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Review on cold thermal energy storage applied to refrigeration systems using phase change materials

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ABSTRACT

This paper presents a thorough review on the recent developments and latest research studies on cold thermal energy storage (CTES) using phase change materials (PCM) applied to refrigeration systems. The presented study includes a classification of the different types of PCMs applied for air conditioning (AC) systems (20 °C) to low-temperature freezing of food (−60 °C). An overview of the influencing thermophysical properties of PCMs, as well as their respective characterisation methods, are presented. The current available PCMs on the market in the temperature range 10 °C to −65 °C are listed. Finally, research on CTES using PCMs in refrigeration systems are reviewed and grouped into applications for food transport and packaging, commercial refrigeration and various other refrigeration systems. The findings show that using ice/water as PCM for AC applications is the most commonly studied system, due to widespread use of these systems, expected growth in the future and low cost of using water as the PCM. Over the last ten years the published research integrating CTES in different parts of the food cold chain, using water-salt solutions and paraffin PCM in both active and passive methods, has increased. Suggestions for the integration of CTES in supermarkets and industrial applications are also emerging. The technology has received increased interest from the scientific community the last five years, due to the benefits of achieving peak shaving of the refrigeration demand, exploiting low-cost electricity hours and offering backup refrigeration in case of blackouts.

1. Introduction

Climate change is the biggest challenge faced by our society today. The need for a transition towards more sustainable energy sources is immediate. An increased focus on energy efficiency in transport, industry, and the building sector is observed as they are characterized by high energy consumption and emissions [1]. Energy efficiency has the potential to account for 44% of the required reduction of CO_2 emissions in 2040, which is a level consistent with the two-degree scenario set by the Paris Agreement [1]. Decarbonisation of industry and transport is another important measure to reduce CO_2 emissions and is contributing to an increase in the demand for electricity [2,3]. The demand pattern is characterized by peaks and valleys, which is challenging to the electrical grid. The demand profile is becoming more and more pronounced. Indeed, air conditioning (AC) for residential and commercial buildings is expected to have a significant impact on the peak power use towards 2050 [4]. The International Energy Agency predicts that AC will contribute with a share of 40% of the total peak power demand in hot climates such as India and certain parts of South-East Asia in 2050. Peak shaving is one of the key features of thermal energy storage (TES), working from a diurnal to a seasonal timescale [5]. An overview of the potential load reductions, energy savings and reduction in CO_2 emissions using TES technology in Spain, Germany and the European context was presented by Arce et al. [6]. Focusing on a realistic implementation rate in the industrial and building sector the potential thermal load reduction was found to be 8% and 9% in Germany and Spain, respectively. The study also estimates potential energy savings of 7.5% and a reduction in CO_2 emissions of 7.5% in the European Union. This demonstrates the importance of integrating TES in the design of thermal energy systems energy system.

Latent heat storage (LHS) is characterized by a high volumetric thermal energy storage capacity compared to sensible heat storage (SHS). The use of LHS is found to be more competitive and attractive in many applications due to the reduction in the required storage volume [7,8]. The use of LHS is advantageous in applications where the high volume and weight can limit the energy efficiency, such as in transport applications. A considerable part of the research on applications of phase change material (PCM) has been focused around integrating PCMs in building applications. PCMs can be integrated into building materials,

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Nomenclature

AC	Air-Conditioning
TES	Thermal Energy Storage
CTES	Cold thermal energy storage
PCM	Phase change material
MPCM	Micro-encapsulated phase change material
HEX	Heat exchanger
HTF	Heat transfer fluid
HVAC	Heating, ventilation, and air conditioning
DSC	Differential Scanning Calorimetry
LHS	Latent heat storage
SHS	Sensible heat storage
COP	Coefficient of performance
MT	Medium temperature

such as concrete or gypsum boards, to reduce heat transfer to/from the inside of the building. Integrating PCMs into building envelopes is an application of TES where the process of storing and releasing energy is not actively controlled but occurs as a consequence of a change in the ambient temperature. This technique is applied both in hot and cold climates. An extensive review of the integration of PCM in building materials since 1980 can be found in [9]. An overview of PCMs suitable for cooling and heating of buildings is presented by Cabeza et al. [10]. The reviews by Baetens et al. [11] and Zhou et al. [12] give an overview of the suitable PCMs and various methods for implementation of PCM in building materials. The performance enhancement in buildings using PCMs considering the implementation of both active and passive methods was presented by [13]. Based on the reviewed literature from 2004 to 2017, the authors stated that more research has to be conducted on microencapsulated PCMs (MPCMs), heat transfer enhancement techniques and implementation of alternative control strategies of heating, ventilation and, air conditioning (HVAC) equipment after integrating PCMs.

The focus of the present review is on latent TES systems using PCM for the temperature range covering AC applications (20 °C) to low-temperature freezing of food (−60 °C). For these applications, the integrated TES units are commonly referred to as cold thermal energy storage (CTES) systems. CTES using PCM has gained attention both scientifically and commercially over the last two decades, but a widespread implementation in refrigeration is still lacking. The use of PCM TES is more common in high-temperature applications, such as solar process heating [14] and concentrated solar thermal power plants [15] when compared to low-temperature applications. This is probably because of the high initial costs of the low-temperature integrated system and the challenging system design, such as for transport application. Over the last decade, intensive research was carried out on the identification of the appropriate PCMs for refrigeration applications. Several reviews on PCMs specifically for low-temperature applications were performed over this period [16–18]. The study performed by Oró et al. [16] includes a comprehensive list of commercially available PCMs in 2012 with phase change temperature from 20 °C to −50 °C.

For the past twenty years, CTES technology has received increased attention as a way to cope with high peaks in refrigeration demands in various applications. CTES provides attractive solutions to reduce the required installed capacity of the refrigeration equipment and offers a backup solution in case of system failure. The identification of a peak/off-peak demand structure is one of the most important requirements to make a successful CTES implementation in a refrigeration system [5]. To date, most of the published work on CTES focused on small-scale applications, such as domestic refrigeration [18,19] and domestic heat pump/AC systems [20]. Systems involving large-scale CTES are less studied, especially for commercial and industrial refrigeration. This might be due to the space inconvenience and the requirements for high capacity infrastructure when conducting experimental characterisation on larger systems in the laboratory. Another reason might be the high generated costs and lack of full-scale installations fitted with measurement equipment for detailed performance monitoring. First, this review paper gives an overview of the different types of PCMs, the important thermophysical properties for PCMs, and the most commonly used material characterisation techniques reported up to this date. Then, a thorough and complete overview of CTES systems applied to food transport and packaging, supermarkets, commercial refrigeration systems and various refrigeration systems with capacities larger than 5 kW is presented.

2. Phase change materials

2.1. Classification of phase change materials

PCMs are a group of latent TES materials that takes advantage of the solid/liquid phase transition for storing energy. The liquid/gas and solid/gas phase transitions are not preferred due to the technical difficulties in handling the large volume change. PCMs are generally classified into three groups: organic, inorganic, and eutectic materials (please see overview given by Sharma et al. [21]). Organic PCMs can be further classified into paraffin and non-paraffin compounds. Paraffins are chains of hydrocarbon molecules of different length, while non-paraffins covers the other organics substances that can be used as PCMs e.g. sugars alcohols and fatty acids [7,16]. The inorganic PCMs can be divided into salt hydrates and metallics. The eutectics include any compound created by a combination of organic and/or inorganic PCMs. The two most frequently studied groups of PCMs for subzero applications are eutectic water-salt solutions and paraffins. In this range, paraffins have an available operating range down to −53.5 °C. Sugar alcohols and fatty acids have melting points above 0 °C. Eutectic water-salt solutions are available down to −62 °C, but some commercial products have melting points as low as −114 °C [17]. Li et al. [17] presented a thorough overview of the latent heat of fusion and phase change temperature of PCMs in the temperature range from 0 °C to −120 °C. The reader is directed to Sharma et al. [21] for a detailed description of the chemical composition of the three groups of PCMs.

Table 1 gives an overview of the important properties of the most commonly used types of PCMs for CTES in the temperature range from 0 °C to −62 °C. Generally, the inorganic PCMs have higher thermal conductivity and larger heat storage capacity than the organic PCMs. But their main drawbacks are that they suffer from a high degree of supercooling and phase segregation when compared to organic PCMs. On the other hand, the organic PCMs have low supercooling due to self-nucleating properties, no phase segregation and a congruent phase change. However, the main challenge of organic PCMs is the low

Table 1
Comparison of the thermophysical properties of some groups of PCMs for CTES in the subzero temperature range [26,27,21,17].

	Organics		Inorganics	
Property	Paraffins/ Paraffin mixtures	Alkanones	Eutectic water-salt solution	Alcohol solutions (70–100 wt% H_2O)
Phase change temperature [°C]	−0.5 to −53.5	−3.8 to −55.4	−1.6 to −62	0 to −20
Heat of fusion [kJ kg^{-1}]	110 to 216.2	134.5 to 190.4	116.84 to 314.1	250 to 334
Phase segregation	Low	Low	High	Low
Supercooling	Low	Low	High	High
Flammability	Yes	Yes	No	No

thermal conductivity and flammability [12]. The eutectic PCMs generally have high storage capacity, but the access to data about their thermophysical properties is generally limited [22–25].

2.2. Properties and characterization methods of PCMs

This section summarizes the most important selection criteria for PCMs based on thermophysical properties relevant to refrigeration applications. The reader is guided to the recommended characterisation techniques for each property. The different enhancement strategies to tackle the most significant drawbacks of the PCMs are discussed. Table 2 gives an overview of the important selection criteria classified into thermal, physical, kinetic, chemical, economic and environmental aspects that need to be considered when selecting a PCM [5,7,21]. These characteristics should be carefully addressed when selecting a PCM for a particular application.

2.2.1. Latent and specific heat capacities

A high latent heat capacity and a suitable phase change temperature of the PCM are the first selection criteria to satisfy when selecting a PCM [28,7,17]. The most common way of measuring the latent heat capacity and specific heat capacity of PCMs is the Differential Scanning Calorimetry (DSC) technique [29]. For latent heat capacity measurements, the two recommended methods applied to PCMs are the dynamic method and the step method. The dynamic method involves heating/cooling the sample at a constant rate, e.g. increasing/decreasing the temperature by 0.5, 1 or 5 K min^{-1}. In the step method, the heating or cooling is not continuous. The sample is heated in short periods, followed by periods of constant temperature to allow the sample to reach thermal equilibrium at each step. A varying heating/cooling rate is often utilised, with slower ramping of temperature around the phase change temperature. For a detailed description of both methods applied for PCMs, the reader is directed to Castellón et al [30] and Barreneche et al. [31]. Both methods show comparable results for melting temperatures for salt hydrate and paraffin PCMs. However, considerable deviations between the two methods have been found for melting enthalpies of paraffin PCMs [31]. Generally, the dynamic method is preferred over the step method because the analytical procedure is time-saving when analyzing the DSC curves [31]. When using a DSC for the PCM characterization, a low heating/cooling rate is preferred. Scanning rates of 1 K min^{-1} or lower is recommended to be applied after each thermal equilibrium in the sample to achieve good accuracy and repeatability of the results [32–34].

The specific heat capacity of the PCM is identified for both liquid and solid phases using one of the three available operation modes using the DSC technique: dynamic, isostep and areas method. In the dynamic method the sample is heated with a constant heating rate, but normally with higher heating rates than for latent heat capacity measurements (10 to 20 K min^{-1}). The isostep method consists of many short segments of dynamic stages from the starting temperature to the final temperature. Before and after each dynamic step, there are isothermal segments to stabilise the temperature within the sample. The heating rate during the dynamic step is normally low (1–2 K min^{-1}). The areas method consists of isothermal segments without any dynamic heating stages between each step. The temperature is increased rapidly by 1 K between each isotherm. A thorough description of all three methods can be found in Ferrer et al. [35]. The areas method was proven to give the most accurate results (maximum 3% error to tabulated values) for three common sensible TES materials (water, rock and potassium nitrate) [35].

Table 2
Selection criteria for PCM [5,7,21].

Category	Property
Thermal	Suitable phase change temperature; High latent heat capacity; Good heat transfer characteristics
Physical	Favorable phase equilibrium; High density; Small volume change; Low vapour pressure
Kinetic	No supercooling; Sufficient crystallisation rate
Chemical	Long term stability; Compatibility of PCM with other materials; No toxicity; No flammability concerns
Economic and environmental	Abundant; Available; Cost-effective; Good recyclability

2.2.2. Thermal conductivity

The thermal conductivity characterisation of PCMs is necessary to evaluate the heat transfer and properly design the heat exchanger (HEX) of the CTES system for increased performance. PCMs, and mainly the organic ones, suffer from low conductivity. A high thermal conductivity results in a higher heat transfer rate of the storage unit [29]. Three common methods are generally used to determine the thermal conductivity of PCMs: The laser flash, transient hot wire and transient hot disk technique [36]. The selection of the appropriate experimental method depends on the state of the material and its physical properties, such as viscosity. The reader is directed to Table 3 representing the appropriate methods to characterise different groups of PCMs. The laser flash method is a direct, non-steady-state technique which is well described by Parker et al. [37] and dos Santos et al. [38]. In this method, the specimen is disc-shaped and its front face is exposed to a uniform heat pulse of short duration. The temperature rise on the rear face is then recorded. The hot wire technique involves measurement of the temperature rise of a thin metal wire when a step voltage is applied to it. The wire is either immersed or embedded in the sample to be measured. A detailed description of the hot wire method can be found in [39] and [40]. The hot disc method uses a flat sensor consisting of a thin metal spiral that is put between two halves of a disc-shaped sample. Electrical current is passed through the spiral, increasing its temperature. By recording the temperature response in the sensor over a given time, the thermal conductivity can be calculated. For details on the hot disk method, the reader is directed to the work by Gustafsson [41]. Favourable features of the hot disk method are the possibility to measure powders of varying particle size, heterogeneous samples and highly conducting materials [42]. However, the equipment is more expensive than for the hot wire method [43].

2.3. Main PCM limitations

Some PCMs, especially inorganic salt hydrate PCMs, experience phase segregation/separation. The phase separation of the PCM results in two or more phases that can be observed in the TES unit after a melting - solidification process [55]. Semi-congruent or in-congruent melting occurs when the phase with the higher density sinks to the

Table 3
Recommended method for thermal conductivity measurement of different materials, including some examples references from the literature.

Method	Application domain	Examples of characterised materials	References
Laser flash	Solids	Erythirol	[44]
	Composites	Paraffin w/nanoparticle	[45]
Hot wire	Solids	Various paraffins	[46]
	Composites	Paraffin w/graphite	[47]
	Liquids	Various paraffins	[46]
	Slurries	MPCM suspension	[8]
	Granular solids	Construction sand	[48]
Hot disk	Solids	Ice	[49]
	Composites	Paraffin and nano-graphite	[50]
		Paraffin and expanded graphite	[51]
		Fatty acid w/ fibers/clay/ graphite	[52]
	Liquids	Water	[49]
		Ethylene glycol	[53]
		Methanol	[53]
	Powders	Various metal powders	[54]

bottom of the storage, while the phase with the lower density travels to the top [56].

Supercooling is another limiting factor, it refers to the phenomena where the temperature of the PCM is decreased below its solidification temperature and not initiating the nucleation process within the material which enables the phase change [5,7,57]. Supercooling is an undesirable effect that makes practical use of the PCM challenging, as the CTES system is often designed to work within a narrow temperature range. In integrated systems, a solution could be the decrease of the evaporation temperatures in the refrigeration system to initiate the solidification process. However, this may result in a reduced coefficient of performance (COP) of the refrigeration system.

2.4. Enhancement techniques for PCMs

2.4.1. Physical properties enhancements

Different methods are applied to prevent the phase separation including gelling, adding thickening agents or mechanical stirring [7]. Gelling additives, such as cellulose derivatives, will form a three-dimensional matrix inside the PCM that acts as a barrier in the phase separation process [10,56]. Thickening is a technique used to increase the viscosity of the material by adding thickening agents without changing the melting point of the PCM. However, adding thickening agents could result in a significant reduction in the latent heat capacity. The reported reduction in the latent heat capacity is ranging from about 4% [58] up to 20–35% [59]. The reduction in latent heat capacity depends on the amount of thickening material added to the PCM. It is reported that the introduction of small amounts of thickening and nucleating agents (0.5% to 4%) are sufficient to reduce supercooling and prevent phase separation in inorganic salt PCMs while preserving the latent heat capacity [60,61]. According to Farid et al. [55], the thermal conductivity of the PCM might also be reduced when adding thickening agents.

The encapsulation technique of PCM is another reported solution to enhance the properties of the PCMs. It also prevents the PCM from undergoing phase segregation. The PCMs can be macro-encapsulated or micro-encapsulated, depending on the size of the holder. More detailed information about the encapsulation technique and its effect on the thermal performance of PCMs are available in [62]. Macro-encapsulation refers to the process of filling PCM in containers of various geometrical shapes (e.g. spheres, slabs or tubes) and materials (e.g. polymers or metals) [7]. The size of these containers is usually larger than 1 cm [10]. Microencapsulation consists of filling PCM in a small solid shell with a size ranging from 1 μm to 1000 μm, which creates a fine powder of MPCM. The MPCM is often mixed with water or another liquid to create a suspension to be used in CTES systems. The concentration of MPCM in the suspension is typically ranging from 5% to 40% [57]. A low concentration of MPCMs is often preferred where the suspensions are used as a pumpable heat transfer fluid (HTF) due to the increased pressure drop associated with higher MPCM concentration [63]. For more details about the micro-encapsulation techniques and property characterisation of organic PCMs, the reader is directed to Khadiran et al. [64]. A detailed overview of microencapsulation and macroencapsulation techniques for inorganic PCMs is also presented by Milian et al. [65].

