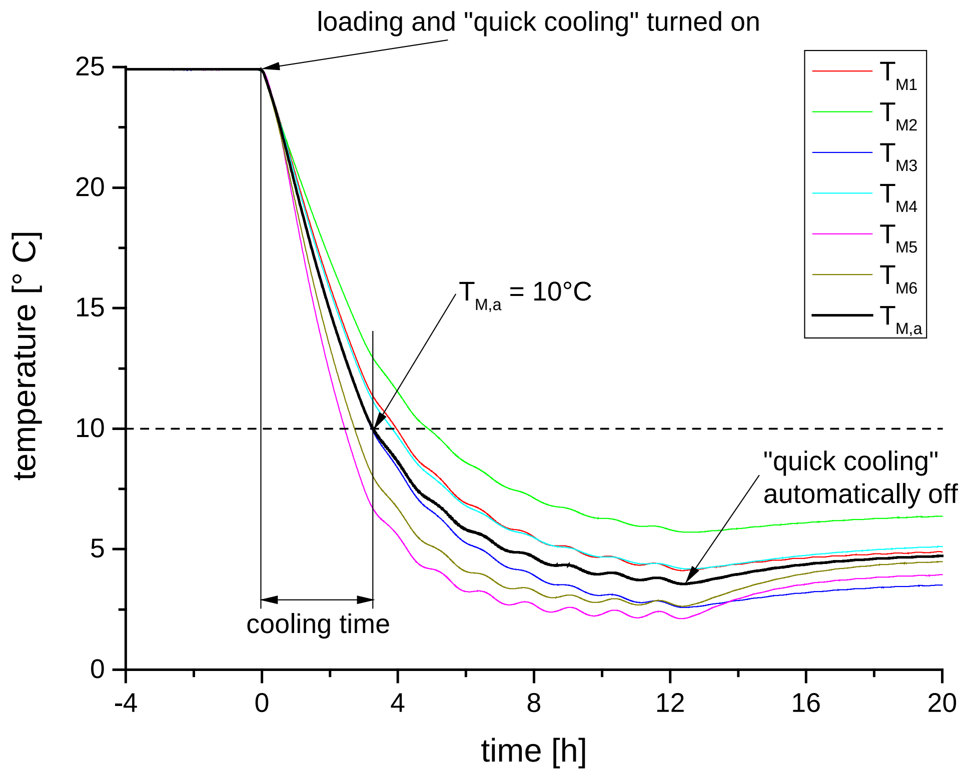

Fig. 5 Temperatures of the M-packages during the cooling capacity test according to IEC 62552:2015.

The influence of the latent heat storage elements integrated into the fresh-food compartment on the cooling time is exemplarily shown in Fig. 6. The cooling time of the refrigerator-freezer C1 equipped with PCM was reduced by 33 % from 5.9 to 3.9 h. Fig. 7 summarizes the results of all cooling capacity measurements. The cooling time could be significantly shortened by the PCM for all refrigerating appliances, i.e. between 0.55 to 2.00 h in absolute terms and between 16 to 33 % in relative terms.

