

Phase Change Materials for Performance Enhancement in Household Refrigeration: A Review

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Abstract *This paper reviews the use of phase change materials (PCMs) to improve the performance of household vapour-compression refrigerators. It first summarizes PCM selection criteria (phase-change temperature matching the thermostat range, high latent heat, adequate thermal conductivity, low supercooling/segregation, limited volume change, and chemical stability/safety). Furthermore, it outlines the main PCM classes (organic, inorganic, eutectic) together with practical measures such as encapsulation and conductivity enhancement via composites. The review also compiles examples of commercially available PCMs with melting temperatures relevant for refrigeration applications (approximately from −21 °C to +7 °C), highlighting that suitable market-ready solutions already exist. The core of the review compares PCM integration concepts at key locations: (i) at the evaporator, where improved heat transfer can raise evaporating temperature, extend compressor off-time, reduce temperature fluctuations, and support demand-side management; (ii) at the condenser, where lower condensing temperature and shorter on-time are possible but may be offset by more frequent compressor cycling; and (iii) inside the refrigerated compartment, where added thermal inertia dampens temperature swings, mitigates door-opening disturbances, and improves resilience during power outages. Finally, combined placements (e.g., evaporator + condenser) are discussed as a route to synergistic benefits, provided phase-change temperatures and geometry are selected appropriately.*

Keywords *household refrigerator, vapor-compression, phase change materials, heat transfer, energy efficiency*

Highlights

- *Market-ready PCMs already cover typical refrigeration temperature ranges.*
- *Compartment PCM adds thermal inertia, smoothing temperature swings and improving holdover.*
- *Evaporator PCM can improve heat transfer, stabilize operation, and reduce on/off cycling.*
- *Evaporator + condenser PCM can be beneficial if phase-change temperatures are well matched.*

1 INTRODUCTION

The heating and cooling sector, which accounts for 50 % of global energy consumption [1], plays a pivotal role in this transition. Reducing the energy consumption for heating by 50 %, which is technically feasible, would have a greater impact than if all global road transport achieved zero energy consumption, which is clearly impossible for road transport. One of the potentials is seen in phase change materials (PCMs). They enable efficient thermal energy storage by absorbing and releasing heat during phase transitions, allowing load shifting, peak demand reduction, and cost savings through the use of off-peak or renewable energy, enhance overall energy efficiency by stabilizing thermal conditions, reducing active heating and cooling requirements, and providing reliable thermal buffering across a wide range of applications and temperature ranges [2-4].

Even though refrigerators and freezers may seem to have low power consumption, their mode of operation and worldwide distribution add up to a high electricity demand. The International Institute of Refrigeration estimated more than 2 billion operating refrigeration units in their 2019 report [5]. Therefore, a small increase in the performance of these appliances yields enormous energy savings. Most ideas for improving the performance of refrigeration systems fall into the following categories: (i) development of energy-efficient compressors, (ii) improvement of thermal insulation, (iii) enhancement of heat transfer of heat exchangers, i.e., condensers and evaporators, (iv) advanced control and operation strategies, (v) refrigerant and lubricant selection and (vi) optimized refrigeration cycle and system architecture.

Household refrigerators and freezers usually operate intermittently by a simple on/off control. The use of variable-speed compressors (VSCs) would allow the transition to a continuous operation. This would decrease mechanical friction and throttling losses in the compressor, increase the evaporator temperature, and decrease the condenser temperature. Improvements of thermal insulation are limited. Currently, polyurethane is mostly used as an insulator in the refrigerator, and even though the thermal conductivity of polyurethane boards is very low, a large quantity of heat is gained even at optimum thickness. It is possible to further reduce heat gains from the walls of a refrigeration system using vacuum insulation panels (VIPs). VIPs are very resistant to the heat transfer, more specifically, about 4-times the thermal resistance of a polyurethane board of equal thickness. Both VIPs and VSCs are very promising technologies, unfortunately due to higher cost, their use is limited to specialized appliances only.

The maximum efficiency of refrigeration processes is determined by the temperatures of the evaporator and condenser. A 1 K increase in evaporator temperature usually results in a 3 % to 4 % reduction in power consumption, and a 1 K reduction in condenser temperature reduces power consumption by 2 % to 3 % [6]. Enhancement of heat transfer from heat exchangers can be achieved by larger evaporator and condenser surface area by adding fins. Alternatively, fans also enhance convective heat transfer, however, their own power consumption must be taken into account.

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Another possibility that has attracted much attention in recent years is the use of PCMs, which can absorb large amounts of heat at a nearly constant temperature and are therefore particularly suitable for heat storage. Because of the high potential for increasing the efficiency of refrigerators, this work presents PCMs and their possible use in refrigerators.

To provide broader context for the present review, Fig. 1 compares publication activity in three representative PCM application areas based on a search in ScienceDirect database search for the last 10 years, performed on April 25, 2026: refrigeration applications (−21 °C to 7 °C), domestic heating applications (20 °C to 60 °C), and industrial waste heat recovery (> 80 °C). The comparison is intended to illustrate general research trends. Although PCM technologies have been widely investigated across multiple temperature ranges, refrigeration-related applications remain comparatively less represented, particularly in review literature. This highlights the continued need for focused assessments of PCM integration in cooling and refrigeration systems.

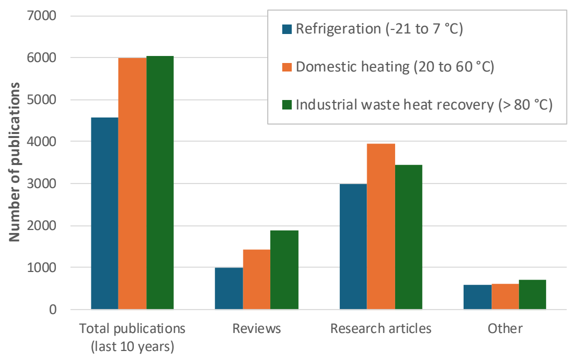

Fig. 1. Comparative publication statistics for selected PCM application areas based on a ScienceDirect database search

While previous reviews [7-13] provide a comprehensive overview of PCM applications in refrigeration systems, this work builds upon both earlier and recent studies to provide a structured, system-level analysis of PCM integration strategies and their practical implications. Rather than focusing solely on newly published studies, this review emphasizes a unified comparison and interpretation of existing results across different system configurations. The main contribution of this review lies in three aspects:

i. A consistent and comparative analysis of PCM integration across different locations within the refrigeration system (evaporator, condenser, compartment, insulation+PCM and combined configurations), which is not systematically addressed in previous reviews;
ii. A system-level perspective focusing on practical performance metrics such as compressor cycling behavior, temperature stability, and operational trade-offs;
iii. An updated overview of commercially available PCMs within the relevant temperature range, highlighting the current state of practical implementation.

In addition, while earlier studies form the foundation of this field, we have also incorporated recent literature to reflect ongoing developments, particularly in system-level evaluation and material availability.

In section 2 PCM materials, their classification and properties are presented. In section 3 state-of-the-art PCM placements at different locations in the refrigeration system are described, as well as their advantages, disadvantages and working principles. Sections 4 and 5 outline discussion and conclusions, respectively.

2 PCM MATERIALS FOR COLD THERMAL STORAGE

Almost any substance can serve as a PCM, as long as it can undergo the phase transitions when the external conditions in the application are met. In other words, phase change temperature of PCM should be suitable for the process in which PCM is used. However, certain physical, chemical, and economic properties are desirable for the PCM [7]. Table 1 gathers the most important physical, chemical, and economic properties that should be considered when selecting the appropriate PCM. While conventional PCMs are widely used in CTES applications, there is growing interest in exploring sustainable bio-based alternatives, derived from biomass and bio-waste materials [14-16].