Intensive research has also been performed to limit the supercooling effect. Generally, two methods are applied: Active and passive methods. The passive method involves the addition of nucleating agents that has a similar crystal structure as the PCM itself. The nucleating agent acts as initial support for the crystal growth of the PCM once it reaches its solidification temperature. This method was found to be the most efficient and has shown a reduction in the supercooling of PCMs up to 90% using only 1 wt% nucleators [66]. The active methods are procedures to initiate the solidification process of the liquid PCM by applying an external force such as mechanical stirring, high-pressure air injection or ultrasonic waves. Injection of high-pressure air is a technique to agitate the liquid PCM in order to induce the nucleation process, i.e formation of the first stable crystal that can support further crystal growth [67]. Ultrasound irradiation also consists of creating agitation in the liquid PCM to initiate nucleation [68]. Both active and passive strategies are thoroughly described by Beaupere et al. [66].

2.4.2. Thermal properties enhancements

Low thermal conductivity is one of the major barriers for a widespread use of PCMs in TES systems, mainly for the organic PCMs. For this reason, developing new techniques for thermal conductivity enhancement has been attracting researchers over the last decade. The common solution consists of adding highly conductive materials to the PCM to enhance its thermal conductivity. The additive materials are classified into three groups; carbon-based, metal-based and other materials [69,70]. The inserts/additives can further be grouped in 3D (networks/foam), 2D (layered and flake materials), 1D (Fibers, nanotubes) and zero-dimensional (nanoparticles) structures [71]. The addition of carbon-based nanostructures to PCMs is reported to achieve greater enhancement of thermal conductivity compared to metallic-based particles. This is due to the high aspect ratio (length to width ratio) of the carbon nanostructures, creating highly conductive paths within the PCM [72]. It was shown that introducing a mass fraction of various carbon nano-additives from 0.1% to 10% increased the thermal conductivity of paraffin PCM in the range from 5% to 45% [73]. For a more detailed overview on thermal conductivity enhancement of paraffin-based PCMs, the reader is directed to Bose and Amirtham [73]. A recent review published by Wu et al. [71] covered the detailed theory and mechanisms of thermal conductivity, as well as the different types of inserts and additives applied to PCMs. It was concluded that graphite networks, graphene and titanium oxide foam, as well as boron nitride nanoparticles, were the most performant additives for increasing the thermal conductivity of PCMs. Enhancing the thermal performance of a TES unit can be performed by acting on the thermal properties of PCMs or by optimising the HEX geometry of the storage unit, such as adding fins. This second enhancement solution is not covered in this review but is available in [74].

2.5. PCMs on the market

The number of available PCM on the market has been continuously growing over the last years, including new types of PCMs and a substantial increase in the number of suppliers. Table 4 gives a current overview of the commercially available PCM with melting temperature in the range from −65 °C to 10 °C. The PCMs are available in different forms, e.g. in bulk, macro-encapsulated or as a dry micro-encapsulated powder. Because the market is continuously expanding, it is difficult to provide a complete list of the PCMs. To help the reader making the selection of the appropriate PCM for a specific application, an updated list of the available PCMs in the market until the date is given in Table 4. The table provides information on the different existing PCMs, their melting temperature, latent heat capacity, classification and the available suppliers.

3. Applications of PCM

PCM used as an LHS medium has gained a large interest over the years. The current research is focusing on integration into domestic refrigeration, AC applications, refrigerated transport, supermarket refrigeration systems and into large-scale industrial refrigeration systems. Over the past 15 years, investigations on PCM application was mainly dedicated to building applications [11,9,10,12,75,76] and domestic refrigeration [77,18,19]. Therefore, the authors will in this review provide the reader with the latest PCM integration technology applied to refrigerated transport and packaging, supermarket refrigeration and various other refrigeration systems.

Table 4
Commercially available PCMs in the temperature range from −65 °C to 10 °C, sorted by melting temperature. All information taken from the datasheet of the respective manufacturers.

Material	T_m [°C]	Latent heat [kJ/kg]	Type of product	Producer
E-65	−65	240	Inorganic	PCM Products
SP-50	−52 to −48	200	Inorganic	Rubitherm GmbH
E-50	−50	175	Inorganic	PCM Products
PureTemp-37	−37	145	Bio-based organic	PureTemp LCC
E-37	−37	225	Inorganic	PCM Products
E-34	−34	200	Inorganic	PCM Products
ATS-40	−33	300	Inorganic	Axiotherm GmbH
E-32	−32	225	Inorganic	PCM Products
va-Q-accu −32G	−32	243	n.a.	va-Q-tec
PCM-30	−30	150–160	Organic	Microtek Laboratories
HS30N	−30	224	Inorganic	PLUSS Advanced Technologies
E-29	−29	250	Inorganic	PCM Products
SP-30	−29 to −28	250	Inorganic	Rubitherm GmbH
SP-28	−29 to −28	260	Inorganic	Rubitherm GmbH
HS26N	−26	274	Inorganic	PLUSS Advanced Technologies
E-26	−26	265	Inorganic	PCM Products
SP-24	−25 to −23	285	Inorganic	Rubitherm GmbH
HS23N	−23	262	Inorganic	PLUSS Advanced Technologies
E-22	−22	305	Inorganic	PCM Products
CrodaTherm −22	−23	217	n.a	Croda Europe
va-Q-accu −21G	−21	234	n.a.	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 to −19	285	Inorganic	Rubitherm GmbH
E-19	−19	300	Inorganic	PCM Products
HS18N	−18	242	Inorganic	PLUSS Advanced Technologies
ClimSel C-18	−18	288	Inorganic	Climator AB
SP-17	−18 to −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 LCC
ATS-12	−12	360	Inorganic	Axiotherm GmbH
E-11	−12	310	Inorganic	PCM Products
SP-11	−12 to −11	240	Inorganic	Rubitherm GmbH
SP-11 UK	−12 to −10	330	Inorganic	Rubitherm GmbH
PCM-10	−10	175–185	Organic	Microtek Laboratories
MPCM-10	−10	170–180	Organic	Microtek Laboratories
MPCM-10D	−10	170–180	Organic	Microtek Laboratories
HS10N	−10	290	Inorganic	PLUSS Advanced Technologies
RT-9 HC	−9	250	Organic	Rubitherm Technologies
HS7N	−7	296	Inorganic	PLUSS Advanced Technologies
SP-7	−7 to −5	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	−4	330	Inorganic	PCM Products
HS3N	−3	346	Inorganic	PLUSS Advanced Technologies
ATS-3	−3	330	Inorganic	Axiotherm GmbH
PureTemp −2	−2	277	Bio-based organic	PureTemp LCC
E-2	−2	325	Inorganic	PCM Products
RT0	0	175	Organic	Rubitherm GmbH
E0	0	395	Inorganic	PCM Products
va-Q-accu + 00G	0	330	n.a.	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
SP5 gel	2 to 7	155	Inorganic	Rubitherm GmbH
va-Q-accu + 05G	2 to 8	240	n.a.	va-Q-tec
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	5	187	Organic	PureTemp LLC
A4	4	235	Organic	PCM Products
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	5	191	Bio-based organic	Croda
SP7 gel	5 to 8	155	Inorganic	Rubitherm GmbH
ATP 6	6	275	Organic	Axiotherm GmbH
A6	6	185	Organic	PCM Products
A6.5	6.5	190	Organic	PCM Products
CrodaTherm 6.5	6.8	184	Organic plant-based	Croda
Gaia OM PCM7	7	180	Organic	Global-E-Systems
ClimSel C7	8	123	Inorganic	Climator AB
A7	7	190	Organic	PCM Products
PureTemp 8	8	178	Organic	PureTemp LLC
OM08	8	175	Organic	PLUSS Advanced Technologies
RT8	8	175	Organic	Rubitherm GmbH
RT8 HC	8	190	Organic	Rubitherm GmbH
S8	8	130	Inorganic	PCM Products
A8	8	180	Organic	PCM Products
A9	9	190	Organic	PCM Products
CrodaTherm 9.5	9.7	186	Bio-based organic	Croda
RT10	10	160	Organic	Rubitherm GmbH
RT10 HC	10	200	Organic	Rubitherm GmbH
A10	10	210	Organic	PCM Products
S10	10	170	Inorganic	PCM Products
SP9 gel	10 to 11	155	Inorganic	Rubitherm GmbH

3.1. PCM applications in food transport and packaging

The research interest into the food cold chain has increased substantially over the last few years [78]. A homogeneous temperature through the cold chain is essential to preserve the food quality and avoid microbial growth [79]. Relevant studies have demonstrated a significant variation of temperature and humidity through the many links of the food cold chain, especially during transportation [80,81]. The use of temperature loggers in packaged food products revealed that the food product temperature is on average 2 °C higher than the recommended values for 30% of the products when located in the display cabinet, 70% during transport to consumer and 40% in the domestic refrigerator [82]. These findings demonstrate the advantage of using PCMs when it comes to the product temperature stabilisation during the different links of the cold chain, mainly at the transport phase. The findings in the literature suggest different approaches to integrate PCMs in the transport link of the cold chain. The application of PCMs has been performed in the walls of the refrigerated vehicle, in the product packaging, or including an active PCM system externally to the storage space. A summary of the reported findings is presented in Table 5, including a description of the application and the applied PCMs. It has been shown that using PCMs in the walls of refrigerated transport vehicles is a highly performant strategy to reduce both peak and average heat transfer. PCM packaging for frozen foodstuff is deeply investigated by the scientific community and was proven to guarantee the thermal protection of the goods during the transport phase.

3.1.1. PCM integration into the walls of refrigerated vehicles

The strategy consists of limiting the heat flux through the walls of the refrigerated vehicle by integrating a PCM in the wall in order to absorb the heat exchanged with the environment. The long experience gained on PCM integration in building materials over the last years is believed to add considerable input when investigating PCM integration in the walls of refrigerated vehicles. The topic though has not gained the same interest as PCMs for buildings, but the interest has been growing through the recent years due to the urgent need to protect the cold chain of the higher recorded ambient temperatures. The required temperature for food transportation in refrigerated transport ranges from −25 °C (ice cream) to 15 °C (tropical fruits) [83]. PCM can be integrated either by including PCM layers in the insulating walls [84–86] or by creating a composite insulation material and dispersing an MPCM into traditional insulation material [87,88]. The main objective of integrating PCM in the walls of refrigerated vehicles is to reduce the peak and average heat transfer rate from the external environment to the refrigerated enclosure. This allows for a more uniform distribution of incoming heat flux from the environment to the refrigerated enclosure during the day. It was showed that integrating PCMs in the container wall can reduce the peak and average heat transfer rate by up to 29.1% and 16.3%, respectively [89]. Moreover, this technique was found to achieve a delay in the heat transfer peak between the external environment and the refrigerated enclosure due to the absorption of the incoming heat load in the PCM. The reported shifts in the heat transfer peak are ranging from 2 to 2.5 h when employing PCM-filled copper pipes inside the wall [89] and from 3 to 4.5 h when using a multi-layer PCM wall [86,85].

Ahmed et al. [89] investigated the reduction of peak and average heat transfer rates by integrating RT-5 [90] as a PCM filled into copper pipes in the walls of a refrigerated vehicle. The experimental work showed a reduction in average peak heat transfer rate of 29.1% and a reduction in daily heat transfer rates of 16.3%. Glouannec et al. [84] proposed to add a 5 mm layer of Energain PCM plates to a standard wall for a refrigerated vehicle. Starting from the inside wall of the refrigerated enclosure, the wall consisted of a polyester and fibreglass composite, polyurethane foam insulation, the PCM panel, an air gap and finally the outer steel plate of the vehicle. An experimental comparison showed that the PCM wall limited the increase in peak heat flux to 3.2 W m^{-2}, while the peak heat flux of the reference wall increased by 7.5 W m^{-2}. A reduction in average daytime energy consumption of 25% was demonstrated. However, the experimental tests were carried out for a total of 8 h and only considering 4 h to be daytime operation (30 °C).

Copertaro et al. [86] numerically investigated nine different PCMs as the outer layer in the sandwich wall of a standard 20 ft ISO refrigerated container using the software COMSOL Multiphysics. The PCMs were selected according to the Italian climate conditions. The most promising PCM was found to be RT35HC [90]. A peak heat transfer rate reduction between 20.01% and 25.01% and a daily energy rate reduction of 4.55–4.74% compared to a standard vehicle wall were recorded for summer climate conditions in Milan, Ancona and Palermo. The experimental results were found to be in good agreement with the numerical results considering the measured and simulated incoming heat fluxes through the wall (mean absolute error 4.23% during 24 h) using the PCM RT35HC. Fioretti et al. [85] employed a similar multi-layer wall

Table 5
Main results from use of PCM in food transport and packaging.

Application	Theoretical (T) Experimental (E)	PCM (T_m [°C])	Main result (value)	Reference
Wall for refrigerated vehicle	E	RT5 (5)	Peak shift (2 to 2.5 h); Peak heat transfer reduction (29.1%); Average heat transfer reduction (16.3%)	[89]
Wall for refrigerated vehicle	T/E	Energain PCM panel (21)	Average heat transfer reduction daytime (25%)	[84]
Wall of 20 ft ISO container	T/E	RT35HC (35)	Peak shift (3 h); Peak heat transfer reduction (20%); Average heat transfer reduction (about 4.5%)	[86]
Wall for refrigerated vehicle	T/E	RT35HC (35)	Peak shift (3.5 to 4.5 h); Peak heat transfer reduction (5.5 to 8.5%)	[85]
Wall for refrigerated vehicle	T/E	Composite PU/PCM C18 Inertek (18)	Average heat transfer reduction (0.3 to 4.1%)	[88]
Storage container for cold/hot food	T/E	RT-2 (2); PT-15 (-15); PT-63 (63)	Increase in storage time (320% to 400%)	[91]
Storage container for ice cream	T/E	E-21 (-21)	Decrease in product temperature when stored in room temperature (10 K)	[92]
Storage container for ice cream	E	E-21 (-21)	Decrease in product surface temperature during heat load test (17 K)	[93]
Packaging for chilled food	T/E	RT5 (5)	Increase in thermal buffering capacity; Increased shelf life of ham (6.7%)	[96]
Packaging for blood bags	E	Mixture of n-alkanes (4.8)	Correct storage temperature for 6 h (8 times increase)	[98]
PCM-HEX system for refrigerated transport	T/E	Inorganic salt-water solution (−26.8)	Reduction in annual cost (51 to 86.4%); Storage space kept at −18 °C for 10 h	[99,100]

construction using the same PCM (RT35HC) and PCM thickness for a refrigerated container considered by Copertaro et al. [86]. From the inside of the container, the wall consists of an internal metal sheet, a polyurethane foam insulation layer, the PCM placed in a polyethylene panel, a polyvinyl chloride film and finally an external metal sheet (see Fig. 1). The experimental results relative to two days of experiments under summer climate conditions in Ancona showed a reduction in peak heat transfer rate between 5.55% and 8.57%.

Michel et al. [88] presented a numerical model of a multi-layer wall using COMSOL software. One of the layers is a composite material which consists of a PCM/polyurethane (PU) foam, combining both the standard insulation layer and the PCM layer. The PCM layer is placed between two layers of PU foam so that the total thickness of the multi-layer wall is 6 cm. The study was carried out using various thicknesses of the PU-PCM layer (from 1.5 cm to 2 cm) and the two PU layers (from 0.5 to 4 cm), always adding up to a total of 6 cm. The change in thickness of the two PU layers affects the position of the PU-PCM layer within the wall, which is done to evaluate the effect of the PCM layer position on the heat transfer through the multi-layer wall. The deviation in heat flux through the composite plate between the numerical and experimental results were found to be acceptable (less than 2% during steady-state periods and less than 8.5% overall). The results from the numerical study have shown that the achieved reductions of the heat transfer exchange rate were in the range of 0.3% to 4.1%. It was also shown that the closer the PCM multi-layer plate to the external wall of the vehicle, the more important the heat transfer reduction is (4.1%). This results is found to be in accordance with those found by Copertaro et al. [86] where the maximum reductions were recorded in the range from 4.55% to 4.74% when the PCM layer is located close to the external surface. Through the investigated literature, it was observed that the largest reductions in the heat transfer rate are recorded when the PCM is placed towards the external wall of the refrigerated vehicle in PCM multi-layer walls. Only a few studies were focusing on the effect of PCM location inside the vehicle wall on the heat transfer rate, therefore, more research is needed to present the optimal design.