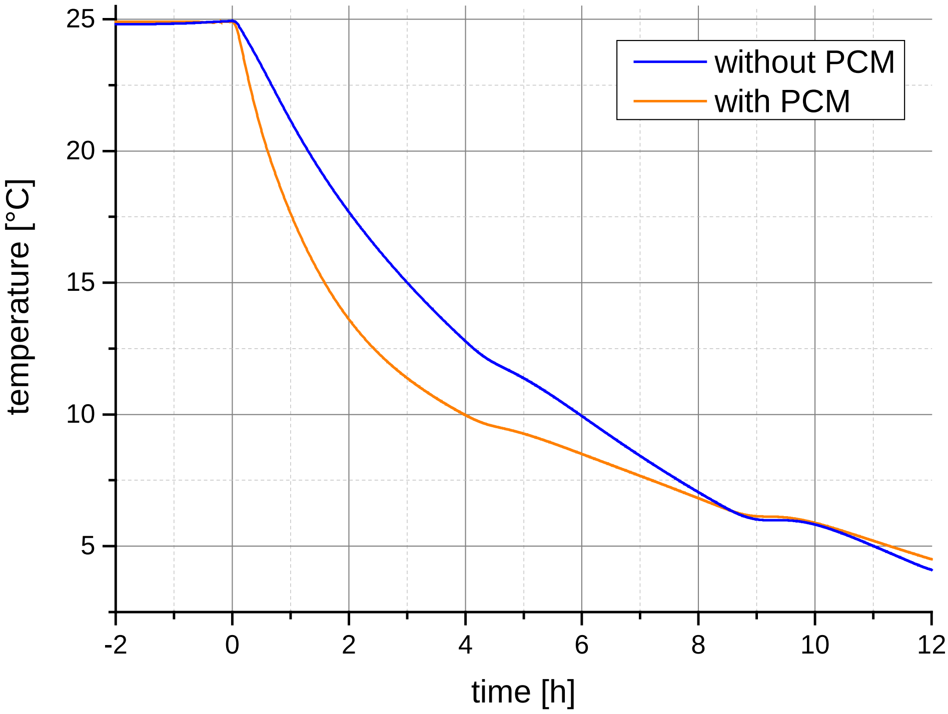

Fig. 6 Mean temperatures of M-packages ($T_{M,a}$) during cooling capacity test of refrigerating appliance C1 without (blue) and with PCM (orange).

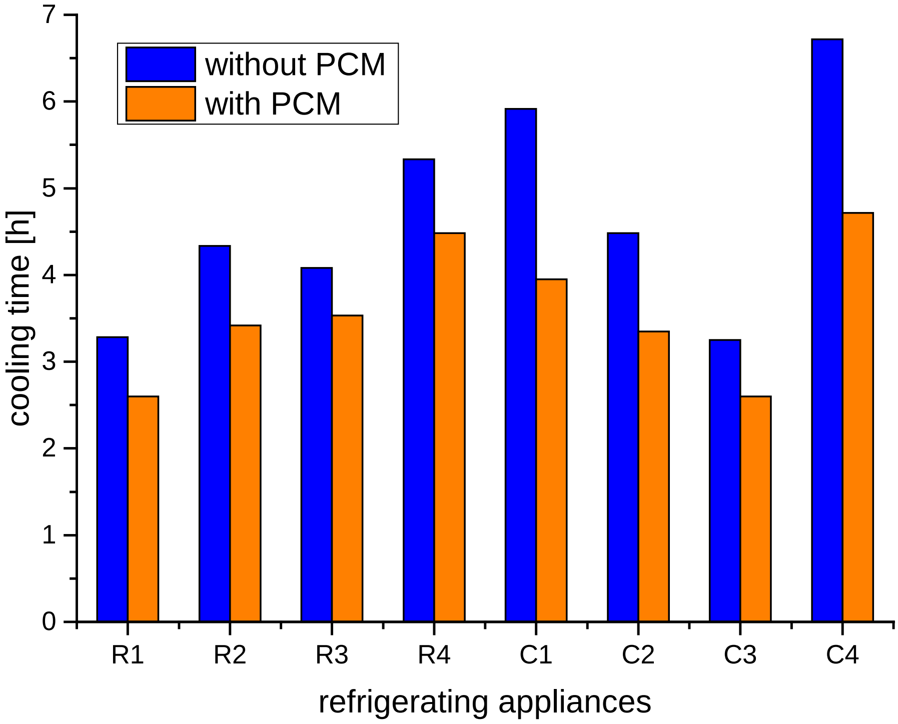

Fig. 7 Cooling capacity test of the studied refrigerating appliances without (blue) and with PCM (orange).

3.2 Temperature rise

The temperature rise time in case of (external) switch off, only tested on freezers so far, will in the future be a decisive factor in the context of the use of refrigerators as "smart appliances" for energy peak shaving. Although network connectivity of household refrigerators/freezers is currently not a commercial reality, due to their large number, they might play a role here in the future. The European Commission is currently engaged in a horizontal preparatory study on this subject (LOT 33, 2019). The actual temperature rise test in the IEC standard (IEC 62662:2015, Part 2, Annex C) determines the time taken for the temperature of a specific load in the freezer compartment to rise from -18 °C to -9 °C after power is disconnected. Analogously, in this study the temperature rise time was determined in which a specific load in the refrigerator compartment rises from X °C to Y °C.