Table 1. Important desired (required) physical, chemical and economic properties of PCMs

Physical properties	Chemical properties	Economic properties
suitable phase change temperature	chemically stable	price-performance
completely reversible freeze/melt cycle	low vapor pressure	abundance
high enthalpy change	compatibility with other material	recyclability
high specific heat capacity	non-toxic	
high thermal conductivity	non-flammable	
low supercooling		
low phase separation		
low volume change		
small temperature glide during phase change		

An additional desirable property is a small temperature glide during phase change. Some PCMs, particularly mixtures, undergo phase transition over a temperature range rather than at a single temperature. While this may be acceptable in applications with broader temperature tolerance, it can negatively affect performance in refrigeration systems where stable and well-defined temperatures are required.

As already mentioned, a suitable phase change temperature must absolutely be fulfilled in order to be able to use the material as PCM at all. A high enthalpy change allows the material to store/release a large amount of energy during the phase change. Similarly, a high specific heat capacity allows the material to store/release large amounts of energy during heating/cooling of the material. High thermal conductivity of the material is important, because it allows faster heat transfer from the system or environment to PCM, resulting in faster responses. Thermal conductivity of PCM can be improved by fabrication of PCM composites, e.g. by adding nanoparticles, metal foam, or expanded graphite into pure sub- stance.

Supercooling refers to the phenomenon where a liquid is cooled below its equilibrium phase change temperature without immediate solidification. This results in delayed nucleation and can significantly affect system performance by lowering the effective operating temperature. In contrast, material hysteresis describes the intrinsic difference between melting and freezing curves of a PCM (Fig. 2), independent of supercooling effects. In practical systems, once nucleation occurs, the release of latent heat often causes the temperature to increase toward the equilibrium freezing temperature. A high degree of supercooling can be reduced with suitable nucleating agents.

Phase separation (segregation) worsens heat transfer inside the PCM and is therefore undesirable. Gelled or thickened mixtures can partially eliminate the phase separation problem. Large volume changes due to phase change are unwanted because they can cause bursting of the container in which PCM is stored. Alternatively, PCM encapsulation provides the ability to store the material in smaller, separated parts, making it easier to control volume changes of PCM. Other advantages of encapsulation include a large heat transfer surface area and reduced risk to the environment in the event of a leakage [17]. The density of PCM is also important, however, it depends on design conditions, whether mass or volume is the limitation. Usually, high density means high heat of fusion per unit volume and low heat of fusion per unit weight [18].

PCMs should be chemically stable and should not degrade over time or due to phase change in order to ensure a durable process. In addition, a low vapor pressure is desirable [7]. In the case of corrosive PCM or other types of incompatibilities with other materials, encapsulation of PCM in chemically neutral (inert) material should be considered. Non-toxic and non-flammable PCMs are desirable in terms of low impact to the environment and the customer. In addition, recyclability of PCMs should also be considered to reduce environmental impact. The price of PCM, which is related to the abundance of PCM, is an important (if not the most important) factor in the feasibility study.

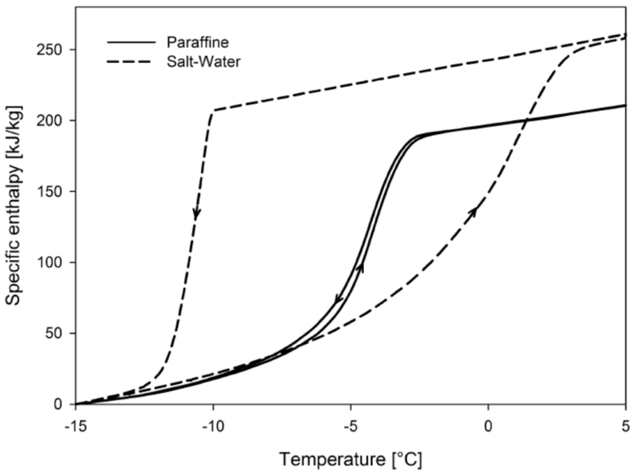

Fig. 2. Specific enthalpy as a function of temperature of the paraffin derivative (solid lines) compared to a salt-water mixture (dashed lines) (reproduced from Ref. [19] with permission from Elsevier, © 2015)

In general, PCMs are divided into 3 groups based on the source of PCM, namely organic, inorganic, and eutectic PCMs. Each group is further subdivided into subgroups as shown on Fig. 3, while Table 2 summarizes the general advantages and drawbacks of each group.

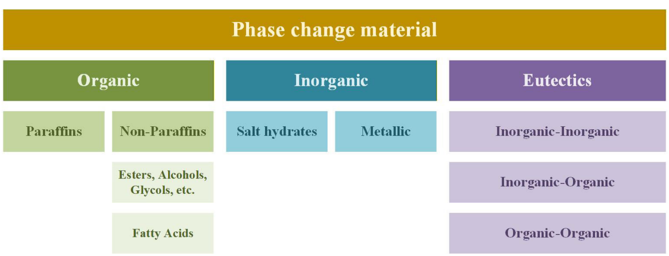

Fig. 3. Classification of PCMs (adapted from [18])

Organic PCMs are divided into paraffins and non-paraffins, which are further subdivided into fatty acids and hydrocarbonates. Examples of parrafins are paraffin wax, *n*-tridecane, and *n*-trioctane. In general, paraffins have the chemical formula C_nH2_{n+2}, where n is further explained in [20,21]. They are quite expensive but are still most commercially used PCM due to their properties. Fatty acids are about two to three-times more expensive in comparison to paraffins [18]. They have the chemical formula $CH_3(CH_2)_x$ COOH, where x is further explained in [6,23]. Examples of fatty acids are acetic acid and stearic acid, while other non-paraffins are: beeswax, esters, and glycerol (glycerin).

Table 2. General properties for specific type of PCM [7-10,18,22]

Desired properties	Organic	Inorganic	Eutectic
high enthalpy change	low	high	high
high specific heat capacity	low	high	high
high thermal conductivity	low	high	low
low supercooling	almost none	high	low
low phase segregation	low	high	low
low volume change	high	smaller than organic	moderate
compatibility	non-corrosive	corrosive	n.a,
chemical stability	good	good	good
non-toxicity	non-toxic	partially	n.a.
non-flamability	highly flammable	low flammability	flammable (organic-based), nonflammable (salt-based)
low price	low	low	high
recyclability	partially	yes	n.a.
abundance	yes	yes	no

Inorganic PCMs are divided into salt hydrates with chemical formula $AB \cdot n\,H_2O$ and metallic materials, i.e. metals with high latent heat capacity. Salt hydrates are the oldest and most studied PCMs and their cost is low due to their easy availability. Nevertheless, salt hydrates have many drawbacks, such as corrosion of metal material, supercooling, and phase separation, i.e., salts settle to the bottom (due to higher density) and reduce the active volume. Metals as PCMs are not seriously considered for commercialization due to high density and high cost.

Eutectic PCMs consist of two or more components combined at a specific composition that results in a single, well-defined melting and solidification temperature. Unlike non-eutectic mixtures, they undergo phase change at nearly constant temperature, similar to pure substances. Eutectic behavior can occur in both organic and inorganic systems, including salt hydrates, and is therefore not a separate material class but a compositional characteristic. Consequently, the classification presented in Fig. 3 distinguishes materials primarily by their chemical nature, while eutectic mixtures may exist within each category.

The advantage of a mixture is the ability to carefully adjust the temperature of phase change and to use the advantages of both components, resulting in better properties of the substance. However, eutectic substances are expensive.

In research, water is often used as PCM because it has outstanding heat transfer and heat storage properties (i.e., high latent heat, high specific heat, and high thermal conductivity), low environmental impact, and low price. However, the main disadvantages of water are phase separation (ice floats on liquid water), large volume change during solidification and the need for severe supercooling to freeze. In addition, the phase change temperature is not optimal for either the fresh food compartment or the freezer. More details about the optimal phase change temperatures of PCM for refrigeration systems are presented in Section 3.

Over the last years, the number of PCMs available on the market has increased. This includes new types of PCMs and a significant increase in the number of suppliers. Table 3 gathers commercially available PCMs with a melting temperature (T_m) between −21 °C and

7 °C. These PCMs are available in a variety of forms, including bulk, macro-encapsulated, and dry micro-encapsulated powder. For more details and other commercially available PCMs (with $T_m < -12$ °C or $T_m > 8$ °C) see [8].