3.1.2. PCM integration into products packaging and containers

Integrating PCM into the storage containers and food packaging has been found as a suitable solution to increase the thermal mass of packaging so that the storage temperature is kept stable for longer periods. Ice cream is a very temperature-sensitive product. Therefore, it has been found to be a popular application that has attracted researchers to investigate the performance of PCM packaging [91–93]. Oró et al. [91] investigated both experimentally and numerically the benefits of using different PCMs as an additional layer in an insulated bin to store hot or cold food, as described in Fig. 2. The numerical model was solved using the fully implicit finite volume method and the numerical results were found to have an acceptable agreement with the experimental data. The results using the PCMs PT-15 and PT-63 [94] have shown an increased safe time for transportation of 400% and 320% in the case of ice cream and hot water storage, respectively. Scoop ice cream sold in restaurants and bars are often kept in 5-litre rectangular steel ice cream trays to fit in the display freezers, typically keeping the ice cream below −8 °C after it has been removed from the storage freezer. Oró et al. [92] proposed to add a layer of the PCM E-21 [95] around the sides of the tray to increase its thermal mass. The PCM occupied the volume between the trays that is available when they are placed side by side in the display freezer so that no extra freezer space was required. The experimental results demonstrated that after 3 h under 25 °C ambient conditions, the temperature increase in the centre and outer part of the ice cream was reduced by 3 °C and 10 °C, respectively.

Packaging for transport and ice cream storage using a salt-hydrate PCM was proposed by Leducq et al. [93]. The design was compared to a standard cardboard box and a box with expanded polystyrene as insulation materials. After 40 min of heat load test under ambient temperature conditions, it was found that the product surface temperature increased by 18 °C for the cardboard box, 9 °C for the conventional insulation and 1 °C for the PCM packaging. Hoang et al. [96] studied the thermal behaviour of the organic PCM RT5 [90]) encapsulated in a biodegradable polyester plate to be used in packaging for transportation of chilled food. A numerical heat transfer model was developed and experimentally validated. The model showed good agreement with experimental results with a maximum temperature deviation of less than 0.8 °C and 1.9 °C at the PCM plate centre and surface, respectively. A time-dependent air temperature profile representing different parts of the meat cold chain was used as an input to the simulation. The thermal

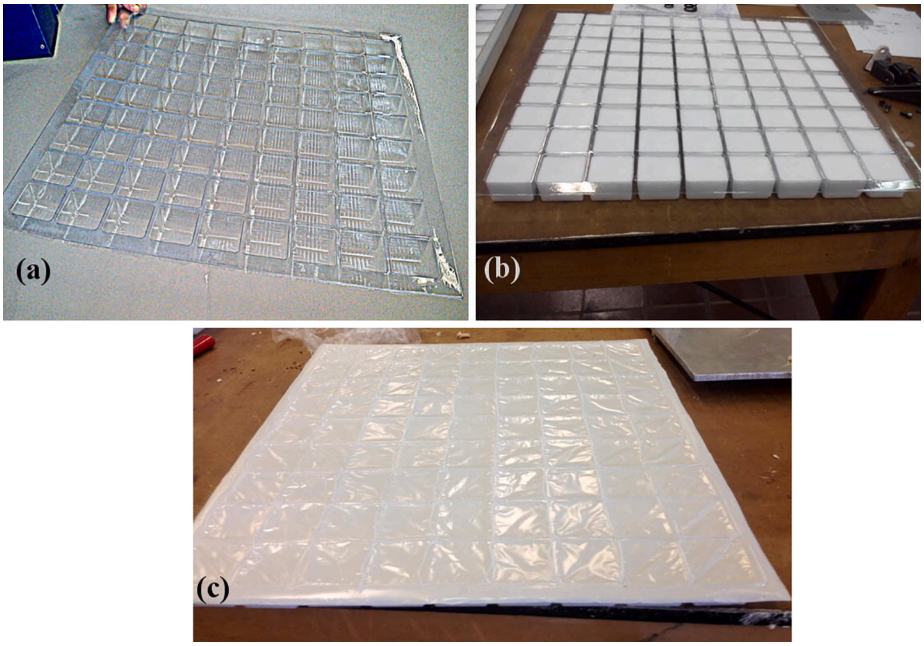


Fig. 1. Constructon of a PCM layer for a multi-layer wall: (a) polyethylene panel, (b) RT35HC encapsulation (PCM), (c) polyvinyl chloride closing layer [85]. Reprinted from Energy conversion and management, 122, Fioretti, R., Principi, P., Copertaro, A refrigerated container envelope with a PCM (phase change material) layer: Experimental and theoretical investigation in a representative town in central Italy, 131–141, Copyright (2016), with permission from Elsevier.

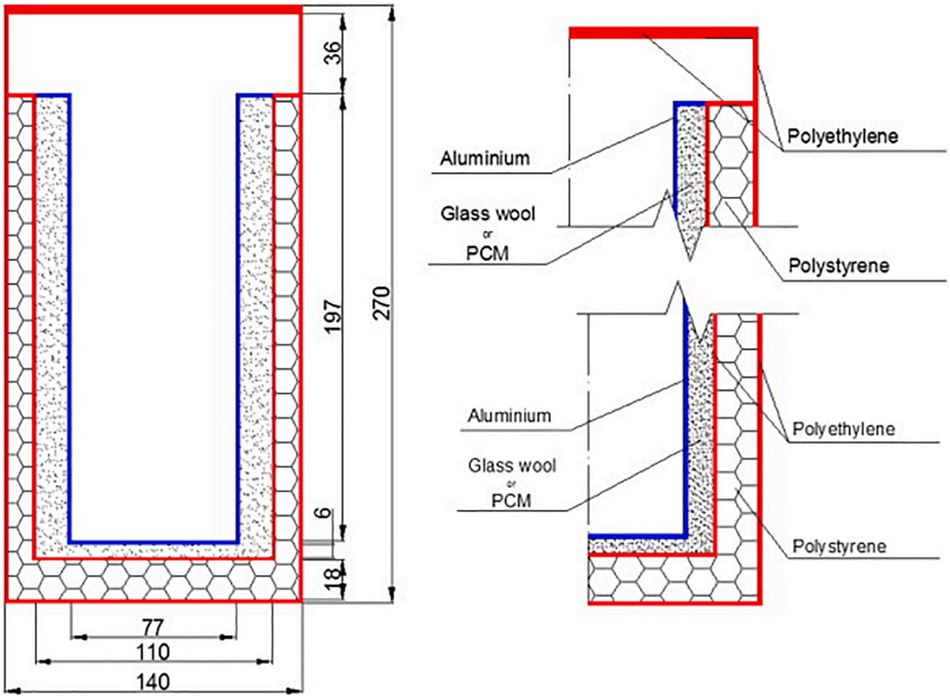


Fig. 2. Bin with PCM for transport and storage of food [91]. Reprinted from Applied Thermal Engineering, 58, Oró, E., Cabeza, L.F., Farid, M.M., Experimental and numerical analysis of a chilly bin incorporating phase change material, 61–67, Copyright (2013), with permission from Elsevier.

performance benefits of PCM packaging for foodstuff is well demonstrated. Indeed better thermal buffering characteristics were found when compared to a standard cardboard packaging. The surface peak temperature was reduced by 12.5 °C when using the PCM packaging. One way to improve the competitiveness of such system is to examine the safety aspect when using PCM for food storage application. Indeed, a PCM leakage from packaging can result in food contamination. In this review, the authors point out that food safety during transport does not only depend on the storage temperature, but also on a performant system design which prevents PCM leakage issues.

Transport and storage of biological material and vaccines require careful temperature control through the cold chain. Many vaccines are heat sensitive, which can affect their efficiency. A new generation of vaccines is nowadays available, which has an improved resistance experiencing temperature fluctuations. However, some of the new vaccines are freeze sensitive, proving that stable temperature during transport and storage is essential [97]. In this review, the authors report the only available research dedicated to medical and biological goods packaging including PCM [98]. The authors suggested using a mixture of n-alkanes as the PCM in a package device for transport of blood bags. The packaging could keep the blood samples below 10 °C during 6 h under 22 °C ambient temperature conditions. Until the date, research on packaging using PCM for foodstuff has been more attractive than for biomedical goods. Another urgent reason to increase the interest on investigating vaccines and biomedical goods storage, is the need of many countries with difficult climate conditions (high temperature and high humidity ratio), due to the limited access to electricity and refrigeration equipment to a secure and sustainable health care system.

3.1.3. Active PCM systems

An alternative approach of using PCM in refrigerated vehicles was proposed by Liu et al. [99]. The authors presented a novel design of a refrigeration system for the vehicle as represented in Fig. 3. The conventional diesel-driven refrigeration unit usually installed above the driver compartment is replaced by a phase change thermal storage unit (PCTSU). The PCM consists of a water-salt solution which has a melting point of −26.8 °C. The PCM is macro-encapsulated in thin and flat plastic capsules and stacked with 6 mm distance into an insulated

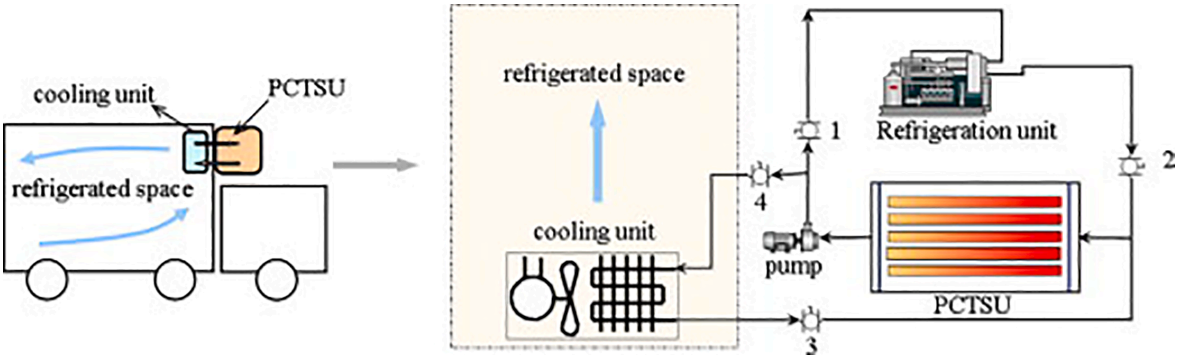


Fig. 3. System design of an on-board PCM unit integrated in the refrigeration system of a refrigerated vehicle [99]. Reprinted from Applied Energy, 92, Liu, M., Saman, W., Bruno, F., Development of a novel refrigeration system for refrigerated trucks incorporating phase change material, 336–342, Copyright (2012), with permission from Elsevier.

container. The secondary refrigerant (Dynalene HC-40) is pumped into the PCTSU to reject heat to the PCM. The cold HTF then circulates the air HEX in the refrigerated space to maintain the desired air temperature during transportation. Once the vehicle is stationary at a warehouse or depot, the PCTSU can be charged by connecting the system to an external refrigeration system through valves 1 and 2 as described in Fig. 3. The secondary refrigerant is cooled by the refrigeration system and circulates through the PCTSU to ensure the cold charging process. A prototype of the PCTSU was constructed and experimentally tested in a secondary refrigerant circuit connected to a cold room representing the refrigerated vehicle. The results revealed that the storage capacity of the PCTSU prototype was insufficient to keep −18 °C in the refrigerated space for the requested 10 h. To cover the daily energy demand of about 15 kWh of the refrigerated vehicle, the authors calculated the required amount of PCM to be 360 kg. Calculations showed that using an external refrigeration system which has a COP ranging from 1.0 to 1.5, the novel PCM-based system demonstrates important cost savings in the range of 51.0% to 86.4% under Australian ambient conditions. In a further work [100], a numerical model was developed using TRNSYS software to simulate the performance of the entire system. The one-dimensional model of the PCTSU was validated and showed reasonable agreement with the experimental results considering the heat transfer rates and HTF outlet temperature during the discharging process [101]. The results from the system simulation revealed that the refrigerated space could be kept at −18 °C for the requested 10 h during the warmest day of the year [100]. During door openings of the vehicle, the temperature inside the refrigerated space increased by about 8 K, and it would take 30 min for the system to restore it to the setpoint temperature (−18 °C). The authors recommended using a PCM with a lower melting point (−32 °C) in the PCTSU to limit the peak temperature during the door opening and provide higher cooling rate during the following pull-down period. These findings demonstrate again the ability of this technology to present a promising solution for typical refrigerated transport routes.

3.1.4. Summary and discussion

A summary of the reviewed literature on PCM applications in food transport and packaging is given in Table 5. For the past ten years, PCM integration into the walls of refrigerated vehicles and containers has been extensively investigated by applying both experimental and numerical methods. A special focus was dedicated to the development of multi-layer insulation materials including PCMs in order to replace the standard sandwich wall in refrigerated vehicles [84–86,88]. From the reviewed literature, it was shown that using a multi-layer PCM wall is an efficient technique to reduce the peak heat transfer rate from the environment to the refrigerated space. However, the most promising wall design in terms of performance looks to be the standard sandwich wall inserted with PCM-filled copper pipes as presented by Ahmed et al. [89]. This design demonstrated up to 29.1% and 16.3% reductions in the peak and the average heat transfer rates, respectively. For multi-layer PCM walls, the highest energy savings are demonstrated when the PCM layer is located closest to the external wall. On the other hand, the copper pipe wall design showed significant reductions in the average heat transfer rate by placing the PCM-filled copper pipes close to the internal wall. The PCM applied in this study had a melting temperature of 5 °C, which is close to the air temperature of the refrigerated space. This contrasts with the PCM selection for the multi-layer wall configurations. When the PCM layer was located closest to the external side of the wall, the selected PCMs had melting points closer to the ambient temperature (18 °C to 35 °C). Few studies can be reported combining different melting temperatures and the location of the PCM inside the wall, and a complete understanding of the effect of these parameters is still missing. A comparison between the PCM-wall and the standard insulated wall in terms of production cost and weight has to the authors knowledge not yet been carried out. The experimental procedure presented by Fioretti et al. [85] and Ahmed et al. [89] gives a very good representation of the real-life performance of the PCM-walls by considering a full-size container tested in real ambient conditions for up to 1 month, side-by-side of a standard container. Although the full-scale procedure is clearly more complex and costly compared to investigating a small section of a PCM multi-layer wall, the former demonstrates the real-life performance needed to increase the confidence of manufacturers to consider this novel technology as a viable alternative to traditional insulation materials.

PCMs used for food packaging and containers are reported for a broad range of melting temperatures, from −26.8 °C to 5 °C. PCM packaging of temperature-sensitive goods was proven to provide sufficient thermal comfort to the goods during high-temperature exposure and thus guarantees the food quality between the links of the cold chain, e.g. from the food supplier warehouse to the supermarket refrigerated display cabinets [98,92,93]. In the light of the recent outbreak of the pandemic COVID-19 [102], PCM packaging of medical goods could have played an important role for safe and urgent transport of temperature-sensitive medical goods such as medications, blood samples and vaccines to hospitals between countries. This would be particularly important in developing countries where access to electricity and refrigeration is limited.

The fundamentally new approach for the refrigeration system for refrigerated vehicles using an onboard PCM-HEX and a pumped HTF circuit presented by Liu et al. [101] looks to be very promising. It is clear that the system presents significant environmental benefits by replacing the standard diesel-driven refrigeration system on the vehicle by an active PCM-HEX unit. Instead of burning diesel to maintain the adequate temperature in the refrigerated space, the PCM-HEX unit can be charged by an external refrigeration system at the warehouse with higher efficiency and preferably powered by renewable energy. Also, the authors state that the novel system will reduce the local pollution of NO_X and particulate matter which is a known issue for diesel engines [103].

3.2. PCM application in commercial refrigeration

Refrigeration is typically responsible for 35–60% of the total energy consumption in supermarkets, depending on location, size and share of frozen/chilled food in the retail area [104,105]. Commercial refrigeration systems cover a wide range of different equipment from small plug-in vending machines, food service coolers and display cabinets to large centralised supermarket refrigeration systems. In this review, a presentation of the different integration scenarios of CTES into supermarket refrigeration systems is given. Two approaches of PCM integration in supermarkets are commonly investigated: A distributed storage which is directly integrated into the display cabinets and a centralised storage integrated into the main refrigeration system circuit. The latest research on PCM integration in various refrigerated vending machines and beverage coolers is also presented. A summary of the reviewed literature on PCM implementation related to commercial refrigeration is given in Table 6. The possibility of implementing a storage in the supermarket is becoming popular as it is often reported to be a cost-effective way to reduce the share of refrigeration in the total energy consumption and energy savings up to 6.4% is reported [106]. The implementation of CTES in CO_2 supermarket refrigeration was reported by Gullo et al. [107] as a key factor for energy efficiency enhancements of these systems, and up to 5.6% reduction in the daily energy consumption is reported in the literature [108]. Furthermore, experimental studies have shown that cold storage can offer a control strategy to stabilise the air temperature inside the display cabinet [109,110].

Key benefits of integrating CTES into commercial refrigeration systems are the possibility to shift energy purchases to low-cost periods by using the storage to achieve peak shaving of the refrigeration demand. Consequently, the power consumption stabilisation through the day will be achieved [111]. Furthermore, the use of local renewable electric energy production (e.g. installing photovoltaic panels on the roof) is increasing in the supermarket sector. The use of CTES can correct the mismatch between energy availability and demand, thereby maximising

Table 6
Main results of PCM application in commercial refrigeration.