While the -18 °C is clearly defined as the maximum permissible temperature in the compartment of a three- or four-star freezer (IEC 62552:2015, Part 2, Table 2), i.e. the lower temperature limit (X °C) can be defined analogously as the maximum permissible temperature of 8 °C in the fresh-food compartment. The upper temperature limit of -9 °C stated in the original freezer test is more or less arbitrary, i.e. not defined anywhere else (two-star freezer < -12 °C, one-star freezer < -6 °C). The only remaining definition is that during a defrost period, which is comparable to a switch off, the temperature may rise by a maximum of 3 K. Following this analogy, the upper temperature limit Y °C for determining the temperature rise time in fresh food compartments was set to 11 °C here. Like in section 3.1, the refrigerating appliances were loaded with 4.5 kg test and M-packages per 100 l (fresh-food compartment) volume according to the filling plan. In analogy to the freezer temperature rise test, the power supply was switched off once stable operating conditions were achieved, and the temperature rise time was determined as the the time during which the arithmetic mean of the temperatures of all M-packages $T_{M,a}$ rises from 8 °C to 11 °C.

Fig. 8 shows exemplary temperature curves of the M-packages of such a measurement. The influence of the latent heat storage elements integrated into the fresh-food compartment on the temperature rise time is exemplarily shown in Fig. 9. While the temperature of the warmest M-package without PCM rises continuously, the temperature curve with PCM shows a clear temperature plateau in the range of the melting temperature. Thereby, the temperature rise time of refrigerator R1 equipped with PCM was increased by 145 % from 2.2 to 5.4 h. It is also evident that when considering an upper temperature limit of $T_{M,a}$ = 12 °C instead of $T_{M,a}$ = 11 °C, the increase would even be greater.

Fig. 10 summarizes the results of all temperature rise time measurements. The temperature rise time could be significantly increased by the PCM for all refrigerating appliances, i.e. between 2.15 to 4.48 h in absolute terms and between 75 to 145 % in relative terms.

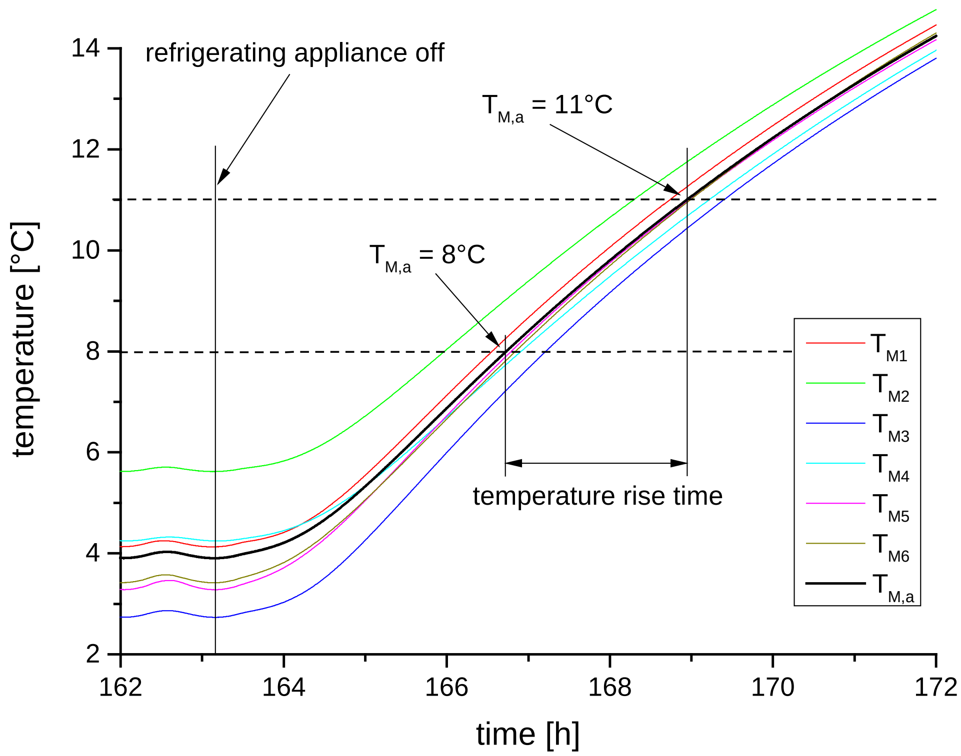

Fig. 8 Temperatures of the M-packages during the temperature rise time test in analogy to IEC 62552:2015.