From an economic perspective, the cost of PCM materials varies significantly depending on composition, purity, and encapsulation. Typical commercial PCM materials are generally in the range of approximately 3 to 20 EUR/kg, depending on material type and form.

Table 3. Commercially available PCMs in the temperature range from −21 °C to 7 °C, sorted by melting temperature

Material	T_m [°C]	Latent heat [kJ kg^{-1}]	Type	Producer
va-Q-accu – 21G	−21	234	/	va-Q-tec
ClimSel C-21	−21	285	inorganic	Climator AB
PureTemp –21	−21	239	bio-based organic	PureTemp LLC
E-21	−21	285	inorganic	PCM Products
ATS-21	−21	320	inorganic	Axiotherm GmbH
SP-21	−21	285	inorganic	Rubitherm GmbH
E-19	−19	300	inorganic	PCM Products
HS18N	−18	242	inorganic	PLUSS Advanced Technologies
BioPCM®	−18	200	organic	Phase-change Energy Solutions Inc.
ClimSel C-18	−18	288	inorganic	Climator AB
SP-17	−17	300	inorganic	Rubitherm GmbH
E-15	−15	320	inorganic	PCM Products
HS15N	−15	308	inorganic	PLUSS Advanced Technologies
PureTemp –15	−15	301	bio-based organic	PureTemp LLC
BioPCM®	−15	200	organic	Phase-change Energy Solutions Inc.
ATS-12	−12	360	inorganic	Axiotherm GmbH
E-11	−11	310	inorganic	PCM Products
SP-11	−11	240	inorganic	Rubitherm GmbH
SP-11 UK	−11	330	inorganic	Rubitherm GmbH
PCM-10	−10	180	inorganic	Microtek Laboratories
MPCM-10	−10	175	inorganic	Microtek Laboratories
MPCM-10D	−10	175	inorganic	Microtek Laboratories
HS10N	−10	290	inorganic	PLUSS Advanced Technologies
RT-9 HC	−9	250	organic	Rubitherm GmbH
HS7N	−7	296	inorganic	PLUSS Advanced Technologies
SP-7	−7	290	inorganic	Rubitherm GmbH
ATS-6	−6	360	inorganic	Axiotherm GmbH
E-6	−6	300	inorganic	PCM Products
RT-4	−4	180	organic	Rubitherm GmbH
E-3	−3	330	inorganic	PCM Products
HS3N	−3	346	inorganic	PLUSS Advanced Technologies
ATS-3	−3	330	inorganic	Axiotherm GmbH
PureTemp –2	−2	277	inorganic	PureTemp LLC
E-2	−2	325	inorganic	PCM Products
RT0	0	175	organic	Rubitherm GmbH
ClimSel CZ	0	393	inorganic	Climator AB
E0	0	395	inorganic	PCM Products
va-Q-accu +00G	0	330	/	va-Q-tec
HS01	1	350	inorganic	PLUSS Advanced Technologies
A2	2	230	organic	PCM Products
ATP 2	2	215	organic	Axiotherm GmbH
RT2 HC	2	200	organic	Rubitherm GmbH
OM03	3	229	organic	PLUSS Advanced Technologies
FS03	3	161	organic (fatty acid)	PLUSS Advanced Technologies
RT3 HC	3	190	organic	Rubitherm GmbH
A3	3	230	organic	PCM Products
RT4	4	175	organic	Rubitherm GmbH
PureTemp 4	4	187	organic	PureTemp LLC
A4	4	235	organic	PCM Products
BioPCM®	4	210	organic	Phase-change Energy Solutions Inc.
SP5 gel	5	155	inorganic	Rubitherm GmbH
va-Q-accu +05G	5	240	/	va-Q-tec
RT5	5	180	organic	Rubitherm GmbH
RT5 HC	5	250	organic	Rubitherm GmbH
OM05P	5	216	organic	PLUSS Advanced Technologies
A5	5	170	organic	PCM Products
CrodaTherm	5	191	bio-based organic	Croda
ATP 6	6	275	organic	Axiotherm GmbH
A6	6	185	organic	PCM Products
BioPCM®	6	210	organic	Phase-change Energy Solutions Inc.
A6.5	6.5	190	organic	PCM Products
CrodaTherm 6.5	6.8	184	Organic plant-based	Croda
Gaia OM PCM 7	7	180	organic	Global-E-Systems
ClimSel C7	7	123	inorganic	Climator AB
SP7 gel	7	155	inorganic	Rubitherm GmbH
A7	7	190	organic	PCM Products

The overall system cost associated with PCM integration depends strongly on the design and application, including encapsulation methods and integration complexity.

3 VARIOUS PCM PLACEMENTS IN THE REFRIGERATION SYSTEM

PCM can be placed in different areas of the refrigerator as shown in Fig. 4, including coupling with the evaporator, coupling with the condenser, placement inside the refrigerated compartment, and integration within cabinet walls. The most studied placement is the placement of PCM at the evaporator [19,20,23-37] and in the compartment (cabinet) [38-43]. Further, there are studies on the placement of PCM at the condenser [35,44-48], and few that consider PCM at different locations in the vapor-compression system [49]. Some studies even consider different combinations of PCM placements, e.g., at the condenser & compartment [21], and at the evaporator & condenser [19,35,50].

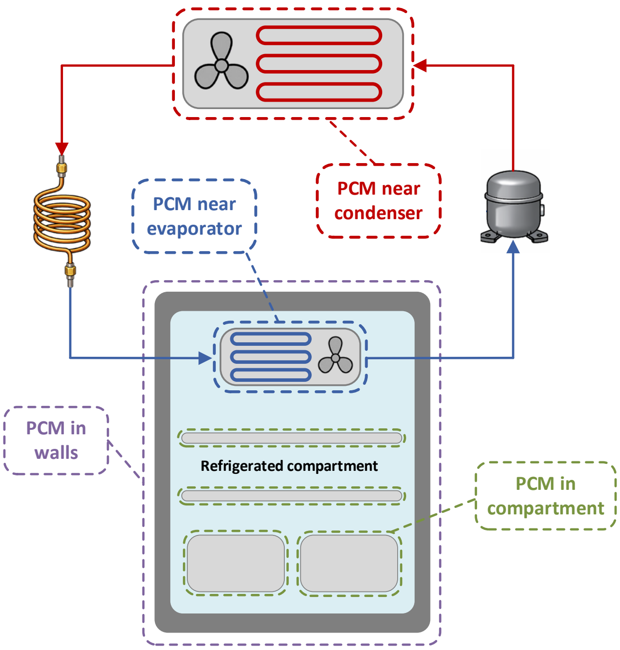

Fig. 4. Representative PCM integration locations in a vapor-compression household refrigerator

3.1 PCM at the Evaporator

During the compressor ON time, heat transfer from PCM at the evaporator causes cooling of PCM, leading to its solidification. When it solidifies, PCM is "charged" and has stored cold energy. During the compressor OFF time, the discharge process begins, resulting in heat transfer from the compartment to PCM. Meanwhile, PCM begins to liquefy and heat up. As a result, the temperature in the compartment remains lower for a longer period of time (Fig. 5). As already mentioned, PCM additionally causes a higher evaporation temperature at the evaporator due to better heat transfer conditions between PCM and the evaporator wall (compared to evaporator wall and air), resulting in a higher COP.

Figure 5a shows the evolution of the evaporation pressure in the evaporator for a refrigerator with and without PCM. The evaporation pressure is directly related to the evaporation temperature, i.e. the higher the pressure, the higher the temperature. During the compressor ON time, the evaporating pressure is higher when using PCM than in the absence of PCM. The difference in this particular case is 0.14 bar, which corresponds to a difference of about 3 K in evaporating temperature. During the compressor OFF time, the evolution of the pressure in the evaporator exhibits flat plateau corresponding to the liquefaction of PCM. In addition, longer compressor ON and OFF times can be observed, which is also shown in Fig. 5b, where temperature fluctuations inside the compartments are shown for three cases: I) without PCM, II) water/ice as PCM, and III) eutectic aqueous solution as PCM. In both cases where PCM is used, a longer compressor OFF time is observed.