System Configuration	Theoretical (T) Experimental (E)	PCM (T_m [°C])	Main results (Value)	Reference
Cabinet shelf with heat pipes and PCM	E	De-ionized water with 2% borax (−0.5)	Food temperature reduction during defrost (3.5 K); Reduced temperature peak during defrost (1.5 K)	[109]
Cabinet shelf with heat pipes and PCM	E	RT3 (2.5); RT4 (3.8); RT5 (5.2)	Product temperature fluctuation reduction (83.3%); Product temperature difference reduction (80%))	[117]
Radiator PCM-HEX in cabinet air duct	T/E	Water with nucleating agent (−2)	Energy savings (up to 5%); Reduction in the maximum cabinet temperature (2 K); Reduced start/stop cycles of compressor (27%)	[110,106]
Fin-tube PCM-HEX in cabinet air duct	E	Water/ice (0)	Reduction in the maximum cabinet temperature (1 K)	[119]
Three-fluid PCM-HEX in cabinet air duct	T	Water/ice (0)	PCM-HEX cooling duty (1.7 kW); High storage capacity (6 kWh per meter width)	[120]
Three-fluid PCM-HEX in cabinet air duct	T	Water/ice (0)	Reduction in the maximum cabinet air temperature during defrost (10 K)	[121]
CTES integrated into CO_2 refrigeration system	T	Water/ice (0)	Peak compressor power reduction (50%); Total energy consumption reduction (14.4%)	[129]
CTES integrated into CO_2 refrigeration system	T	Water/ice (0); PCM (15)	Peak compressor power reduction (15%); Total energy consumption reduction (5.6%)	[108]
CTES integrated into CO_2 refrigeration system	T	Water/ice (0)	Compressor power reduction during discharge (5% to 68%)	[111]
PCM-HEX in air duct of a bottle cooler	E	Water/ice (0); RT4 (4)	Energy consumption reduction (4–10%); Increase in compressor cycle time (118%)	[130]
PCM slab on evaporator of a bottle cooler	T/E	Water/ice (0)	Reduced compressor on/off ratio (36% to 26%)	[131]
CTES for dispenser beverage cooler	E	Water/ice (0)	Energy consumption reduction (15%)	[132]

the potential of the local energy production. Last but not least, the cold storage can increase the system reliability by supplying the cooling capacity under different unforeseen conditions such as a power blackout situation or component failure in the refrigeration system. There are three strategies to operate a CTES that is integrated into a refrigeration system. The three scenarios are: The full storage (Fig. 4a), partial storage with load levelling (Fig. 4b) and partial storage with load limiting (Fig. 4c). In the full storage scenario, the storage can cover the entire refrigeration load during peak hours, while a high capacity refrigeration system is required to fully charge the CTES during off-peak hours. In the load levelling scenario, the capacity of the storage and the refrigeration system is designed so that the refrigeration system operates at a near-constant load through the day. The load limiting scenario represents the case where the capacity of the storage is designed to cover a certain refrigeration load so that the power consumption of the refrigeration system does not exceed a given value during peak hours (e.g. to avoid an electricity tariff). In most applications, the load-levelling or load-limiting strategies will be the most favourable, due to reasonable investment costs for the CTES and the possibility to reduce the capacity requirement of the refrigeration system [5].

3.2.1. Supermarket display cabinets

Two main types of display cabinets are installed in supermarkets: The open style cabinet and the closed style display cabinet with glass doors. In the open type, one or more air curtains isolate the foodstuff from the external environment. About 70% of the cooling load of refrigerated display cabinets originates from air infiltration [112,113]. Replacing the open type cabinets by cabinets with glass doors can reduce the energy consumption in the range of 30 to 40 % [114,115]. A reduction in warm air entering the cabinets reduces the frost formation on the evaporator coils, resulting in less frequent defrost cycles. Despite these obvious benefits, the open type cabinets are frequently installed, mainly because it gives the customers easy access to the products. Nevertheless, it has been demonstrated that fitting doors to an open display cabinet have no negative effect on the product sales [116]. An efficient way to reduce the high energy consumption of these types of display cabinets is to integrate PCM cold storage. There are commonly two investigated strategies of integration: Into the cabinet shelf [109,117], or integrating an additional PCM storage at the rear wall of the cabinet [110,106]. The product temperature for chilled food in supermarket display cabinets normally range between 0 °C and 5 °C, and avoiding temperature fluctuations is key to preserve the food quality [79]. Suitable PCMs for this application have a melting temperature in the range from −5 °C to 5 °C, depending on the main objective of the CTES. Lu et al. [118] identified water-based PCMs as the most suitable candidates for implementing in display cabinets for chilled food. Water-based PCMs are preferred over paraffin PCMs due to their higher latent heat capacity and better thermal conductivity. Water has 2.5 times the latent storage capacity and about 2.7 times higher thermal conductivity compared to paraffin RT-2 and RT-4 [118,90].

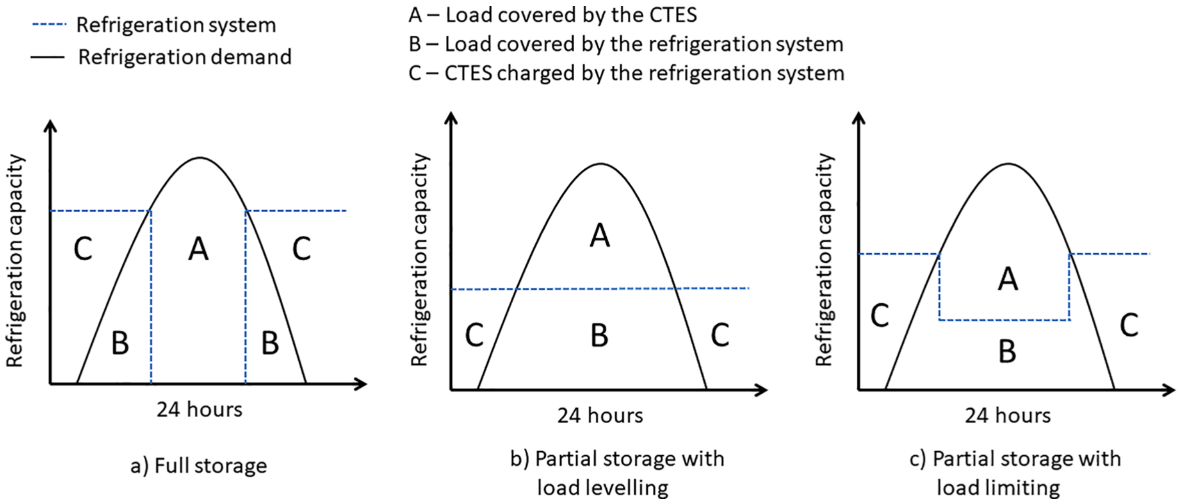


Fig. 4. Different strategies for operating a CTES system integrated into a refrigeration system.

Lu et al. [109] presented a new design of a cabinet shelf in an open type display cabinet, represented in Fig. 5a. The novel cabinet shelf was 30 mm thick and composed of 8 heat pipes that were evenly distributed over the width of the shelf, and the PCM was included between them (See Fig. 5b). The applied PCM consisted of de-ionized water with an addition of 2% borax which has a melting point of −0.5 °C. The objective of the study was to decrease the temperature difference between the products placed at the first row and last row of one shelf and between the products placed at the left, middle and right of the shelf. Furthermore, the objective was to decrease the product temperature peak that occurs during the defrosting process. The experimental results showed a reduction in the front-back and right-left product temperature variation compared to the standard shelf of 1.4 K (47%) and 1.7 K (68%), respectively. Furthermore, the rise in food temperature during the defrosting process was reduced by 1.5 K, while no increase in cabinet power consumption was recorded.

A similar design to that proposed by Lu et al. [109] was investigated by Wu et al. [117] using a shelf thickness of 20 mm and heat pipe spacing of 150 mm, whereas Lu et al. [109] used a shelf thickness of 30 mm and heat pipe spacing of 230 mm. Different organic PCMs were experimentally tested: RT3, RT4 and RT5 which have a melting temperature of 3 °C, 4 °C and 5 °C, respectively [90]. The results showed that integrating RT4 into the shelf provided the best overall results. Indeed, the temperature difference between packages in the left–right direction was reduced by 80% compared to a standard shelf. However, the novel shelf was not able to reduce the temperature difference between the packages in the front to back direction. The average food package temperature and food temperature fluctuation were decreased by 32% and 83.3%, respectively. The highest reduction in food package temperature variation in the width direction was obtained by Wu et al. [117], whereas the shelf design presented by Lu et al. [109] also gave important reductions in both depth (47%) and width (68%) directions.

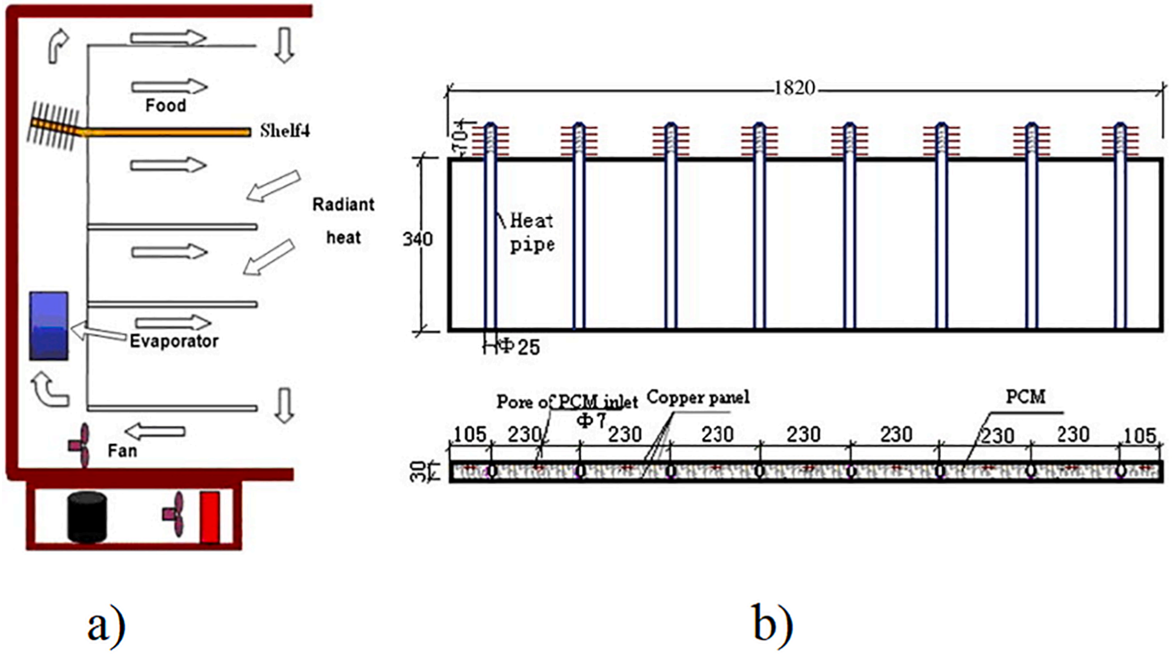


Fig. 5. Open display cabinet employing a cabinet shelf with heat pipes and PCM: a) Display cabinet b) Novel cabinet shelf [109]. Reprinted from Applied Thermal Engineering, 30, Lu, Y., Zhang, W., Yuan, P., Xue, M., Qu, Z., Tao, W., Experimental study of heat transfer intensification by using a novel combined shelf in food refrigerated display cabinets (experimental study of a novel cabinets), 85–91, Copyright (2010), with permission from Elsevier.

This can be attributed to the higher thermal conductivity and the lower melting point of the water-based PCM used by Lu et al. [109], obtaining comparable results to Wu et al. [117] while applying an 80 mm longer distance between each pipe in the shelf. Further investigations considering the selection of the appropriate PCM and the optimum location of the heat pipes for the cabinet shelf to clarify the effect of these parameters and to find the optimal design.

Another strategy to implement cold storage in display cabinets is to integrate a PCM-HEX in the air circulation duct. This configuration was experimentally investigated by Alzuwaid et al. [110] to reduce the energy consumption and decrease both the food product and air temperature in the cabinet. In this study, two single-panel radiators were filled with the PCM which consists of a mixture of water and a nucleating agent with a melting temperature of −2 °C. As it can be seen in Fig. 6, the PCM-HEX unit was installed downstream of the evaporator at the back of the cabinet and referred to as a radiator. The charging process is initiated when cold air from the evaporator flows across the surface of the PCM-HEX unit during the compressor ON period. During the compressor OFF period (e.g. during the defrosting period) the air temperature in the cabinet rises above the melting temperature of the PCM. The cabinet air is circulated through the PCM-HEX unit by using the fan. The air temperature decreases as soon as it is in contact with the charged PCM-HEX unit until it is completely discharged (when the PCM temperature exceeds the inlet air temperature). The results have shown a reduction of 5% in the energy consumption over 24 h. Furthermore, the maximum cabinet temperature during the compressor off-period was also reduced by 2 K. The authors completed their work by experimental validation of a numerical 2D CFD model developed for the entire system using ANSYS Fluent software [106]. The findings have shown a potential energy saving of 6.4% compared to the standard cabinet without a PCM storage. The compressor lifetime was found to be enhanced as the number of compressor cycles (ON/OFF function) was reduced by 27%.

Ben-Abdallah et al. [119] used a fin-and-tube HEX design for a PCM storage unit located in the rear air duct of an open display cabinet. The PCM-HEX unit has a total heat transfer area of 25 m^2 and 7 kg of water is used as the PCM. The experimental results have shown that during a 2 h compressor OFF period, the integration of the PCM-HEX unit has limited the product temperature rise to 1 K. In the case of a cabinet without PCM integration, a 2 K increase of the product temperature was observed under the same operating conditions. Moreover, it was also found that the PCM charging process is approximately two times longer than the discharging process due to the larger temperature difference between the air and the PCM during discharging of the storage.

Until the date, research focusing on PCM storage integration into closed-style display cabinets are limited to theoretical studies. Sevault et al. [120] presented a design of a cold storage unit using water as the PCM, located in the air circulation duct of the cabinet (Fig. 7). The storage consists of a container composed of CO_2 refrigerant coils with integrated small air ducts to ensure the charging and discharging processes, respectively. A 2D CFD study in Ansys Fluent was performed to evaluate the influence of the distance between the air ducts and the CO_2 coils on the heat transfer, charging and discharging time. The results have shown that a 20 mm centre-to-centre distance of the coils and air passages was suitable to cover defrost periods. The storage demonstrated a maximum cooling duty of about 1.7 kW and a total capacity of 6 kWh per meter width.

A similar concept using water as the PCM was investigated theoretically by Jokiel et al. [121]. The storage unit consists of a PCM container composed of horizontal tubes where the refrigerant circulates and vertical tubes for the cabinet air circulation to charge and discharge the storage. The PCM-HEX was placed downstream of the evaporator in the air duct of the cabinet. Dynamic simulations of the cabinet with a novel integration of the PCM-HEX unit were performed in the software Dymola. The results have shown a reduction in the maximum cabinet air temperature during the defrosting period of up to 10 K compared to the cabinet without PCM storage. Even though both studies performed by Sevault et al. [120] and Jokiel et al. [121] show interesting strategies to implement active PCM storages in display cabinets, they obviously need to be completed with experimental studies to validate the theoretical results.

3.2.2. PCM integration into supermarket refrigeration system

The second strategy for a successful implementation of CTES in supermarkets involves the integration of a centralised storage into the central or main refrigeration circuit. The use of SHS storage units has been a popular choice among researchers over the last ten years [122–126]. However, the use of PCMs as LHS mediums for cold storage was found to be rarely investigated for supermarkets refrigeration systems, even though they are commercially available (water/ice as the storage medium), e.g. from Calmac Corp. [127] and Viessmann

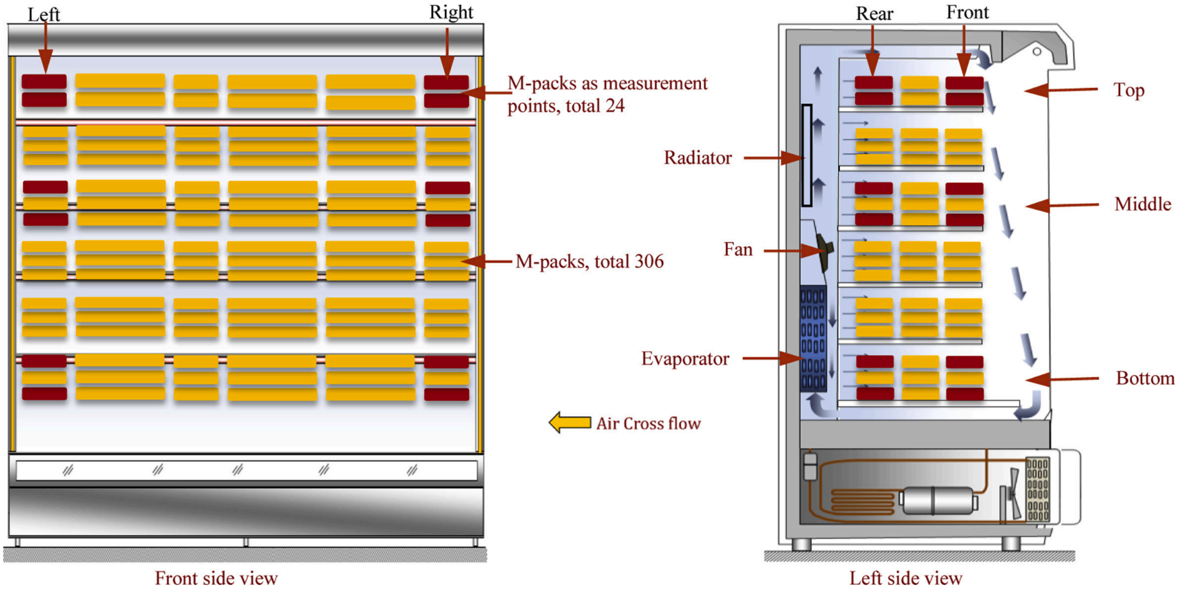


Fig. 6. Open display cabinet with integrated PCM-HEX (radiator) at the back wall [110]. Reprinted from Applied Thermal Engineering, 75, Alzuwaid, F., Ge, Y., Tassou, S., Raeisi, A., Gowreesunker, L., The novel use of phase change materials in a refrigerated display cabinet: An experimental investigation, 770–778, Copyright (2015), with permission from Elsevier.