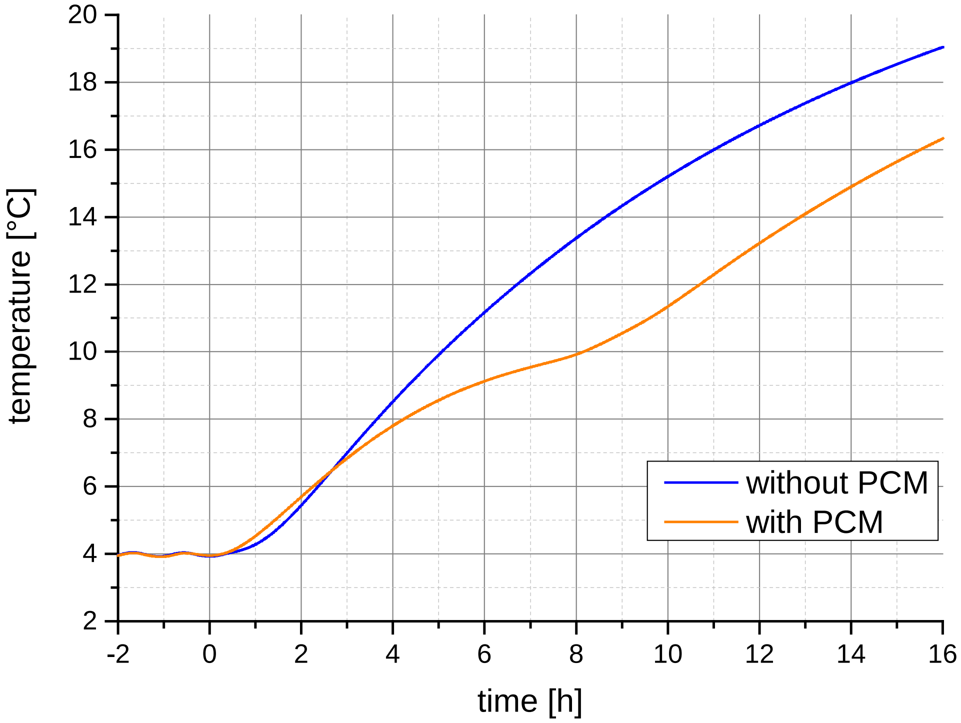

Fig. 9 Mean temperatures of M-packages ($T_{M,a}$) during the temperature rise time test of refrigerating appliance R1 without (blue) and with PCM (orange).

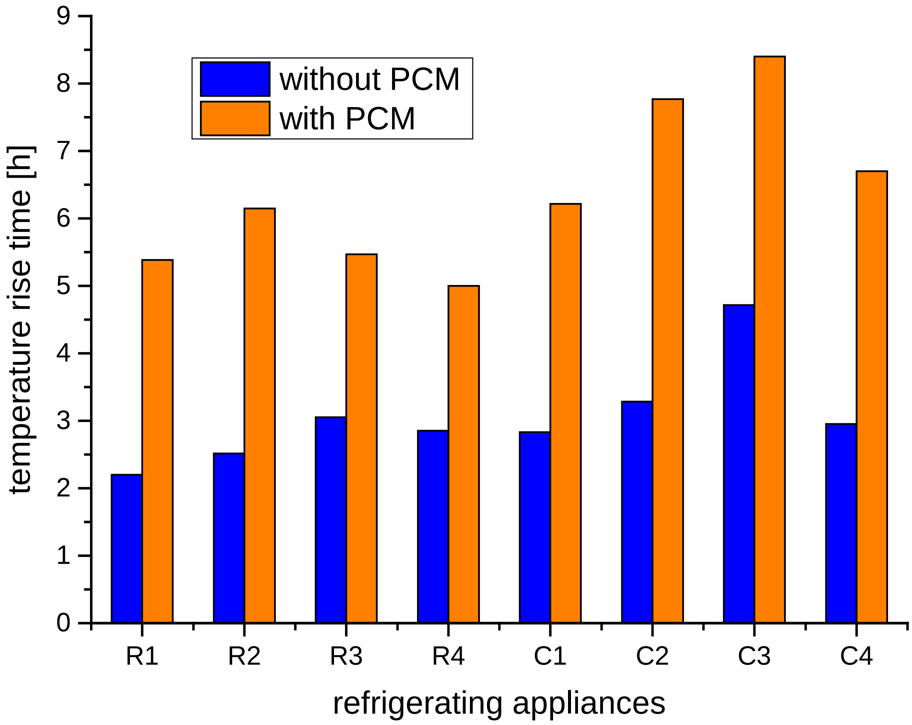

Fig. 10 Temperature rise time of the studied refrigerating appliances without (blue) and with PCM (orange).