The main advantage of using PCM at the evaporator is the improvement of the coefficient of performance (COP) of the system due to the higher evaporator temperature (Fig. 5a) and the higher density of the refrigerant at the compressor inlet [25] (the mass flow from the evaporator by the fixed volumetric displacement of compressor is higher). According to the review paper [11], COP increase of 2 % to 74 % can be expected, depending on the type of PCM used, thermal load, ambient temperature, and operating conditions. More specifically, the use of PCM in contact with the evaporator improves heat transfer from the evaporator [24]. As a result, a higher evaporator temperature (and pressure) is obtained during the compressor ON time. In turn, the compressor inlet temperature also increases. Thus, the performance improvement of a system equipped with PCM on the evaporator side is somewhat limited by the high condensation temperature. Nevertheless, the use of PCM at the evaporator leads to an increase in performance, since the compressor efficiency is generally more sensitive to the evaporation temperature.

In addition to a higher evaporator temperature, PCM can also store excess cooling capacity of the system, i.e., it helps the refrigeration system with cold storage. As a result, a longer compressor OFF time (e.g., 310 % and 456 % longer in [19] and [31], respectively) and a lower ON-to-OFF time ratio (e.g., 25 % and 12.6 % lower in [19] and [31], respectively) are achieved (Fig. 5b), resulting in lower overall energy consumption (e.g., 10 %, 13.7 % and 17 % lower in [32], [51] and [19], respectively) and preventing the destructive effect of frequent compressor start/stop. A longer compressor OFF time is also beneficial in terms of future demand side management (DSM) concepts. DSM generally refers to the specific control of power use to meet a fluctuating power supply. Specifically for refrigeration, DSM aims to reduce energy consumption during peak hours and shift energy purchases to low-cost periods. The potential to shift refrigerator demand to off-peak hours results in a reduction in customer bills of approximately 11 % [52]. Furthermore, PCM as a cold energy storage helps maintain food quality due to lower and less frequent temperature fluctuations inside the compartment [39]. The measured results by Rahimi et al. [51] indicated that by placing a PCM slab under the evaporator surface, the cabin temperature remains in the standard range (PCM slab with copper showed 1.7 °C and 5.1 °C temperature difference between the lowest and the highest cabin temperatures).

In addition, PCM can be helpful in case of power outages, because it increases the thermal capacity of the compartment and compensates for the heat gain through the compartment walls. Another advantage related to the lower ON-to-OFF ratio is less generated noise due to the lower overall ON time of the compressor. Table 4 gathers main benefits and drawbacks of using PCM at the evaporator.

The phase change temperature of PCM should be within the temperature range of the refrigerator thermostat [11], i.e. between the lower temperature at which compressor is stopped and the higher temperature at which compressor is started. Therefore, refrigerator's thermostat temperature range represents the upper and lower limits of applicable phase change temperatures of PCMs. In a case of high phase change temperature of PCM (closer to the upper limit)

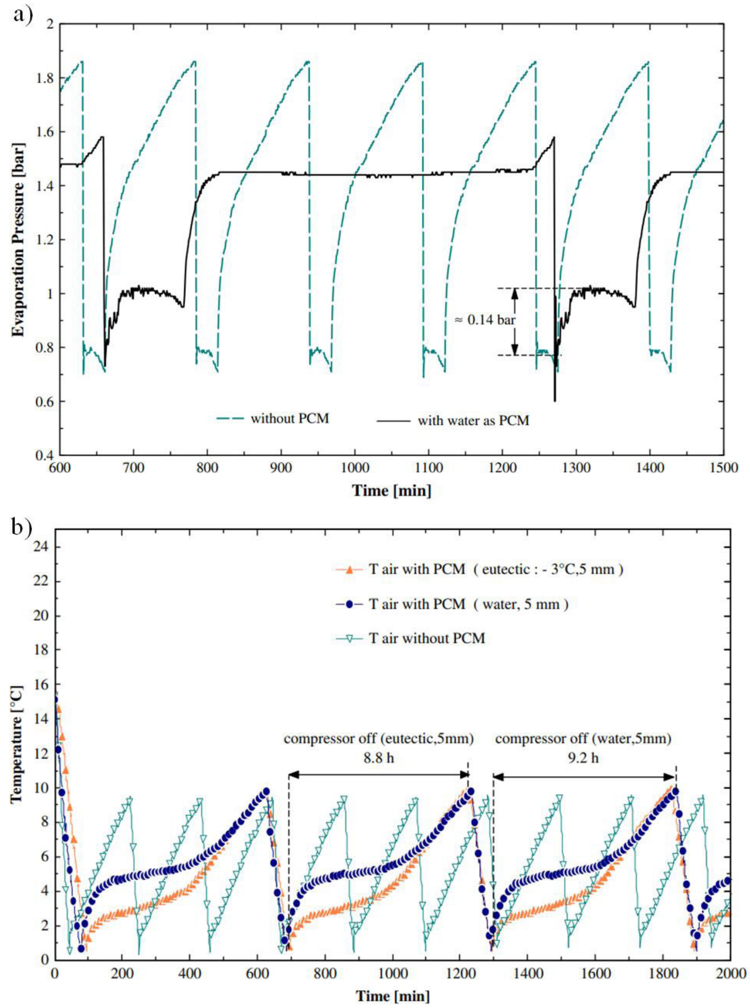

Fig. 5. a) Evolution of evaporation pressure (temperature) with and without PCM and b) evolution of average air temperature in compartment with and without PCM (reproduced from Ref. [25] with permission from Elsevier, © 2009)

system performance is better because the compressor ON-to-OFF ratio is reduced and COP is higher owing to the higher evaporation temperature, while stored food quality is decreased due to higher temperature in compartment. On the contrary, in case of lower phase change temperature of PCM (closer to the lower limit), PCM does not perform well because phase change might occur partially. It is therefore critical to select PCM with the correct phase change temperature based on expected thermal load.

Table 4. Benefits and drawbacks of PCM at the evaporator

Benefit
Higher COP
Longer compressor OFF time
Lower compressor ON-to-OFF time ratio ⟶ lower energy consumption
Slower temperature changes in compartment
More stable conditions against thermal load variations (i.e. outside temperature and door openings)
Higher refrigerant density and more controlled temperature at compressor inlet
Positive effect in case of power outage
Less overall noise
Drawback
Higher condensation temperature
Longer compressor ON time

With high degree of supercooling, the rate of nucleation in PCM substance is very slow resulting in a long freezing time. In a refrigeration system, a high supercooling degree will cause lower evaporating temperature and reduce the refrigeration efficiency. The thickness of PCM is also important. In general, thicker PCM performs better due to larger heat storage capacity. However, there is a limit of PCM that can be solidified during compressor ON time and above that limit thickness increase has no beneficial effects [25]. For example, in Fig. 6 temperature distribution of 10 mm thick PCM at the end of compressor ON time is shown. Measurements indicate that only about 60 % of PCM is solidified, which corresponds to complete solidification of 6 mm thick PCM. Therefore, increasing the thickness above 6 mm does not provide additional benefits under the studied conditions, as heat transfer limitations dominate. However, this limitation may be mitigated if the thermal conductivity of the PCM is enhanced, for example through the use of fins, metal matrices or high-conductivity additives.