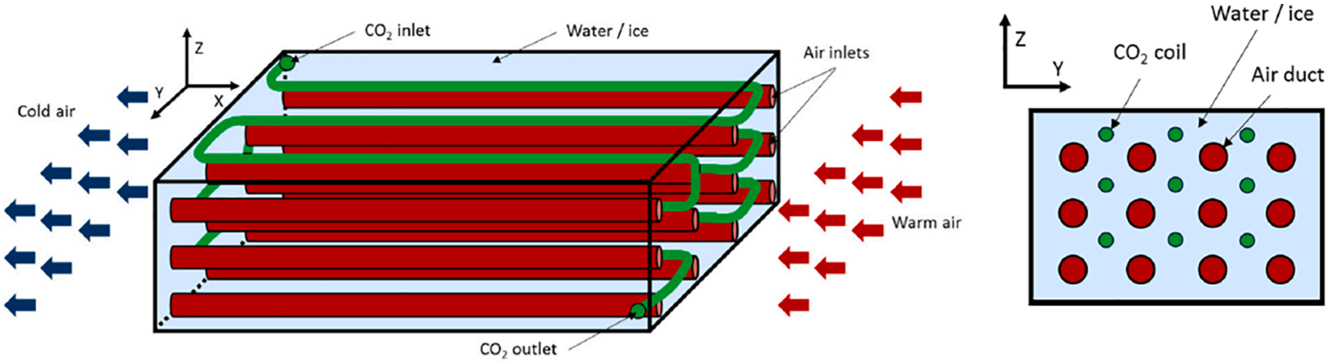


Fig. 7. PCM-HEX unit with air ducts and refrigerant tubes [120]. ©IIF/IIR. Published with the authorization of the International Institute of Refrigeration (IIR): www.iifiir.org.

Refrigeration Solutions [128]. Only a few investigations on the integration of CTES into CO_2 supermarket refrigeration systems have been performed the last five years. For a detailed overview of CO_2 refrigeration technology for supermarkets, the reader is directed to Gullo et al. [107]. The most common objective of the storage integration is to improve the system COP by reducing the throttling losses under unfavourable environmental conditions, such as high ambient temperatures. Fig. 8 presents an overview of the different configurations to

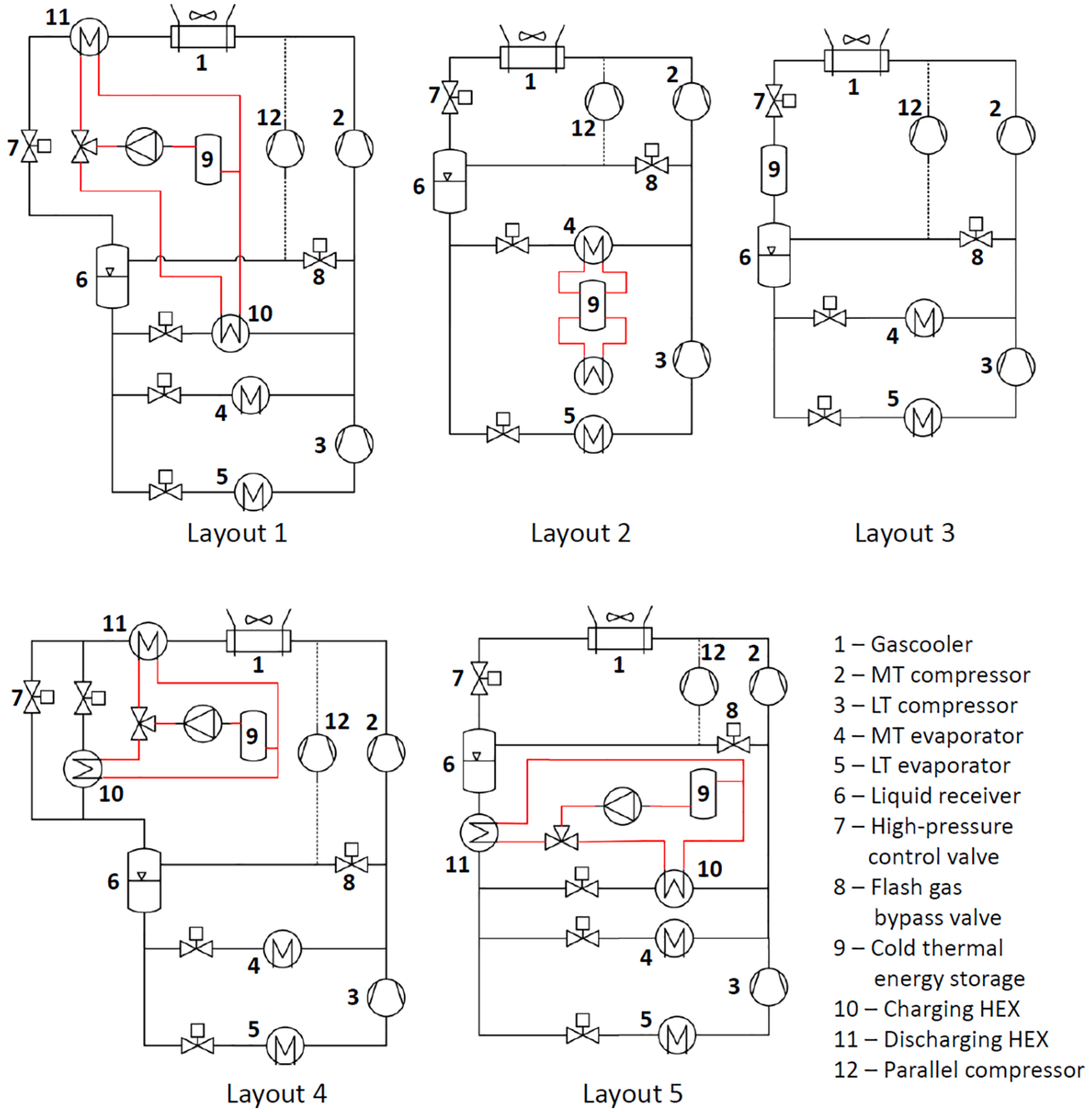


Fig. 8. Integration of CTES into a CO_2 refrigeration system: 1) Downstream of the gascooler using ice/water as the PCM 2) into the MT display cabinet 3) Upstream of the pressure receiver and using ice/water as the PCM 4) Downstream of the gascooler, using a 15 °C PCM 5) Downstream of the pressure receiver. Optional parallel compression indicated by a dashed line in each configuration.

integrate CTES into a transcritical CO_2 booster refrigeration system found in the literature. The most important components of the refrigeration system and the CTES system is indicated in Fig. 8. The possibility to include parallel compression is shown by a dashed line in all the layouts.

Heerup and Green [129] suggested to integrate a coil-in-tank LHS using ice as the storage medium between the high-pressure control valve and the liquid receiver (Layout 3 in Fig. 8, without parallel compression). The storage capacity is 144 kWh, which is equivalent to 33% of the cooling load for 6 h. The CO_2 circulates directly through the coil which is immersed in water. The charging and discharging processes are achieved by varying the liquid receiver pressure corresponding to −5 °C and 5 °C, respectively. The objective of the storage integration is to achieve energy and cost savings by shifting the refrigeration load from the day to the night, taking advantage of the difference in the ambient temperature conditions and the electricity pricing. The load is reduced during the daytime operation by condensing the flash gas that is formed after the expansion through the high-pressure control valve, reducing the load on the medium temperature (MT) compressors. Theoretical calculations using climate data from Denmark (cold) and San Francisco (warm) have revealed that the annual energy savings from implementing the ice storage are ranging from 4% (cold climate) to 14.4% (warm climate), as well as a reduction in peak power consumption of 50% during the warmest days of the year. The payback period was found to be more than 5 years, which is generally longer than accepted by the supermarket sector. The study did not evaluate the possibility to reduce the size of the other components (e.g. gas cooler, compressor pack) in the refrigeration system due to reduction of peak load by 50%. Taking this factor into account could possibly reduce the payback time of the system further.

Fidorra et al. [108] presented two different configurations to integrate CTES into a transcritical CO_2 booster refrigeration system with parallel compression (Layout 1 and 4 in Fig. 4). In both configurations, the storage is connected to the CO_2 refrigeration system employing a secondary HTF circuit via a charging and a discharging HEX. The discharging HEX is located downstream of the gascooler in both configurations. The objective of the storage integration is to decrease the temperature of the refrigerant downstream of the gas cooler during periods of high ambient temperatures, and consequently reducing the throttling losses and increasing the system COP. The first configuration (Layout 1, Fig. 4) utilises ice/water as the storage medium, and the charging HEX is therefore operated at the MT evaporation temperature (−8 °C). In the second configuration (Layout 4, Fig. 4), a PCM with a melting point of 15 °C is selected. An additional evaporation level at the liquid receiver pressure level (40 bar, 5.3 °C) is included upstream the pressure receiver to charge the PCM storage through the charging HEX. The load from the charging process is handled by the auxiliary compressor. Case studies applying different ambient conditions and storage capacities were simulated using a commercial dynamic simulation software (TIL-library/Modelica), and the results were compared to the system without storage. The results have shown that the reduction in daily energy consumption for layout 1 and 4 was up to 3.5% and 5.6%, respectively. The more important energy saving in layout 4 is due to the higher charging temperature compared to layout 1 (5.3 °C compared to −8 °C). Furthermore, up to 15% reduction in maximum compressor power was achieved for both configurations. This study shows again the potential for improving the efficiency of the refrigeration systems in supermarkets. A more detailed modelling of the heat transfer mechanisms of the storage and introducing thermophysical PCM properties into the numerical model is recommended to further improve the confidence in the results. Furthermore, a validation of this study by experimental results is currently missing.

Fidorra et al. [111] extended the previous work by carrying out a simplified thermodynamic analysis comparing the reduction in energy consumption and peak compressor power of four different configurations of CTES integration into a transcritical CO_2 refrigeration system under various ambient conditions. All the configurations use ice/water as the LHS medium. The four studied configurations for the implementation of CTES are layout 1, 2, 3 and 5 as presented in Fig. 4, but without parallel compression. Layout 1 is equal to the first configuration in Fidorra et al. [108] and was explained previously. In layout 2 the storage is located inside the display cabinet where the MT evaporator satisfies both the cooling needs and the PCM storage charging process. In layout 3 the storage is located upstream of the liquid receiver, similar to the configuration presented by Heerup and Green [129]. During the discharging process, the refrigerant liquid–vapour separation process is further enhanced by the integration of the CTES, where a part of the flash gas resulting from the throttling through the high-pressure valve is condensed thus the power consumption due to the compression of the flash gas is reduced. Layout 5 is equal to layout 1 except for the location of the discharging HEX, which is now located at the liquid receiver outlet. During the discharging process, the liquid CO_2 is subcooled before the expansion valves at the MT and low temperature (LT) evaporators to increase the evaporation capacity and thereby increase the system COP. The results have indicated that the highest reduction in the compressor power for high ambient temperature (40 °C) is achieved using layout 2 presented in Fig. 4. In fact, up to 68% power reduction was obtained assuming that the storage could cover the entire cooling load of the display cabinet. The maximum reduction in compressor peak power was 45.2%, 41.8% and 5.7% for layout 1, 3 and 5, respectively. The results for layout 3 is reasonably consistent with the findings reported by Heerup and Green [129], which showed up to 50% reduction in the compressor peak power. Transient numerical modelling of the storage taking into account the heat transfer in the CTES unit, supported by experimental validation of the results, should be further developed.

The largest performance penalty of CO_2 refrigeration system occurs during operation under high ambient temperature conditions, as a consequence of the throttling losses through the high-pressure control valve. Consequently, a centralised storage connected downstream the gas cooler is likely to limit this drawback most effectively. For this reason, layout 5 will not offer any benefits at higher ambient temperature conditions. This configuration will most likely be too costly compared to the achieved reduction in energy consumption (5.7%). Layout 1 and 4 presented in Fig. 4 utilises a secondary HTF circuit to achieve the charging and discharging processes of the storage. To reduce the investment costs and the payback period for the LHS, it could be beneficial to investigate a storage design where the primary refrigerant circulates through the LHS itself, without a secondary HTF circuit. This is believed to reduce the number of additional components and avoid heat transfer across multiple temperature levels via the secondary HTF circuit, thus improving the efficiency of the storage.

3.2.3. *PCM integration into beverage coolers and vending machines*

PCM cold storage integration into bottle coolers is an interesting application. Introducing CTES in these units could give multiple benefits, such as enabling operation of the cooler independently from the electrical grid, thermal protection of the goods in case of component failure in the refrigeration system or a blackout situation and stabilisation of the product temperature. Extensive research on PCM integration into domestic refrigerators and freezers has been carried out in the past [18,19]. Since the size and structure of bottle coolers and refrigerated vending machines are similar to a domestic refrigerator, some of the reported advantages could be transferable to bottle coolers. A few examples of reported benefits of integrating PCM into the evaporator section of domestic refrigerators are the decreased fluctuation of the air temperature inside the refrigerator and more stable conditions against thermal load variations [18].

Beek and Jong [130] presented a study aiming to develop and build a standard-size 350 dm^3 bottle cooler vending machine integrated with PCM, keeping the bottles at a temperature of 2.5 °C. Water and the paraffin RT4 (melting point 4 °C [90]) was considered as the PCMs in the storage. The main purpose of the storage is to provide the peak cooling demand during the cooling down of new products when they are placed in the cooler (pull-down load) so that the refrigeration system can be sized for the average refrigeration load rather than the peak load. The novel vending machine is composed of a triple-layer glass door and vacuum insulated panels on the three other sides to reduce the heat transfer and air infiltration from the ambient, thereby reducing the cooling load. The PCM storage consists of three PCM-HEX units located at the rear wall of the cabinet as represented in Fig. 9a. A PCM-HEX is represented in Fig. 9b and consists of a tube-and-plate HEX placed inside a thin metal container. The tube-and-plate HEX consists of copper tubes where the refrigerant circulates, attached to a conducting plate. During the charging process, the PCM storage unit acts as an additional evaporator to the main evaporator located at the bottom of the cabinet. The discharging process takes place during the pull-down load where the fan circulates the cabinet air over the PCM-HEX, while simultaneously all the refrigerant is circulating through the main evaporator to maximise its cooling capacity. The numerical results revealed that using water as the PCM resulted in shorter time required to reduce the product temperature to 2.5 °C during the pull-down period compared to PCM RT4 for all conditions and compressor sizes. Consequently, water was selected as the PCM for the experimental study. The experimental results showed a 77% decrease in the total energy consumption compared to a standard glass door beverage cooler. The PCM integration share was calculated to 4–10%, while the rest was ensured by the cooling load reducing measures such as improved insulation in the walls. Furthermore, integrating the PCM storage allowed for a smaller compressor size to be used in the novel bottler cooler compared to the standard model, increasing the compressor cycle time by 118%.

Ezan et al. [131] numerically investigated the use of water as a latent storage medium to increase the compressor OFF-period in a commercial closed beverage cooler. The bottle cooler and its main components are represented in Fig. 10a. A 3D CFD model was developed in ANSYS FLUENT and validated with experimental results. The PCM storage is displayed in Fig. 10b and consists of a flat container that is attached to the surface of the evaporator which is located at the rear wall of the bottle cooler. The thickness of the PCM container was varied from 2 mm to 10 mm, and the effect on the energy consumption and the thermal stability was compared to a bottle cooler without PCM storage. The integration of a 6 mm thickness PCM storage has revealed a reduction in the ratio of compressor ON to OFF period from 36% to 26% compared to the model without storage. Nevertheless, only the model without storage was experimentally validated. Consequently, there is a need to complete this promising study by experimental validation of the numerical model performed for the case with the storage. The numerical results reveal that the storage was never fully charged, it was partly liquid at the upper part even at the end of the compressor ON period. This indicates that this storage design is sub-optimal, and the PCM-HEX design with integrated refrigerant tubes proposed by Beek and Jong [130] is a better configuration to ensure complete charging of the storage.