3.2. Energy consumption

Even though performance tests have now been internationally standardized with the global standard IEC 62552:2015, the daily energy consumption remains the most important technical specification of a refrigerating appliance. Therefore, the effects of all modifications on power consumption were measured to facilitate their later implementation into practice. A summary of the results including the energy consumption measurements obtained during the experiments of this study is given in Tables 4 and 5. In all cases with PCM, the results show that the cooling capacity as well as temperature rise time was increased without affecting energy consumption. The maximum deviations found here are all within the range of the uncertainty of the energy consumption measurement.

Table 4 – Test results of the studied refrigerators.

Test device			R1 refrigerator	R2 refrigerator	R3 refrigerator	R4 refrigerator
Fridge storage volume		[l]	158	167	320	216
Thermostat set point			3 °C	4 °C	3 °C	4 °C / b5
PCM mass		[g]	2235	2271	2297	2360
		[kg/100l]	1.41	1.36	0.72	1.09
Cooling time	without PCM	[h]	3.28	4.33	4.08	5.33
	with PCM	[h]	2.60	3.42	3.53	4.48
	difference	[h]	-0.68	-0.92	-0.55	-0.85
	relative		126%	127%	116%	119%
Temperature rise time (average)	without PCM	[h]	2.20	2.52	3.05	2.85
	with PCM	[h]	5.38	6.15	5.47	5.00
	difference	[h]	3.18	3.63	2.42	2.15
	relative		245%	244%	179%	175%
Daily energy consumption	without PCM	[kWh/day]	0.377	0.437	0.384	0.375
	with PCM	[kWh/day]	0.371	0.431	0.384	0.379

Table 5 – Test results of the studied refrigerator-freezers.						
Test device			C1 combination	C2 combination	C3 combination	C4 combination
Fridge storage volume		[l]	232	199	247	185
Thermostat set point			1 °C	5	4 °C / -16 °C	3.6
PCM mass		[g]	2963	2814	2235	1791
		[kg/100l]	1.28	1.41	0.90	0.97
Cooling time	without PCM	[h]	5.92	4.48	3.25	6.72
	with PCM	[h]	3.95	3.35	2.60	4.72
	difference	[h]	-1.97	-1.13	-0.65	-2.00
	relative		150%	134%	125%	142%
Temperature rise time (average)	without PCM	[h]	2.83	3.28	4.72	2.95
	with PCM	[h]	6.22	7.77	8.40	6.70
	difference	[h]	3.38	4.48	3.68	3.75
	relative		219%	237%	178%	227%
Daily energy consumption	without PCM	[kWh/day]	1.146	0.716	0.479	0.426
	with PCM	[kWh/day]	1.164	0.710	0.475	0.423

4 Conclusions

A polymer-bound PCM with a phase change temperature around 9 °C was developed and integrated into the fresh-food compartment of different commercially available household refrigerating appliances. In this experimental study, their influence on daily energy consumption, cooling capacity and temperature rise time according to the global standard IEC 62552:2015 was studied.

The results show a considerable positive influence on the performance indicators cooling capacity and temperature rise, without negatively impacting energy consumption. Through the integration of PCM into the appliances, the cooling capacity was increased by up to 33 % and temperature rise time even by up to 145 %.

Given that the present polymer compound is leak proof and (milky) transparent, a direct integration into the fresh-food compartment shelves of household refrigerators/freezers can also be easily implemented into practice. It was shown that this also enhances the suitability of refrigerators/freezers as "smart appliances" to meet the growing demand for balancing energy to compensate the growing volatility of renewable energy.

Nevertheless, future work on developing polymer-bound PCM with lower phase change temperatures and evaluating their effects on cooling capacity and temperature rise time has to be done.

Acknowledgements

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