3.2 PCM at the Condenser

During the compressor ON time, the heat transfer from the condenser to PCM leads to heating of PCM, resulting in its melting. Due to the better heat transfer conditions, the heat transfer is faster compared to an ordinary refrigerator without PCM, while the condensation temperature is lower due to the right selection of the phase change

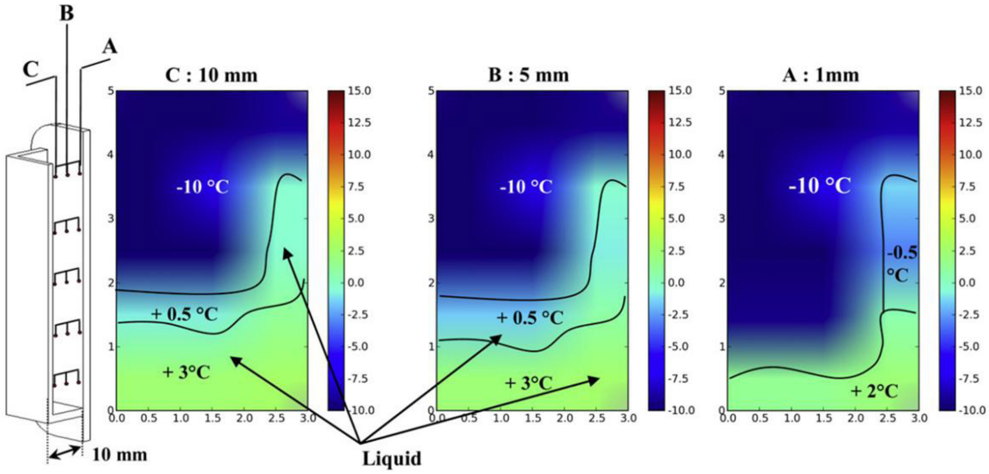

Fig. 6. Partial freezing: temperature distribution in PCM at different distances from the evaporator (reproduced from Ref. [25] with permission from Elsevier, © 2009)

temperature of the PCM. Consequently, the lower condensing temperature improves COP and reduces energy consumption. When PCM is liquefied, it is "charged" and has stored energy (heat). During the compressor OFF time, the heat stored in PCM is released to the environment, which cause the solidification of PCM. This process extends the condenser heat rejection from the compressor ON time to the entire cycle including the compressor OFF time (see Fig.7, where the blue curve is always above ambient temperature).

The idea of using PCM at the condenser is to achieve lower temperatures in the condenser during the compressor ON time [11], which generally results in a higher COP. According to literature [44], PCM at the condenser also causes a higher temperature at the evaporator, which is also beneficial for the increase of the COP. Unfortunately, no evaluation of COP improvement (in %) has been done so far. Lower condensation temperatures (e.g., 22 % lower [45]) are a result of improved heat transfer from the refrigerant (to the environment) due to the contact between the condenser and PCM, which allows heat conduction (i.e., thermal conductivity improvement), and the larger convection surface between the condenser (including PCM) and the environment. As a consequence, to enhanced heat transfer of the condenser, a shorter compressor ON time (e.g., 15 % shorter [47]) is required to reject a similar amount of heat from the compartment. Thus, the ON-to-OFF time ratio is lower (e.g., 22 % lower [47]) due to the shorter ON time and the nearly unchanged OFF time. A lower ON-to-OFF time ratio [47] is directly related to lower energy consumption and according to the literature, refrigerator energy consumption can be reduced between 7.4 % and 18 % [46,48], if PCM is used at the condenser.

Moreover, PCM at the condenser increases system stability by increasing subcooling (and decreasing condensation pressure), resulting in lower temperature fluctuations in the food compartments (Fig. 7a). In this context, increased subcooling refers to a larger temperature difference between the condensing temperature and the liquid refrigerant temperature at the condenser outlet. Unlike an ordinary system where condenser heat rejection is limited to compressor ON time, while during OFF time temperature of condenser equals the ambient temperature, the use of PCM at the condenser allows heat rejection also during compressor OFF time, resulting in a potential increase of overall rejected heat in a compressor cycle (Fig. 7b). A higher condenser temperature (and consequently a higher refrigerant temperature in the condenser) during compressor OFF time brings another benefit, namely the need for lower compressor starting power.

Unfortunately, PCM at condenser brings several disadvantages. Although the ON-to-OFF time ratio of the compressor is lower, resulting in lower energy consumption, it is lower on account of lower compressor ON time, which results in more frequent start/stop of the compressor. This shortcoming negatively affects the compressor performance in long-term use. All the benefits of PCM at the condenser are compromised by this major shortcoming, which may be the reason why PCM at the condenser is not investigated as frequently as PCM at the evaporator. Furthermore, the relatively unchanged compressor OFF time [47] shows that the accumulated cold storage in the compartment remains unchanged. Therefore, PCM at the condenser is not helpful in case of power outages and does not allow shifting energy purchases into off-peak hours.

Figure 7a shows the profiles of average temperatures in the compartment for four different cases. It should be noticed that the average temperature for the case without PCM or M-packs is associated with the average air temperature inside the compartment, which illustrates the largest temperature fluctuations in comparison to the other cases. In other three cases the profiles show the average temperatures of the M-packs loaded inside the compartment. To clarify, M-pack is a package that simulates thermal mass of food in the compartment, which means it contributes to the thermal inertia of a compartment. In [38] M-packs with chemical compositon of 76.42 wt% water, 23.0 wt% oxyethylmethylcellulose, 0.5 wt% sodium chloride, and 0.08 wt% parachloromethacresol were used. Figure 7a shows that the temperature fluctuations are lower when PCM is used. More specifically, the temperature fluctuations decreased from 1.4 °C to 0.25 °C when one PCM is used, while the use of PCM in a cascade arrangement reduces the fluctuations to 0.15 °C.

Figure 7b shows the comparison of condenser midpoint temperatures for the ordinary refrigerator (without PCM) and the novel refrigerator (with PCM). For the ordinary refrigerator, the condenser midpoint temperature rose rapidly from the ambient temperature (about 25 °C) to the highest temperature (about 35 °C) after the compressor was started and remained at this temperature. When the compressor was stopped, the temperature dropped rapidly and approached the ambient temperature. It then increased slightly (due to the influence of the heat capacity of the cabinet) and then slowly decreased until the next cycle began. The average temperature over a complete cycle was 28.6 °C, while the average temperatures during the ON time and the OFF time were 34.8 °C and 25.8 °C, respectively.

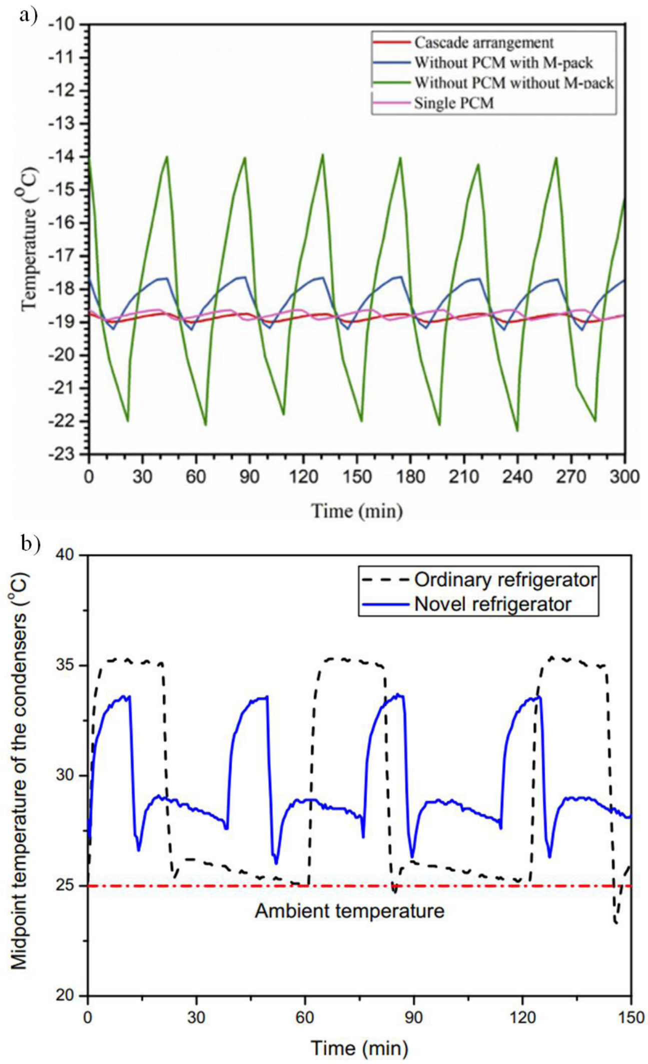

Fig. 7. a) Comparison of the temperature fluctuation in the frozen-food compartment between the four different refrigerators (reproduced from Ref. [47] with permission from Elsevier, © 2019), and (b) comparison of the condenser midpoint temperatures, where "novel refrigerator" uses PCM at the condenser (reproduced from Ref. [44] with permission from Elsevier, © 2011)