Beverage dispensers installed in e.g. catering facilities uses another type of cooling system to serve the beverage at the correct temperature. Some of these beverage coolers have an LHS using water as the storage medium to increase the cooling capacity during hours of high demand for cold beverage. This type of beverage cooler was experimentally investigated by Mađerić et al. [132], and an overview of the system is

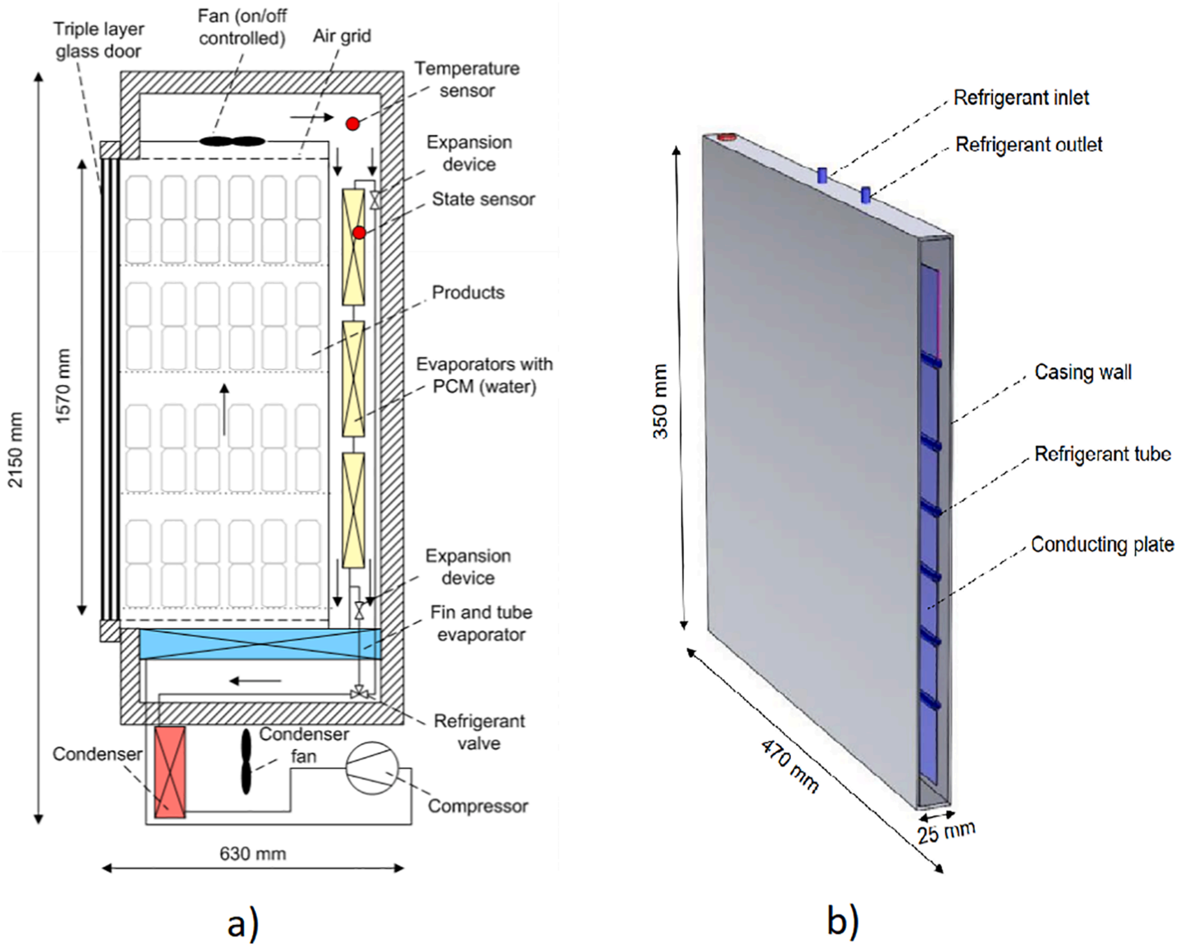
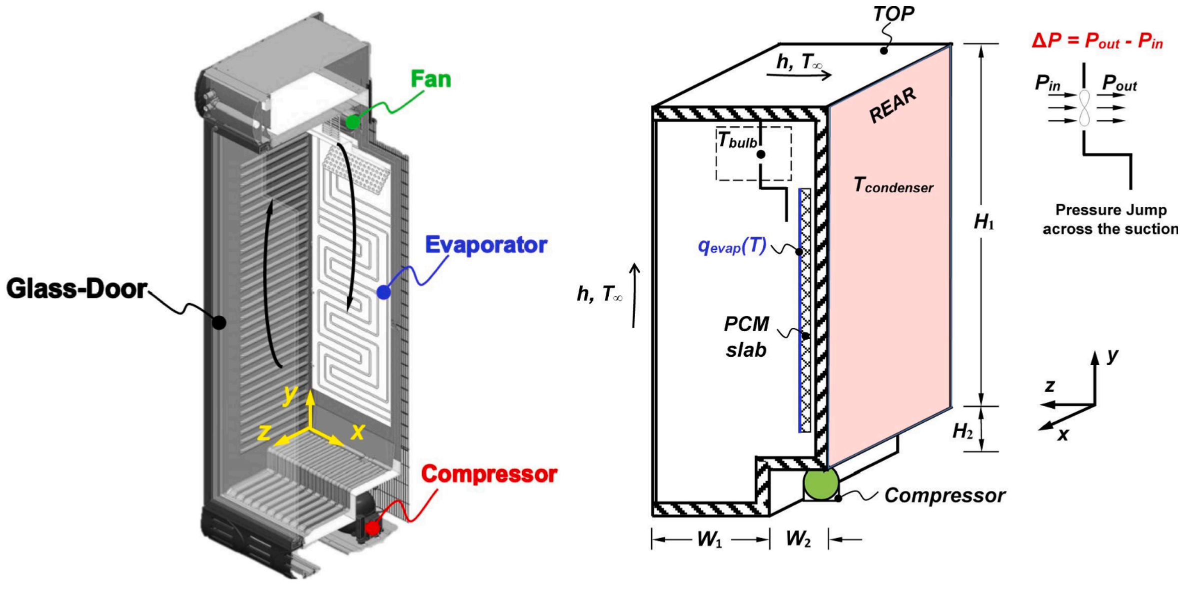


Fig. 9. Beverage cooler vending machine with an integrated PCM evaporator: a) System principle sketch, b) PCM evaporator [130]. Copyrightcopyright IIF/IIR. Published with the authorization of the International Institute of Refrigeration (IIR): www.iifiir.org.



(a) Mathematical model of the cooler (b) 3D section of the cooler

Fig. 10. Beverage cooler vending machine with integrated PCM storage unit: a) Mathematical model of the cooler b) 3D section of the cooler [131]. Reprinted from Energy conversion and management, 142, Ezan, M.A., Doganay, E.O., Yavuz, F.E., Tavman, I.H., A numerical study on the usage of phase change material (PCM) to prolong compressor off period in a beverage cooler, 95–106, Copyright (2017), with permission from Elsevier.

presented in Fig. 11. Referring to Fig. 11, the beverage is first drawn from containers and through tubes by using pressurized CO_2 gas as the driving force. The beverage is then cooled by circulating it inside coils that are immersed in a cold water bath before being served at the dispensing tower. The water bath is cooled by a small refrigeration system. The conventional thermostat in the cold water bath was replaced by an ice bank relay to measure the ice thickness. It was found that compared to using a thermostat-controlled charging and discharging process of the LHS, the energy consumption was reduced by 15%.

3.2.4. Summary and discussion

The results from the reviewed literature on PCM integration in commercial refrigeration applications is presented in Table 6. The common objective of these studies is to determine the optimal design, which results in the appropriate PCM selection to satisfy the cabinet air temperature conditions and limit the temperature fluctuations occurring during the evaporator defrosting periods. The most commonly applied PCM in commercial refrigeration systems was found to be the water/ice solution. The melting temperature of ice satisfies the required temperature conditions for chilled food in the supermarket display cabinets (0 °C to 5 °C. Moreover, water/ice solution is characterized by good heat

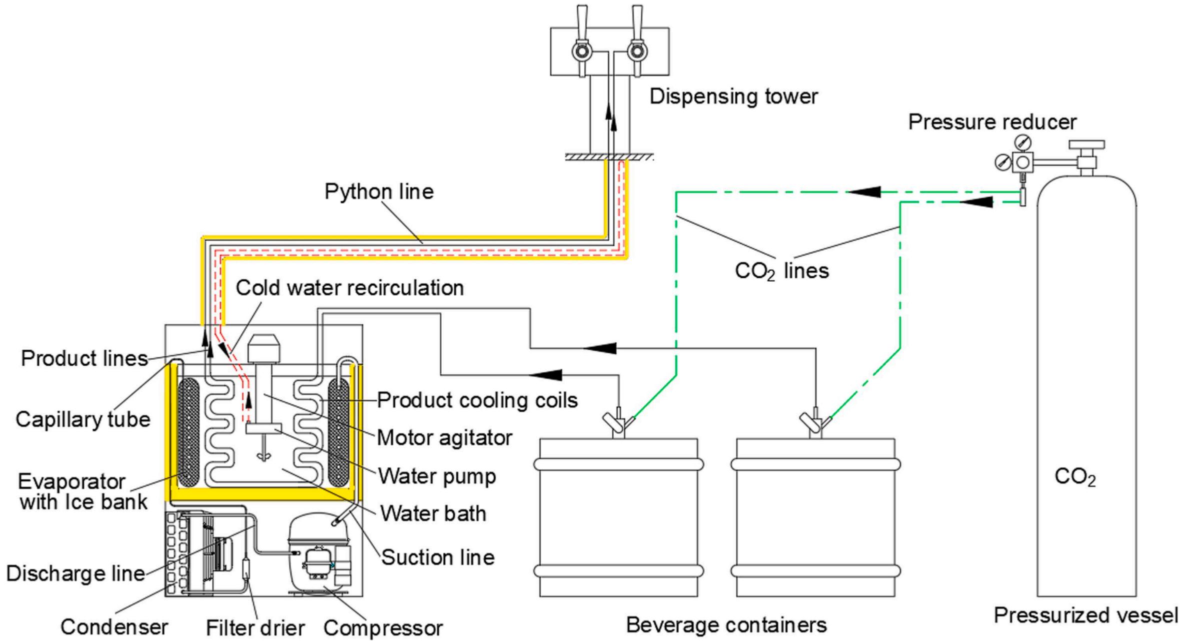


Fig. 11. Beverage cooler for a dispensing tower using a water LHS [132]. Reprinted from Applied Thermal Engineering, 148, Maerić, D., Pavković, B., Lenić, K., An experimental research on energy efficiency of a beverage cooler with the latent heat storage, 270–277, Copyright (2019), with permission from Elsevier.

transfer properties compared to the other commonly used PCM for this type of applications (e.g paraffin-based PCMs). The use of water as a PCM is also safe and non-toxic which preserve food from any damage in case of any leakage. The reviewed literature has shown two different strategies for implementing PCM storage units in the display cabinet: A direct integration into the cabinet shelves or through the installation of a PCM-HEX unit in the main air circulation duct. A PCM-shelf based design in combination with heat pipes was proven to be a performant strategy to reduce product temperature fluctuations (up to 83.3%) [117].

On the other hand, the integration of a PCM-HEX unit in the main air circulation duct of the cabinet was a more popular application over the last 5 years [110,106,120,121,119]. This might be because these PCM-HEX units are more technically feasible, easier to install and requires fewer modifications on the display cabinet itself. In the case of the PCM-shelf design, the shelf will become considerably heavier when including PCM and heat pipes and might require reinforcement of the shelf support. In case of a PCM leakage, the food could be damaged despite using water as the PCM in the shelves. The commonly set performance criteria to evaluate the appropriate display cabinet with an integrated PCM cold storage unit are: Reduction in the energy consumption by up to 5% and reduction in the peak cabinet air temperature during the defrosting period by up to 2 K. There are currently new proposed emerging concepts for PCM-HEX unit designs allowing the display cabinet to be disconnected from the main refrigeration system during the discharging process of the storage [133,121]. These PCM-HEX units can cover the entire refrigeration demand of the cabinet during its discharging process so that each cabinet can operate as a stand-alone unit. Nevertheless, experimental validation needs to be carried out to prove the feasibility of these concepts. Furthermore, the question regarding the optimum location of the PCM-HEX storage in the cabinet remains. This is also a practical matter since the available space to integrate a PCM-HEX unit in the display cabinet is limited, hence restricting the capacity of the storage. Furthermore, a clear description of the control strategy for the discharging process in these emerging concepts is not available to this date.

Although extensive research was carried out on the integration of CTES into the supermarket refrigeration system itself, most of the reported analysis has been limited to analytical approaches only and there is obviously a need for experimental studies to prove the overall system performance and reliability. Investigating a real-scale supermarket refrigeration system at a laboratory level is costly and a complex procedure compared to refrigerated display cabinets and vending machines, although all-in-one CO_2 refrigeration system for supermarkets is explored by Pardiñas et al. [134,135] considering an integrated ice storage into the display cabinets. To the date, few real-scale test facilities are available as this technology should be mature enough to gain more confidence by retail industry and refrigeration system manufacturers. The only way to achieve this goal is to perform more reliable experimental research on this topic. The energy consumption reduction, as well as a lower ON/OFF compressor cycles frequency, are reported to be the main benefits obtained by the PCM cold storage integration into the small commercial refrigeration units. Due to many system and design similarities with domestic refrigerators, where the integration of PCM cold storage has been extensively investigated, more interest should be attributed by the research community in this topic into the development of a new design of bottle coolers and vending machines with an integrated PCM cold storage.

3.3. PCM applications in various refrigeration systems

This section gives an overview of CTES integration into AC chillers systems, refrigerated warehouses and large industrial refrigeration systems. In this section, the refrigeration systems with integrated PCM-CTES are classified into two categories: CTES units integrated into the primary refrigeration circuit based on a PCM/two-phase fluid heat exchange design, and CTES units integrated into the secondary refrigeration circuit based on a PCM/single-phase fluid heat exchange design. The principle of CTES integration for the two categories is illustrated in Fig. 12.

In the first-mentioned category (PCM/two-phase fluid design, Fig. 12a), the CTES unit is directly integrated into the primary refrigerant circuit. During the charging process, the CTES unit acts as an evaporator where the refrigerant extracts heat from the PCM storage unit and evaporates. During the discharging process, the storage acts as a heat sink and the PCM is melting while it absorbs heat from the refrigerant. The refrigerant either condenses or its temperature is decreased, depending on whether the storage is designed to work as a condenser or a subcooler. A simplified refrigeration cycle with a CTES unit integrated as a subcooler is shown in Fig. 12a. In the second category (PCM/single-phase fluid design, Fig. 12b), the storage is integrated into the secondary refrigerant circuit. During the charging process, the temperature of the secondary refrigerant is set below the phase change temperature of the PCM. The temperature of the secondary refrigerant increases as it absorbs heat from the PCM, which solidifies. During the discharging process, the secondary refrigerant is heated by absorbing the refrigeration load. It is cooled down again by circulating it through the storage, which acts as the heat sink. The PCM in the storage is then melting as a result of absorbing the heat from the secondary refrigerant.

A summary of the reviewed literature of the PCM/two-phase fluid design and the PCM/single-phase fluid design are presented in Table 7 and 8, respectively. The presented studies cover CTES integration into AC systems, district cooling systems, refrigerated warehouses, industrial refrigeration systems and low-temperature food processing plants [136–140]. Few researchers report on the overall system performance when integrating a CTES unit into the refrigeration system. It is far more common to evaluate only the performance of the storage itself in terms of efficiency and storage capacity. CTES integration into AC applications has been extensively researched over the last two decades. Large AC systems often apply a secondary refrigerant circuit to reduce the amount of primary refrigerant in the system. For this reason, the majority of the research has been devoted to the development and integration of CTES units based on the PCM/single-phase fluid design. CTES based on the PCM/two-phase fluid design has become increasingly popular over the last five years due to interest of integrating CTES in refrigeration applications without secondary refrigerants. Many promising novel concepts are presented, but still require extensive experimental investigations [141,140]. Technical and economical studies should be carried out to make these systems commercially viable.

3.3.1. PCM-HEX integration into the primary refrigerant circuit

Wang et al. [136] experimentally investigated three possible locations to integrate a shell-and-tube PCM-HEX in the refrigerant cycle of a 5 kW air-to-air AC unit. The alternatives consist of the integration of the PCM-HEX as a pre-condenser located between the compressor and the condenser (Fig. 13a), as a subcooler between the condenser and the expansion valve (Fig. 13b) or as a desuperheater between the evaporator and the compressor (Fig. 13c). In alternative A and B, the PCM-HEX is integrated on the high-temperature side of the refrigeration cycle. For this reason, a eutectic PCM with a melting point of 21 °C is selected so that the storage can passively recharge overnight by releasing the stored heat to the cold ambient air. In alternative C a eutectic PCM with a melting temperature of 8 °C was selected according to the evaporation temperature and superheat of the refrigeration system. The purpose of the PCM-HEX in alternative A is to act as an extra condenser to reduce the condensing pressure of the cycle. For alternative B the purpose of the PCM-HEX is to decrease the liquid refrigerant temperature before the expansion valve, increasing the evaporation capacity. The purpose of the PCM-HEX in alternative C is to reduce the superheat of the refrigerant before entering the compressor.