Unlike the ordinary refrigerator, the condenser midpoint temperature of the novel refrigerator increased more slowly after the compressor was turned on, reaching the highest temperature, which was about 2 °C lower than that of the ordinary refrigerator. When the compressor stopped, the sudden pressure drop inside the condenser resulted in a sudden drop of the condenser midpoint temperature. After that, the temperature increased rapidly to about 29 °C due to the effect of the PCM whose phase change temperature is higher than the ambient temperature. Then the temperature declined slowly as PCM released heat to the environment, but the minimum temperature was still over 27.5 °C, which was about 2.5 °C higher than the ambient temperature. For the novel refrigerator, the average temperature over a complete cycle was 29.9 °C, and the average temperatures during the ON time and the OFF time were 32.5 °C and 28.8 °C, respectively. For the novel refrigerator, the condenser midpoint temperature was higher than the ambient temperature by 3 °C to 5 °C, which indicates that nearly 50 % of the condensation heat is released into the environment through the PCM during the OFF time. Table 5 gathers the main benefits and drawbacks of using PCM at the condenser.

Kurugonda and Prasad [53] modified a household vapor compression refrigeration system using R134a by adding a PCM at the condenser to store excess heat and a Peltier module at the evaporator to improve cooling efficiency. Experimental results showed that using both components together reduced power consumption by 21 % and increased the coefficient of performance (COP) by 17.6 % compared to a normal cycle. The findings demonstrated that integrating PCMs and Peltier modules enhances the system's energy efficiency and reduces compressor workload.

Table 5. Benefits and drawbacks of PCM at condenser

Benefit
higher COP
shorter compressor ON time
lower ON-to-OFF time ratio ⟶ lower energy consumption
lower condensation temperature and pressure
higher degree of subcooling (greater ΔT below condensing temperature)
continuous heat rejection from condenser even during compressor OFF time
lower starting compressor power due to higher refrigerant temperature in condenser (during OFF time)
Drawback
frequent start/stop of compressor
more refrigerant displacement losses due to frequent start/stop

3.3 PCM in the Compartment

PCM can be integrated into walls, trays or into the top and bottom part of the compartment. The idea of using PCM in the compartment is to increase stored cold in the refrigerator. The results show that the introduction of PCM increases the cooling capacity, i.e. required time to cool a specific load from 25 °C to 10 °C, by up to 33 % [42]. Additionally, PCM increases the temperature rise time, i.e. required time for temperature in the compartment to rise from 8 °C to 11 °C, by up to 145 % [42]. This means that compressor OFF time is longer (e.g., 250 % longer [43]), while ON-to-OFF time ratio is lower (e.g., 38 % lower [43]), which results in lower energy consumption. According to the literature, energy savings from 8.4 % [41] to 12.1 % [43] can be expected. Additionally, longer compressor OFF time allows electricity usage to be shifted to off-peak times, which is beneficial in terms of demands-side management (DSM). Moreover, PCM in the compartment is also beneficial in case of power outages, because temperature in the compartment remains lower for a longer period of time (Fig. 6a). Besides increased stored cold, PCM in the compartment also significantly reduces temperature fluctuations during normal operation (up to 38 % [43]), which results in the enhancement of nutrition properties of stored food [39,43]. In case of door opening, PCM in the compartment reduces temperature fluctuations and lowers the requirement for starting the compressor because incoming warm air can be cooled down by PCM [39] (Fig. 8b).

Figure 8a shows the average air temperature inside the cabinet with and without PCM during the power failure condition. The results show that the air temperature inside the cabinet increased rapidly in the absence of PCM, resulting in large temperature fluctuations.

With PCM, the system was maintained at about 3 °C lower temperature during the power failure time. With power failure, the temperature inside the cabinet begins to rise due to the heat coming from the environment through the insulation. If PCM can be placed in the cabinet, it absorbs some of the heat by changing its phase from solid to liquid. Figure 8b shows the effects of PCM on the average air temperature inside the cabinet. The average temperature fluctuation was between 3 °C and 5.5 °C without PCM, while the temperature

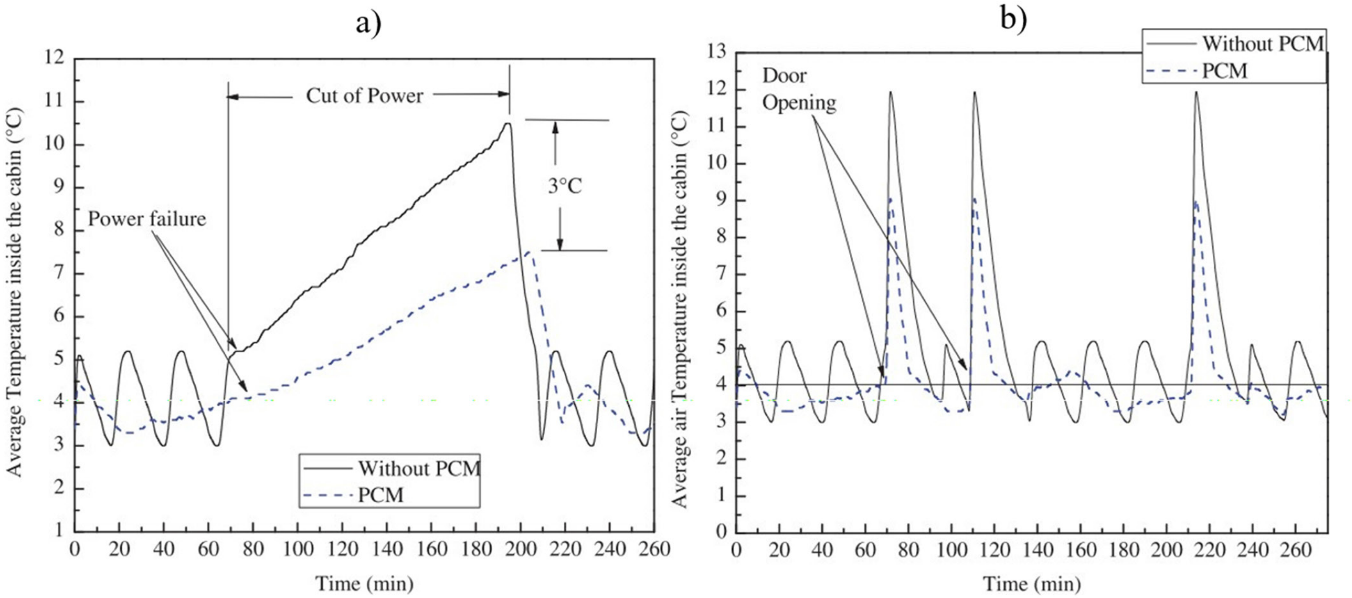

Fig. 8. Average air temperature inside the compartment: a) at power cut off condition, and b) at door opening condition (reproduced from Ref. [39] with permission from Taylor & Francis, © 2017)

fluctuation decreased with PCM. Consequently, the refrigerator with PCM maintained a more stable temperature in the closed-door condition. Additionally, a longer compressor ON and OFF time was observed when PCM was used. On the other hand, in the door opening conditions, the temperature increased rapidly and caused a significant temperature fluctuation in the absence of PCM. With PCM, a smaller temperature fluctuation was observed by about 3 °C, compared to the fluctuation without PCM. This is because the PCM works as a temperature damper.

Table 6. Benefits and drawbacks of PCM in the compartment

Benefit
reduced temperature fluctuations during normal operation
lower sensitivity of temperature fluctuations to door openings
increased cooling capacity and temperature rise time
slower temperature increase in case of power outage
longer compressor OFF time
lower ON-to-OFF time ratio → lower energy consumption
Drawback
longer compressor ON time
reduced usable storage volume, unless PCM is integrated into walls or structural elements

The overall effect of using PCM in the compartment is similar to using PCM at the evaporator, except that is has no effect on the evaporating temperature in the evaporator. Also, PCM may have a larger volume into the compartment, resulting in longer charging times due to more stored cold. The working principle is similar to PCM at the evaporator (Section 3.1). Table 6 gathers benefits and drawbacks of using PCM in the compartment. An important practical consideration is the potential reduction of usable storage volume when PCM is placed directly within the refrigerated compartment. Depending on the integration strategy, PCM may occupy space that would otherwise be available for stored goods. However, this drawback can be mitigated by integrating PCM into structural elements such as walls or shelves, where it may partially replace insulation or serve a dual function. In such configurations, the impact on usable volume may be negligible while still providing thermal stability and improved performance during transient conditions such as door openings or power outages.

3.4 PCM in the Evaporator and the Condenser

The combination of PCM placements can lead to a synergistic effect, i.e., the advantages of one PCM placement outweigh the disadvantages of the other PCM placement. Consequently, the advantages of both PCM placements are expressed and utilized.

As presented in the previous sections, PCM at the evaporator increases the evaporation and condensing temperatures, while the compressor cycle is extended due to the longer compressor OFF time (ON-to-OFF ratio is lower). On the other hand, PCM at the condenser lowers the condensing temperatures while compressor cycle is shortened, resulting in frequent starts and stops of the compressor. The simultaneous use of PCM at these locations leads to beneficial results, as shown in [19]. The duration of the compressor cycle remains almost unchanged (PCM at the evaporator and at the condenser cancel each other out), while the compressor OFF time is longer and consequently the ON-to-OFF time ratio is lower. Thus, energy consumption is reduced. According to the literature, a reduction of 17 % can be expected [19]. Moreover, evaporator temperatures are higher during compressor ON time and lower during compressor OFF time, while condenser temperatures are lower during compressor ON time and higher during compressor OFF time. According to experimental evaluation in [54], this led to a 12.7 % increase in COP. In addition, the higher condenser temperatures during the OFF time indicate that the condenser is also releasing heat during the OFF time, which is an advantage of using PCM on the condenser. On the other hand, the benefit of using PCM at the evaporator is also utilized, namely, temperature fluctuations in the compartment are reduced by 50 % [50].

Figure 9 shows the results for a combined integration of PCM into the evaporator and condenser of a commercial refrigerator. Thermostat settings were adjusted to reach the required average temperature in the compartment of about 5 °C. The cycle duration in both cases (with and without PCM) is similar, however the relative compressor ON time (ON-to-total time ratio) decreases from about 24 % to 20 % with the PCM. The minimum evaporator temperature

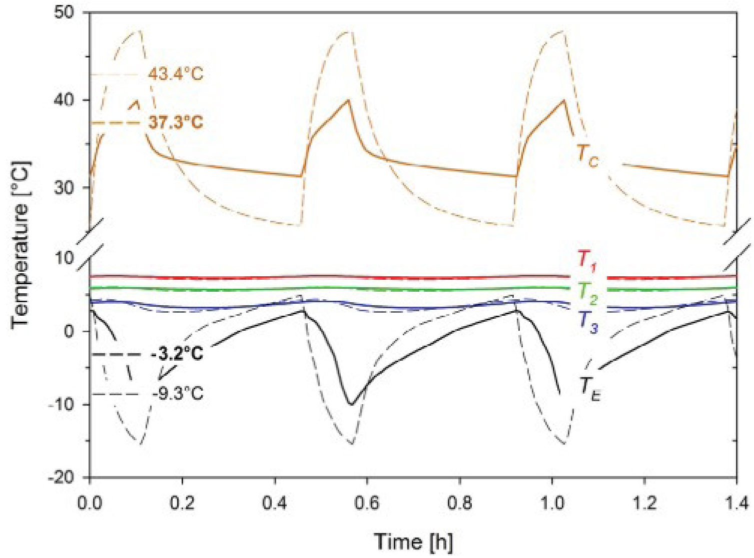

Fig. 9. Temperature of the fresh-food compartment (T_1, T_2, T_3), of the evaporator (T_E) and of the condenser (T_C) without (dashed lines) and with PCM on evaporator and condenser (solid lines); numerical values indicate average evaporator and condenser temperatures during compressor runtime (reproduced from Ref. [19] with permission from Elsevier, © 2015)

is increased with the integration of PCM by 6 °C from about −16 °C to −10 °C and on average during the compressor ON time by 6 °C from about −9.3 °C to −3.2 °C. The maximum condenser temperature is reduced by 8 °C from about 48 °C to 40 °C and on average during the compressor ON time by 6 °C from 43.4 °C to 37.3 °C. Altogether, this leads to a reduction of power consumption by about 17 %.

Although there are not many studies that consider PCM placement at multiple locations at the same time, the numerical study [50] considers PCM placement at the evaporator and condenser. The authors estimate that PCM at the evaporator and condenser simultaneously is better in view of energy consumption and COP compared to separate PCM placement. More specifically, their results show 32 % lower energy consumption, an increase of COP up to 38 %, and 46 % reduction of compressor ON-to-OFF time ratio. Table 7 gathers benefits and drawbacks of using PCM at the evaporator and condenser at the same time.

Table 7. Benefits and drawbacks of PCM at the evaporator and condenser at the same time

Benefit
higher evaporation temperatures during ON time ⟶ higher COP
lower condensing temperatures during ON time ⟶ higher COP
lower ON-to-OFF time ratio ⟶ lower energy consumption
lower temperature fluctuations in the compartment
ability of condenser to reject heat during OFF time
Drawback
phase change temperatures of both PCMs must be adequately selected to achieve synergy
poor options to shift energy purchases to off-peak hours

3.5 PCM in Walls for Thermal Buffering

PCMs can enhance the thermal insulation of refrigeration systems by acting as thermal buffers that absorb and store heat as latent energy, thereby reducing and shifting peak heat transfer rates. Experimental studies, such as those by Fioretti et al. [55], demonstrated that adding a PCM layer (35 °C) to a walk-in freezer reduced peak wall temperatures by up to 14 °C and delayed heat flux peaks by about 4 hours, effectively lowering thermal loads. Similarly, Copertaro et al. [56] found that integrating PCMs into refrigerated container walls decreased peak heat loads by 20 % to 25 % and daily energy consumption by around 4 % to 5 %, confirming PCMs' potential to improve energy efficiency in refrigeration applications.

An important consideration when integrating PCM into walls is the trade-off with conventional insulation. Increasing insulation thickness is generally an effective and cost-efficient way to reduce steady-state heat transfer. In contrast, PCM primarily influences transient thermal behavior by absorbing and releasing heat, thereby reducing peak heat loads and delaying heat flux. For example, researchers in [57] showed, in the context of building envelopes, that insulation is more effective for reducing overall energy consumption, while PCM provides benefits in peak load reduction and thermal buffering, with the combination of both yielding the best performance. Although these findings provide useful insight, it should be noted that such analyses have mainly been conducted for building applications, and similar systematic comparisons for household refrigeration systems remain limited. Therefore, PCM should be considered as a complementary solution to insulation, particularly in applications where transient thermal effects are important.

4 DISCUSSION

It is important to position the contribution of this review within the existing body of literature. While several previous reviews [7-13] have summarized PCM applications in refrigeration systems, they primarily focus on material properties, general integration approaches, and individual case studies. In contrast, the present work emphasizes a structured comparison of PCM integration at different locations within the refrigeration system, considering system-level performance indicators such as compressor cycling, temperature stability, and operational trade-offs. By synthesizing both earlier foundational studies and more recent contributions within a unified framework, this review aims to provide clearer guidance for practical implementation and system design.