For alternatives A and B, it was found that the COP was increased by 6 and 8% compared to the system without PCM storage, respectively. No

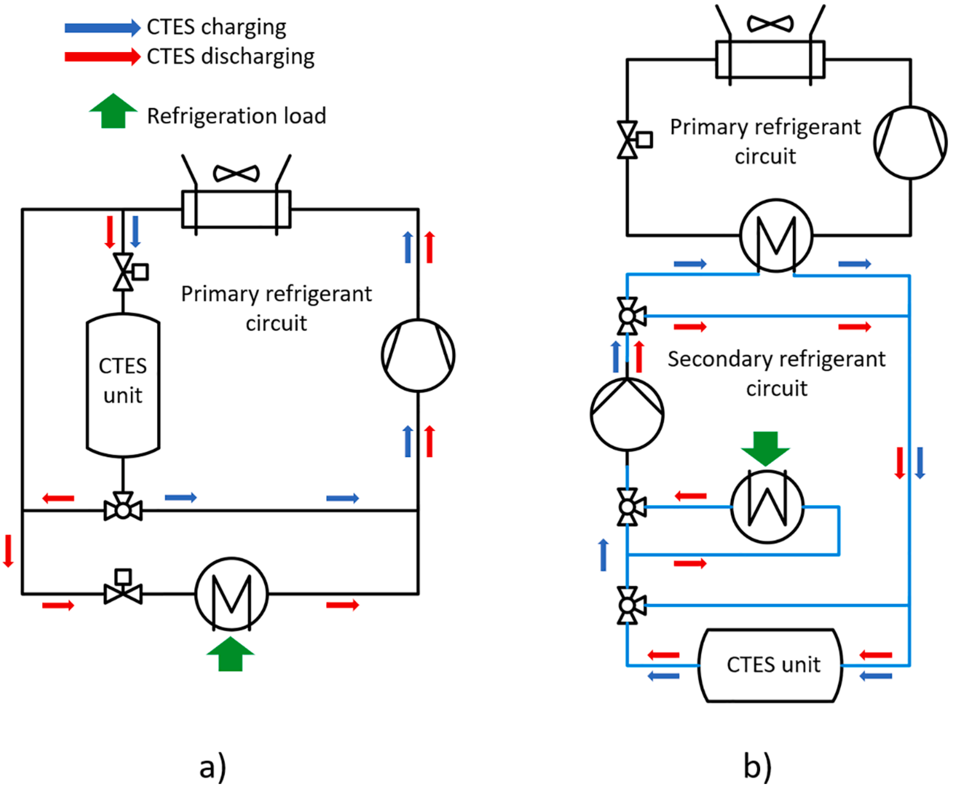


Fig. 12. Strategies of CTES integration in a simplified refrigeration system: a) PCM/two-phase fluid heat exchange, b) PCM/single-phase fluid heat exchange.

Table 7
Main results from application of CTES using PCM/two-phase fluid heat exchange.

Application	Theoretical (T) Experimental (E)	PCM (T_m [°C])	Main result (value)	Reference
Air-to-air heat pump	T/E	No info (8 and 21)	COP increase (6–8%); Stabilize system fluctuations	[136,142,143]
Tube-in-tank CTES for multi-split AC	E	RT28HC (28)	Mean cooling duty discharge of CTES (1.5 kW)	[146]
Tube-in-tank subcooler for multi-split AC	T/E	Parafol 16–97/ graphite mixture (18)	Evaporation capacity increase during discharge (18%); Evaporation capacity increase in high ambient temperature (40%)	[144]
CTES for industrial CO_2/NH_3 cascade	T	Water/ice (0); Adblue (-11)	Peak load reduction (19%)	[141,147]
PCM plates in refrigerated warehouse	T	Water/ice (0)	Even discharge of cold energy; Reasonable payback time (2.6 years)	[138]
CTES for low-temperature freezing processes	T	CO_2 /dry ice (below −50)	Reduced electricity consumption for the same capacity (30%)	[148]
CTES for low-temperature fish freezing process	T	CO_2 /dry ice (−57)	Reduced fish freezing time (3.2%)	[140]

Table 8
Main results from applications utilising PCM/single-phase fluid heat exchange.

Application	Theoretical (T) Experimental (E)	PCM (T_m [°C])	Main contribution (value)	Reference
Coil-in-tank CTES with 8 kW chiller	E	RT8 (8)	High storage capacity in tank (40 kWh); Highest COP for low HTF supply temperature	[161]
CTES tank with 4.2 kW chiller	E	S10 salt hydrate (10)	Storage capacity enhancement compared to water SHS (35.5%)	[165]
CTES tank with 15 kW chiller	E	RT15 MPCM 45% suspension (15)	Storage capacity enhancement compared to water SHS (53%)	[8]
District cooling system with storage	T	Water/ice (0)	Annual energy savings (0 to 4%); Long payback time (22 to 30 years)	[137]
PCM-HEX and AC system	T	Calcium chloride hexahydrate (29)	COP of the combined system (3.07); PCM-HEX show lowest relative irreversibility (6.0%)	[167]
CTES tank with 2000 kW chiller	T	Water/ice (0); RT3HC (3)	Exergy efficiency highest for PCM system (53.44%); Reduced power consumption using PCM (7.58%)	[168]
CTES tank for AC in hypermarket	T	Water/ice (0)	Short payback times (1.5–3.1 years); Highest cost savings for full storage scenario (1.45 mill USD)	[169]

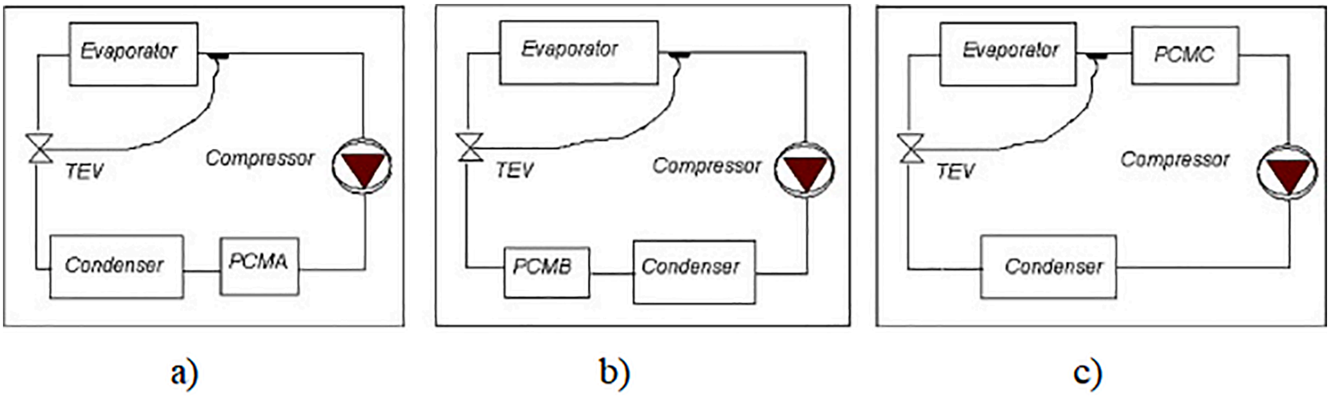


Fig. 13. Different integration scenarios of a PCM-HEX in a refrigeration system: a) Pre-condenser b) Subcooler c) Desuperheater [136]. Reprinted from Applied Thermal Engineering, 27, Wang, F., Maidment, G., Missenden, J., Tozer, R., The novel use of phase change materials in refrigeration plant. Part 1: Experimental investigation, 2893–2901, Copyright (2007), with permission from Elsevier.

improvement in COP was observed for alternative C. The performance benefit of reduced refrigerant superheat provided by the PCM-HEX was counteracted by the effect of an increased pressure drop in the suction line caused by the PCM-HEX. The potential energy savings for UK climatic conditions were obtained by numerical optimisation of the system. It was shown that alternative B provided the highest improvement in COP (8%) for the UK climate [142,143]. Alternatives A and C were found to be beneficial for the system stabilization by lowering the condenser pressure and reducing the peak inlet temperature to the compressor, respectively.

Similarly, Korth et al. [144] carried out theoretical modelling and experimental tests of a tube-in-tank LHS with paraffin Parafol 16–97 as a PCM [145] having a melting point of 18 °C. The objective of the storage was to increase the peak refrigeration capacity by acting as a subcooler integrated after the condenser in a 6 kW AC system. The experimental results have shown an increase in the evaporation capacity of 18% for a condensing temperature of 35 °C. A PCM-HEX integrated into a multi-split AC system has been investigated by Korth et al. [146]. The selected PCM was paraffin RT28HC [90] and integrated into a tube-in-tank storage unit. The CTES unit was operating in parallel with the evaporators during the charging process, and in series between two evaporators during the discharging process (see Fig. 14). The refrigerant condenses through the CTES unit and reduces the load on the compressor. The experimental results have shown that the storage could achieve a mean cooling capacity of 1.5 kW for 2.33 h with 3–4 K temperature difference during discharge. The main benefits of integrating a PCM-HEX unit are proven, but the system performance needs to be further investigated when implemented into a real scale AC system, and an associated control strategy should be established.

Selvnes et al. [139] have proposed a novel design of a CTES unit to be integrated into a pumped CO_2 circuit of an industrial NH_3/CO_2 cascade refrigeration system for a poultry processing plant. The unit is integrated into the return line of the −5 °C evaporation temperature level. The main aim of the unit is to achieve peak shaving of the refrigeration load during high-demand hours while using low-cost electricity to charge the CTES unit during the night. The experimental prototype of the CTES unit is shown in Fig. 15. It consists of a stack of pillow plates shown in Fig. 15b, immersed into a container filled with PCM. The selection of the PCM was based on the application temperature range (Condensing temperature of CO_2 at −5 °C) and consists of paraffin RT-9HC [90]. The pillow plates consist of two metal plates that are welded together in a pattern of spot welds and seam-welded at the edges. The plate is inflated by applying high pressure on the inside, creating flow channels for the refrigerant. The CO_2 circulates through the plate and the flow is directed by the path created by the spot welds while exchanging heat with the PCM. A 2D CFD model of the previously described CTES unit was developed using the Ansys Fluent software [147]. In the numerical analysis, water was selected as the PCM due to lack of temperature-dependent thermophysical data for the PCM RT-9HC. The results revealed that the current version of the software was unable to handle the buoyancy-induced movement of solid PCM in the liquid PCM. The discharging time was found sensitive to the value of a modelling

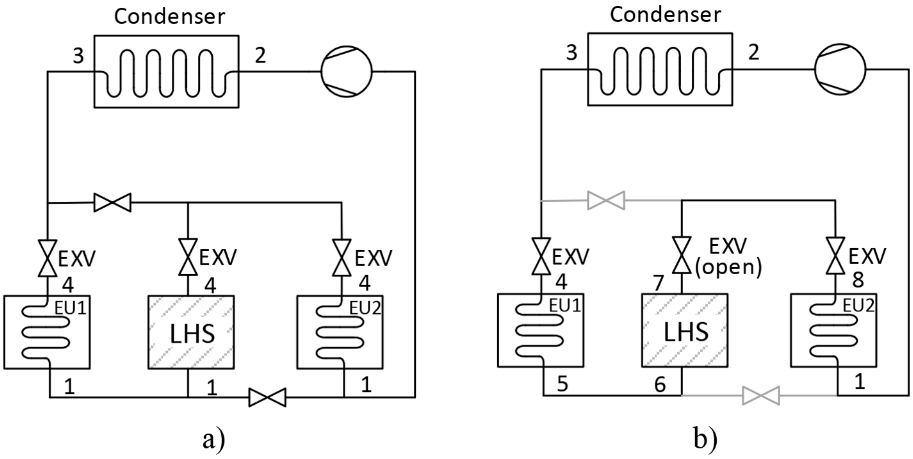


Fig. 14. PCM-HEX integrated into a multi-split AC system: a) Charging of the PCM-HEX b) Discharging of the PCM-HEX [146]. Copyright ©IIF/IIR. Published with the authorization of the International Institute of Refrigeration (IIR): www.iifiir.org.

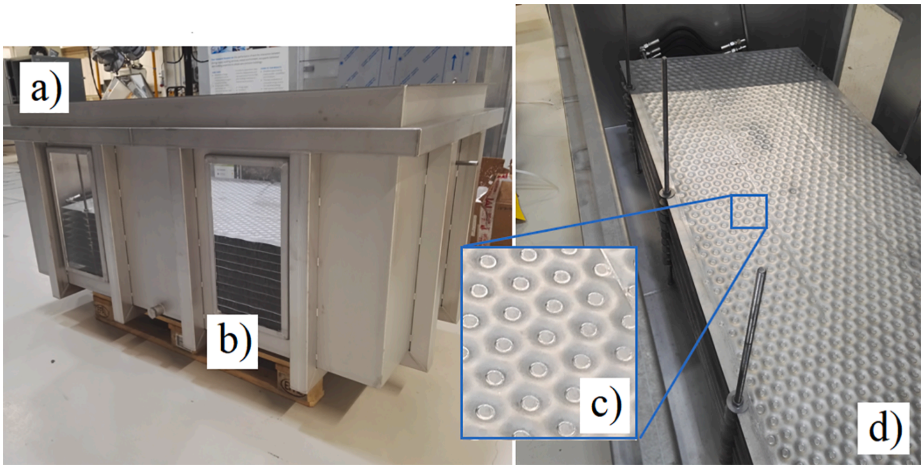


Fig. 15. Prototype CTES unit for a CO_2 refrigeration system: a) CTES unit before assembly b) PCM integration between the pillow plates c) Spot welds to direct the CO_2 flow d) Pillow plate HEX [139]. Copyright ©IIF/IIR. Published with the authorization of the International Institute of Refrigeration (IIR): www.iifiir.org.

constant used in the enthalpy-porosity method for melting/solidification in the software. Experimental investigations are currently being performed to complete this study. The total storage capacity of the CTES unit was found to be about 108 kWh. Selvnes et al. [141] developed a numerical model of the previously reported CTES unit with an increased capacity using Dymola software. The CTES unit was integrated into the −5 °C evaporation level of a pumped CO_2 refrigeration system. The main goal was to achieve peak shaving of the compressor power consumption by condensing the refrigerant through the storage during the discharging process. The system performance has revealed a reduction in the compressor peak power consumption of 19%. The model validations will soon be published by the authors of this review.

Yang et al. [138] proposed to implement PCM panels into a refrigerated warehouse along the walls and ceiling. The PCM panel consists of a tube-in-plate PCM-HEX. The refrigerant circulates inside the tubes to ensure the charging process of the PCM storage during the compressor ON periods. The refrigerated room is passively cooled by the PCM panels when they exchange the heat from the air during compressor OFF periods. The objective of the storage system was to benefit from a peak-valley electric pricing scheme by shifting the refrigeration load. Water was used as the storage medium. The system performance was numerically studied using Ansys Fluent software. A 3D CFD model of a refrigerated room was performed. It was found that PCM panels limited the increase in maximum air temperature to 2 K during the compressor OFF period. The payback time was calculated to be about 2.6 years. The model was not assuming the ambient heat transfer to the warehouse, therefore a complete numerical modelling taking into consideration the air infiltration should enhance the system performance predictions.

Other CTES concepts using solid CO_2 (dry ice) as the storage medium have been proposed. This technique is generally used for storage temperatures below −40 °C. Hafner et al. [148] numerically investigated a shell-and-tube HEX with dry ice as the storage medium. Referring to Fig. 16, the CTES unit was integrated into an NH_3/CO_2 cascade refrigeration system connected to a tunnel freezer for freezing of fish (Air temperature −30 °C). During the charging process, the CO_2 on the tube side sublimates while cooling the CO_2 on the shell side until solidification. During the discharging process, the dry ice on the shell side cools down and condenses the CO_2 gas on the tube side. Up to 30% energy savings were calculated for the same freezing capacity when applying the novel CTES design.

The same concept using a shell-and-tube PCM-HEX with dry ice was numerically studied by Verpe et al. [140]. It was integrated into a CO_2 refrigeration system for a plate freezer in a fishing vessel (CO_2 evaporation temperature down to −50 °C). The study indicates a reduction in the fish freezing time by 3.2% when integrating the storage into the system. These findings suggest that dry ice can be an interesting option for energy savings in applications that require storage under −40 °C. Few other alternative PCMs are available below this temperature (see Table 4). However, there is very limited research on the behaviour of CO_2 during phase transition around the triple point [148]. More experimental research related to heat transfer of dry ice has to be carried out.

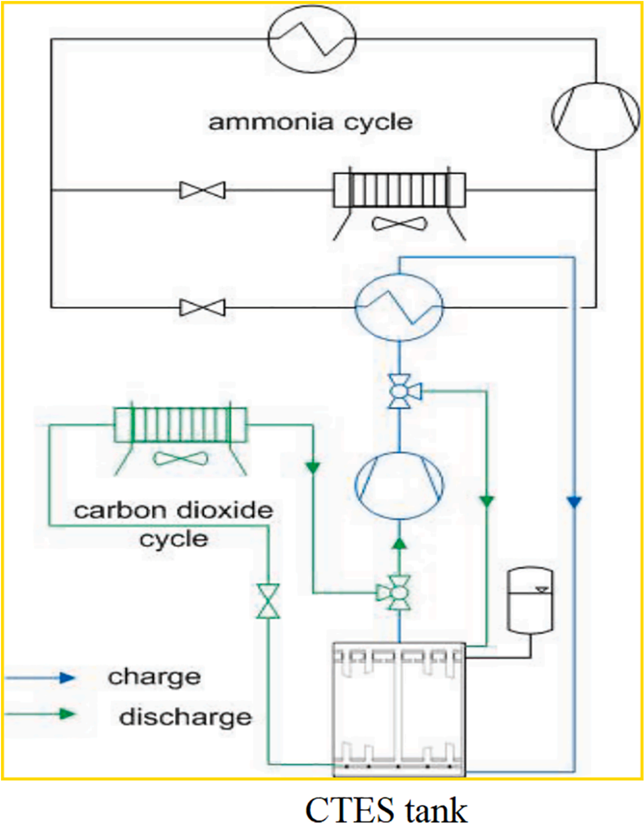


Fig. 16. CTES unit with dry ice as the storage medium in an NH_3/CO_2 cascade refrigeration system [148]. Reprinted from Procedia Food Science, 1, Hafner, A., Nordtvedt, T.S., Rumpf, I., Energy saving potential in freezing applications by applying cold thermal energy storage with solid carbondioxide, 448–454, Copyright (2011), with permission from Elsevier.

3.3.2. PCM-HEX integration into the secondary refrigerant circuit

Integration of CTES into the secondary refrigerant circuit of a refrigeration cycle has been an important research topic for two decades. Significant efforts were dedicated to improving the efficiency of CTES units that can be integrated into large capacity refrigeration systems through the secondary refrigerant circuit (Storage capacity up to 96 kWh [149]). Cylindrical tanks that are filled with macro-encapsulated water (e.g. spheres and small capsules) as the PCM has been a popular CTES configuration over the last 20 years [150–153,149]. In this configuration, the secondary refrigerant flows through the tank to exchange heat with the PCM capsules. Two commonly proposed CTES designs integrated into the secondary refrigerant circuit are the coil-in-tank (Fig. 17) and tube-in-tank designs (Fig. 18) [154–163]. The concept consists of one or multiple coils/tubes that are immersed into the PCM storage tank. The secondary refrigerant flows inside the tubes and exchanges heat with the surrounding PCM to ensure both the charging and the discharging processes.

The performance of a commercial coil-in-tank filled with 1450 kg of the paraffin PCM RT8 [90] was experimentally investigated by Torregrosa-Jaime et al. [161]. The CTES tank was connected to an 8 kW chiller by a secondary refrigerant circuit. The highest system COP during charging was obtained for the lowest refrigerant supply temperature (1 °C) and lowest refrigerant mass flow (1980 kg h^{-1}). It was also found that 40 kWh could be stored in the CTES tank after 6.5 h of charging.

Moreno et al. [165] compared the performance of an SHS tank using water as the storage medium and an LHS tank filled with macro-encapsulated S10 PCM [166]. The CTES tanks were connected to a 4.2 kW water-to-water heat pump for space cooling and heating of a small house. The experimental results demonstrated that the cold energy storage was enhanced by 35.5% when using the PCM as a storage medium. The charging process of the PCM tank was 4.55 times longer than for the SHS water tank. An experimental study of a tube-in-tank CTES integrated into the HTF circuit of a 15 kW AC chiller unit was presented by Allouche et al. [8]. A comparison between SHS and LHS was carried out using water and an MPCM paraffin suspension (45% concentration of RT15 [90]) in the tank, respectively. After 10 h of charging, it was found that the cold storage capacity was enhanced by 46.6% when using the PCM as a storage medium.

Recent theoretical studies on CTES integration in HTF circuits have focused on energy consumption and performance of the total system, exergy analysis and techno-economical calculations [167–169]. Mosaffa et al. [167] carried out a theoretical analysis of a refrigeration system and a CTES-HEX for an AC system of a building. The proposed design included a PCM-HEX which consists of PCM slabs installed in the main air duct of the ventilation system. The numerical analysis and evaluation of the thermal performance were carried out using COMSOL Multiphysics and EES software. A COP of 3.07 is calculated for the refrigeration system with CTES. The exergy analysis revealed that the CTES unit has the lowest relative irreversibility of all the components in the system with 6.0%. Rahdar et al. [168] made an exergetic, economic and environmental comparison between a standard 2000 kW AC chiller without storage, a chiller integrated with an ice-CTES and a chiller integrated with a PCM-CTES. Using multi-objective optimisation, the highest exergetic efficiency of 53.4% was reported for the PCM-CTES system. The annual energy consumption was reduced by 7.58% and 4.59% compared to the standard chiller for the PCM-CTES and ice-CTES, respectively. Due to higher investment costs of the PCM-CTES, the payback time was found to be shortest for the ice-CTES with 3.16 years. A techno-economical study of integrating a CTES tank into the AC system for a hypermarket was carried out by Erdemir and Altuntop [169]. Encapsulated ice/water was chosen as the PCM, and weather data from Turkey was used to calculate the peak cooling loads. The research considered the investment and operational costs to calculate the payback period and cost savings after ten years. Sizing strategies of the CTES from 10% partial storage to full storage was investigated. The shortest payback period was found for load levelling and 10 % partial storage with about 1.5 years. However, the highest cost savings were obtained by the full storage scenario with a total saving of 1.45 mill USD and a payback time of about 3.1 years.

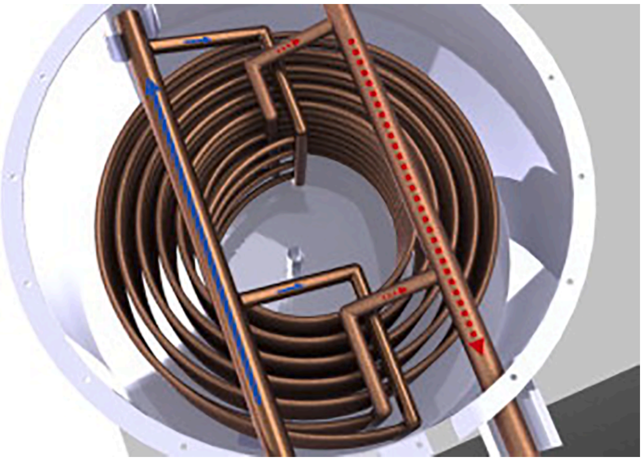
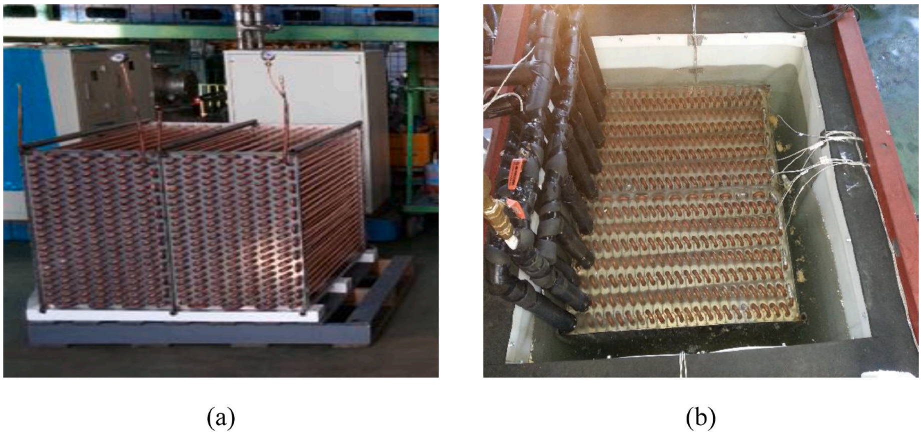


Fig. 17. Coil-in-tank CTES design [162]. Reprinted from Applied Energy, 119, López-Navarro, A., Biosca-Taronger, J., Corberán, J.M., Peñalosa, C., Lázaro, A., Dolado, P., Payá, J., Performance characterization of a PCM storage tank, 151–162, Copyright (2014), with permission from Elsevier.

A district cooling system is a large-scale cold energy production facility that can serve the cooling demand of multiple buildings. Integration of ice-CTES in this type of cooling system was theoretically investigated by Chan et al. [137] using TRNSYS software and compared to a chiller without storage. The results from several case studies have revealed that the annual cost savings range from 0% to 4% under different Chinese electricity tariff structures. The district cooling system with storage had about 30% higher investment cost compared to the standard system. The payback time of the system was calculated to be from 22 to 30 years and was found to be economically non-viable.

3.3.3. Summary and discussion

A summary of the reviewed literature utilising a PCM/two-phase fluid heat exchange and PCM/single-phase fluid heat exchange is given in Table 7 and 8, respectively. It can be clearly seen that the integration of CTES has been considered in various applications of the large industry (e.g. Industrial refrigeration, large AC installations, district cooling). LHS integration into AC application has been a key research area for more than two decades due to several aspects. First, the current share of AC in the peak electricity load for developed countries (e.g. The United States) can be up to 30% [4]. This share is predicted to rise sharply in certain hot-climate regions towards 2050 (E.g. from 10% to over 40% in India). Second, the number of AC units is growing and was estimated to be more than 1.6 billion units worldwide in 2016 [4]. Lastly, water as an available and affordable PCM storage medium has encouraged researches to dedicate significant efforts in developing efficient CTES units for integration into AC systems. Systems using a PCM/two-phase fluid heat exchange have also been a hot topic over the last few years. As it can be depicted in Table 7, these systems have been mainly applied into AC systems and low-temperature food processing plants. The reported benefits of CTES implementation in these systems are: The increased evaporator capacity for AC plants [144], a reduced peak load consumption [141,148] and a reduction in product freezing time for batch processes [140]. The concepts using PCM/two-phase fluid heat exchange were found to be promising due to the elimination of the secondary refrigerant circuit. This can reduce the overall cost of the storage system, especially for refrigeration systems where the ordinary refrigeration load is satisfied directly with the primary refrigerant. This concept allows the evaporation temperature of the primary refrigeration system to be increased during the charging process of the CTES, increasing the efficiency compared to using a secondary refrigerant



(a)

(b)

Fig. 18. Tube-in-tank CTES design a) tube bundle b) finished CTES unit filled with water [164]. Reprinted from Energy and Buildings, 183, Abhishek, A., Kumar, B., Kim, M.H., Lee, Y.T., Chung, J.D., Kim, S.T., Kim,T., Lee, C., Lee, K., Comparison of the performance of ice-on-coil LTES tanks with horizontal and vertical tubes, 45–53, Copyright (2019), with permission from Elsevier.

system [146]. Several novel PCM-HEX designs were proposed, but many of them lack experimental validation to prove the performance of the storage units [147,139,140].

Looking at Table 8 one may note that the systems using a PCM/single-phase fluid heat exchange presented in this review only employ PCMs with a melting temperature above 0 °C. The reported benefits of integrating CTES in the secondary refrigerant circuit of a refrigeration system are: Avoiding part-load operation of the chiller [152], reduced operational costs [167–169] and peak load shifting [168]. The most commonly studied application for CTES integration is AC systems, where water/ice is frequently used as the PCM.

Significant research effort has been devoted to developing CTES units to be integrated into the secondary refrigerant circuit of refrigeration systems. CTES tanks with encapsulated water as the PCM have been extensively studied over the last two decades. The tube-in-tank and coil-in-tank designs have gained more attention over the last five to ten years, due to compact design and low cost. Most of these studies investigated the effect of the secondary refrigerant supply temperature and mass flow rate on the performance of the charging and discharging processes of the CTES unit. The storage capacity of the tested CTES units ranges from a few kWh up to around 40 kWh. To the authors best knowledge, the reported study by Torregrosa-Jaime et al.[161] is the highest amount which was experimentally tested for CTES applications (1450 kg and 40 kWh). Many real-life applications, such as industrial process plants and AC systems, require significant storage capacities to achieve peak shaving. Hence, experimental characterisation of larger lab-scale and prototype CTES units is a key factor to raise the attention on the application of cold storage into these refrigeration systems. For both PCM/two-phase fluid and PCM/single-phase fluid CTES units, there is a lack of detailed numerical modelling research, probably due to limited experimental data to validate the models.

4. Conclusions

This review aims to provide a solid background to the reader about the possible ways of implementation of CTES using PCM in various refrigeration systems. The focus of the review was to establish a state of the art on the PCM integration as cold storage application into refrigeration systems in food transport and packaging, commercial refrigeration, large scale industrial applications and various other refrigeration systems. A brief overview of the different types of PCMs was first given. A brief presentation including the most important material properties as well as their appropriate characterization methods was then given. The main findings from the literature are summarized as follows:

- There are mainly three different ways to integrate PCMs in food transport and packaging applications; PCM integration within the walls of the refrigerated vehicles, into the product container, or the installation of an active CTES system to replace the commonly used diesel-driven refrigeration system in the vehicle. Important research efforts have been dedicated to the development of multi-layer walls with PCM for refrigerated vehicles. The efficiency of this technique was proven by limiting peak heat flux from the external environment up to 29%. It was shown that PCMs integration into food packaging can provide better thermal protection than standard packaging during a breach in the cold chain.
- Two strategies to integrate PCM storage units in supermarket display cabinets are commonly investigated: In the product shelf or by implementing a PCM-HEX in the main air duct. The reported benefits of CTES integration are: The reduced and stabilized cabinet air temperature during the defrosting process, energy savings and product temperature reduction. Water/ice is frequently used as the storage medium in these applications. It should be highlighted that the integration of PCM-CTES into the supermarket refrigeration system has only been studied at a theoretical level using simplified models of the storage. Nevertheless, the studies show that CTES implementation is a promising technique as it allows for a peak shaving and a reduced compressor peak power consumption in supermarket refrigeration systems.
- The implementation of CTES in AC systems has been a hot topic over the last two decades. Significant research effort has been dedicated to developing performant CTES units. The use of encapsulated water as the latent storage medium have been frequently studied. The coil-in-tank and tube-in-tank designs have become very popular during the last ten years, offering a more compact and flexible design. One may distinguish two strategies to achieve an efficient heat transfer process between the refrigeration system and the CTES unit. The first method consists of integrating the PCM-CTES unit in the secondary refrigeration circuit commonly found in AC chiller systems (glycol/brine/water). The reported benefits of this strategy are: Reduced part-load operation of the chiller, reduced energy consumption and an increased storage capacity compared to SHS units. The second strategy found in literature is the direct integration of the CTES into the primary refrigerant circuit using a PCM-refrigerant heat exchange system. This integration strategy is commonly applied in refrigerated warehouses, AC systems and low-temperature food processing plants. Moreover, promising theoretical concepts were also found in the literature, such as using dry ice as the storage medium for low-temperature storage under −40 °C.

5. Recommendations for future investigations

From the summary carried out in the previous section, it is clear that the implementation of CTES technology provides many benefits to key parts of the food cold chain including processing plants, transport and packaging, cold storage facilities and supermarket refrigeration. The intensive research activities performed on PCMs and their integration into refrigeration over the last decade has promoted their utilization at a commercial level. However, various aspects still need further investigations in order to provide commercially viable cold storage techniques and improve their competitiveness. Some of them are presented as follows:

For CTES applications in food transport and packaging:

- The effect of combining different melting temperatures and the location of the PCM layer in the walls of refrigerated vehicles both need to be further investigated. The concept of copper pipes filled with PCM has demonstrated the highest heat transfer reductions, although most researchers have focused on including a PCM layer into the wall. Due to the limited research on this topic, the optimal combination is still not clear. Furthermore, a techno-economic evaluation of the different PCM wall configurations in comparison with a standard insulation wall would provide knowledge on the economic competitiveness of this concept.
- More experimental investigations should be carried out comparing PCM packaging and standard packaging using real temperature conditions experienced in the cold chain, i.e. by field tests or by replicating temperature profiles which have been obtained by measurements in actual transport routes. Further investigations should be performed to determine if the PCM packaging could provide a sufficient thermal buffer to replace the need for the on-board refrigeration system for typical transport routes in the cold chain. Moreover, the experience gained from the research carried out on PCM food packaging should be further applied to develop packaging for temperature-sensitive medical goods. This can ensure safe transport and delivery of goods in locations with limited access to electricity and refrigeration.
- Further development and experimental validation of the active CTES system are needed to replace the diesel-driven refrigeration system in refrigerated vehicles presented by Liu et al. [99]. This novel concept supports a phase-out of a conventional technology associated with significant CO_2 emissions and local pollution. Future research within this topic should include evaluation of energy and emission reductions in various climate conditions and extending the concept from frozen transport (-18 °C) to refrigerated transport (2 °C to 5 °C). Moreover, a detailed infrastructure for the charging of the PCM-HEX at the warehouse still needs to be developed.

For PCM applications in commercial refrigeration, future research should focus on:

- A proper design and a suitable integration scenario of the PCM-HEX unit into supermarket display cabinets are still challenging. Further developments should focus on the experimental validation of PCM-HEX units taking advantage of the available space in the display cabinets, e.g. on top of the cabinet.
- The development and experimental validation of PCM-HEX units that can be integrated into the supermarket refrigeration system to support the promising results from current analytical studies. Important tasks that need to be addressed are the design of the PCM-HEX unit, selection of the appropriate PCM, location for integration and capacity sizing.

For PCM applications in various other refrigeration systems, more research is required addressing the following aspects:

- More advanced research for the integration of CTES into multi-split and single AC units to achieve peak shaving, e.g. the concept presented by Korth et al. [146]. Due to the expected growth in the AC market worldwide in the coming years, future research needs to be focused on the total equivalent warming impact (TEWI) of refrigerants used in these units and introducing flexibility by CTES integration to avoid significant peak loads on the grid.
- Promising novel concepts applying a PCM/two-phase fluid heat exchange are emerging, but experimental validation needs to be carried out to prove the performance of these PCM-HEX units [139,147]. Increased focus on the development and testing of larger lab-scale and prototype CTES units, both for PCM/two-phase fluid and PCM/single-phase fluid heat exchange, is a key factor to encourage manufacturers considering this novel technology for a real scale industrial application.
- The use of the CO_2/dry ice as the storage material for CTES applications below -40 °C is promising, but a practical HEX design and pressure control of the system represent the main limitation of this technique [140,148].

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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