In the first part of this work PCMs in general, their classification and properties are presented. Each group of PCM has some advantages and disadvantages, while the inorganic PCMs stand out for their performance for use in the refrigeration system. This is also reflected in their availability on the market, as can be seen in the table of commercially available PCM with phase change temperatures between −21 °C and 7 °C. The takeaway of the first part of this work is that there are already several commercially available PCMs in different forms that can be usefully utilized in the refrigerator.

The second part of this work focuses on the effects of PCM on the refrigeration system. Different PCM placements are considered and their benefits and drawbacks are also presented. Based on the review, the placement of PCM in the compartment is the easiest to design in terms of shape/size and selecting the correct phase change temperature, and in return offers many advantages with little to no significant disadvantages. The main advantages of using PCM in the compartment are reduced temperature fluctuations in the compartment, lower sensitivity to door opening, and the ability to shift energy purchases to off-peak hours. For PCM in the compartment, the influence of ambient (surrounding) temperature is low, especially if compared to the influence that ambient temperature has on PCM at the condenser. In view of the amount of work needed and the gains achieved, it is reasonable to start by incorporating PCM into the refrigerated compartment.

PCM at the evaporator provides similar benefits as PCM in the compartment with an additional advantage, i.e., improved heat transfer from the evaporator. This leads to higher evaporation temperatures and thus an increase in COP. From this point of view, PCM at the evaporator seems to be a better choice than PCM in the compartment but requires more design efforts. For example, the size of PCM is limited to the size of the evaporator, while the thickness of PCM needs to be carefully selected, as an excessively thick PCM layer may have negative consequences leading to a decrease in COP.

Designing PCM at the condenser requires caution, since the influence of ambient temperature is significant. If too low or too high phase change temperature is selected, no transformation occurs and the efficiency of the system will be reduced because PCM can act as an insulator. Using PCM only at the condenser is a poor option due to frequent starts and stops of the compressor. However, this can be avoided by: (i) using a lower-power compressor, or (ii) increasing the accumulated cold inside compartment, e.g. by using PCM at the evaporator. The latter option seems to be the most interesting, since the advantages of PCM at the evaporator outweigh the disadvantages of PCM at the condenser, and also bring other advantages, such as the possibility of shifting the energy purchases to off-peak hours. Therefore, we believe that the combination of PCM at the condenser and at the evaporator (perhaps also in the compartment) can bring the most advantages and the best performance, but on the other hand, it requires the most effort in design and manufacturing.

Table 8. Summary of options with comments

Option	Location of PCM	Comment
1.	in the compartment	for relatively low effort, a few benefits with little to no risky disadvantages are obtained
2.	at the evaporator	more effort needed, but in return major advantage is gained: higher evaporating temperature that leads to higher COP
3.	at the evaporator and in the compartment	thermal inertia of refrigerator is significantly increased, enabling to shift energy purchases to off-peak hours and the advantages of the options 1. and 2. remain
4.	at the evaporator and condenser	significant effort is needed, however the most and the best advantages can be obtained
5.	at the condenser	in order for benefits to outweigh the drawbacks, a compressor of lower power is required

A key outcome of this structured analysis is that the effectiveness of PCM integration depends strongly on its placement within the system and on the interaction between thermal, hydraulic, and control aspects. This highlights the need to move beyond isolated component-level analysis toward integrated system design, where trade-offs between efficiency, stability, cost, and usability are explicitly considered. Table 8 summarizes our findings.

From a practical implementation perspective, the integration of PCM into refrigeration systems introduces additional design considerations related to system size, complexity, and cost. The incorporation of PCM requires additional volume for storage, encapsulation, and thermal interfaces, which may slightly increase the overall size of the appliance or reduce usable internal volume, depending on the integration strategy. Furthermore, system complexity increases due to the need for effective thermal coupling between PCM and system components, as well as careful selection of phase change temperature and material properties, which may introduce additional design constraints in manufacturing and system control.

From an economic perspective, PCM integration generally leads to higher initial system costs due to material, encapsulation, and integration requirements. The overall cost impact depends strongly on the chosen design, level of integration, and application-specific constraints. However, these additional costs may be partially offset by improved energy efficiency, reduced compressor cycling, and enhanced temperature stability. Despite these potential benefits, comprehensive techno-economic analyses for household refrigeration applications remain limited in the literature, and the overall feasibility depends strongly on operating conditions and system design.

5 CONCLUSIONS

This paper reviews the impact of PCM use in household refrigerators for cold storage. The main message of this article is that cold thermal energy storage using PCMs represents a promising and increasingly important technology for improving energy efficiency and sustainability in refrigeration systems. With climate change being society's biggest challenge, there is an urgent need for energy efficiency improvements, particularly in refrigeration which significantly impacts peak power demand. Cold thermal storage using PCMs offers substantial benefits, including:

- peak shaving of refrigeration demand,
- energy cost reduction by exploiting low-cost electricity hours,
- backup refrigeration during power outages.

The technology shows promise across the entire cold chain - from food transport and packaging to supermarket refrigeration and industrial systems. Scientific interest in this topic has significantly increased over the past five years, with extensive research demonstrating energy savings ranging from 4 % to 15 % across various applications. Although the reported energy savings indicate promising potential, the economic feasibility and payback period of PCM integration depend strongly on system design, PCM cost, and operating conditions. Due to the limited availability of consistent cost data in the literature, a detailed payback analysis is challenging. However, the reported efficiency improvements suggest that PCM integration may lead to reasonable payback periods, particularly in applications with high electricity costs or frequent thermal load fluctuations. Despite proven benefits and commercial availability, widespread implementation in refrigeration is still lacking, primarily due to high initial costs and challenging system design.

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Materiali s fazno spremembo za izboljšanje učinkovitosti gospodinjskih hladilnikov: pregled stanja

Povzetek *V članku je predstavljen pregled uporabe materialov s fazno spremembo (PCM) za izboljšanje učinkovitosti gospodinjskih parno-kompresijskih hladilnikov. Najprej so povzeta merila za izbiro PCM, kot so temperatura faznega prehoda, usklajena s temperaturnim območjem termostata, visoka latentna toplota, ustrezna toplotna prevodnost, majhna stopnja podhlajenja in segregacije, omejena sprememba prostornine ter kemijska stabilnost in varnost. Nato so predstavljene glavne skupine PCM (organski, anorganski in evtektični materiali) ter praktični ukrepi, kot sta enkapsulacija in povečanje toplotne prevodnosti z uporabo kompozitov. Pregled vključuje tudi primere komercialno dostopnih PCM s temperaturami taljenja, primernimi za uporabo v hladilnih sistemih (približno od −21 °C do +7 °C), kar kaže, da so ustrezne tržno dostopne rešitve že na voljo. Osrednji del pregleda primerja različne možnosti vgradnje PCM na ključnih mestih: (i) pri uparjalniku, kjer lahko izboljšan prenos toplote zviša temperaturo uparjanja, podaljša čas mirovanja kompresorja, zmanjša temperaturna nihanja in omogoči učinkovitejše upravljanje odjema električne energije; (ii) pri kondenzatorju, kjer sta mogoča nižja temperatura kondenzacije in krajši čas delovanja kompresorja, vendar lahko te koristi zmanjša pogostejše vklapljanje in izklapljanje kompresorja; ter (iii) v notranjosti hladilnega prostora, kjer povečana toplotna vztrajnost blaži temperaturna nihanja, zmanjšuje vpliv odpiranja vrat in izboljšuje ohranjanje ustrezne temperature ob izpadih električne energije. Na koncu so obravnavane tudi kombinirane postavitve PCM (npr. pri uparjalniku in kondenzatorju), ki lahko omogočijo sinergijske učinke, če so temperature faznega prehoda in geometrija ustrezno izbrane.*

Ključne besede *gospodinjski hladilnik, parno-kompresijski sistem, materiali s fazno spremembo, prenos toplote, energetska učinkovitost*