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Application of Phase Change Materials in Refrigerator and Freezer Appliances: A Comprehensive Review

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A B S T R A C T

Refrigerators and freezers are commonly used for food preservations. Also refrigerated truck trailers and open-type refrigerator display cabinets appliances used for keeping the food in special conditions for specific uses. These appliances need to be low energy consumer along having good temperature conditions for keeping the food compartments in a desired temperature range. One solution to this end is using cold storage materials called phase change materials (PCMs). PCMs have high latent heat of fusion and phase change in a narrow temperature range which makes them possible solution in energy saving field. This paper reviews cold storage techniques in food preservation appliances such as refrigerators, freezers, refrigerated truck trailers, open-type refrigerated display cabinets. Different thermal storage techniques beside different materials used in this field are briefly introduced. The main drawback of PCMs is their low thermal conductivity which is enhanced using enhancement techniques such as using fins and extended surfaces, PCM embedded metal foams, using nanoparticles and Multiple PCM method techniques are discussed. Finally, researches in the field of employing cold storage materials in food preservation devices are reported and tabulated.

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1. Introduction

From the aspect of preservation, foods are classified in two major groups; first is spoilable foods that need to be kept in cold conditions like dairy products, meat, confections and etc. Second is less spoilable foods which need to be maintained in dry, cool and away from direct sunlight like rice, flour, honey and etc.

In food industries there are two main cold conditions for preserving sensitive food products: cold conditions with temperatures more than 0 ℃ which is refrigerator environment. And cold conditions with temperatures below 0 ℃ called freezers which is suitable for high sensitive products like ice cream, meat, butter and other. Thus, keeping the temperature of refrigeration cycle in a desirable range is needed for maintaining the quality of food. The suitable operating temperature range for refrigerator and freezer are 2-5℃ and -24℃, respectively. Consequently, any variations on air temperature inside the cabin space would affect the quality of the food products kept inside. The fluctuations of temperature inside the refrigerator and freezer is dependent on door opening, heat generation during the defrosting period, ambient temperature and possible electrical power failures [1].

The other case that should be considered in refrigeration cycles is the refrigerators energy consumption which is related to ambient temperature, product loading, number of door openings, thermostat setting position and refrigerant migration during the compressor off-cycle [2]. Thus, improving the performance of refrigerators could help to save the energy. There are three categories that can be used to enhancing the performance of refrigerators including the following options [3]:

1. Reducing heat losses by improving the cabinet and door insulation; which is almost expensive.
2. Developing efficient compressors; which is almost expensive and has technical difficulties.
3. Heat transfer enhancement in heat exchangers (evaporator and condenser).

With the above discussions, there is a need to improve

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the performance of the refrigerator and freezer for two major conditions: reducing the temperature fluctuations inside the refrigerator compartments and better energy savings.

One way to increase the energy efficiency of refrigerators is to use energy storage materials within the suitable containers to reduce the mismatch between supply and demand [4]. There are mainly three common methods to storing thermal energy: sensible heat storage (SHS), latent heat storage (LHS) and thermochemical heat storage. For specific amount of energy, LHS needs less mass and volume of material in accordance to SHS. Due to their phase change in a narrow and almost constant temperature as long as the high latent heat of fusion, phase change materials are suitable option for latent heat thermal energy storage systems (LHTESS). These materials are utilized in different applications such as electronic equipment's cooling [5], waste heat recovery [6], building applications [7], engine cooling [8], solar energy [9], heat exchangers [10].

This review presents a comprehensive study of using phase change materials as a promising option for saving energy in cold storage devices such as refrigerators, freezers, refrigerated truck trailers, food refrigerated display cabinets and other refrigeration devices related to preserving foods. First it presents a brief introduction of PCMs, their classification, selection standards, containers, and property measurement approaches. Further the performance enhancement techniques of PCMs are described. The last section is devoted to special cold storage devices that is used in refrigeration systems.

2. Thermal energy storage techniques

Thermal energy is need to be stored in a specific way for further utilization so can decrease the mismatch between supply and demand and also helps to shift the load to off-peak periods [11]. There are three major ways for storing thermal energy:

2.1. Sensible heat storage method

Sensible heat storage is related to storing heat by rising the temperature of a solid or liquid substance [12]. The amount of heat stored is in direct relationship with the mass of material, specific heat capacity and temperature variation between initial and final temperatures without change in the state of substance according to eq. 1 [13]:

$$Q = mC_p\Delta T = mC_p\left(T_f - T_i\right) \tag{1}$$

SHS materials can be divided in two main subgroups:
1) Liquid storage medium with the advantage of easy circulation for a required heat transfer. Water, mineral oil, molten salts and liquid metals and alloys are common examples of liquid storage mediums
2) Solid storage medium: having the advantage of low cost, availability and no vapor pressure issue. Rocks, concrete, sand and bricks are available solid storage mediums [14].

2.2. Thermochemical storage method

This kind of energy storage method is based on the heat released and stored chemically during the reaction of molecules. According to equation [2]:

$$C + heat \rightleftarrows A + B \tag{2}$$

By absorbing energy, C component chemically converts to A and B. The reverse reaction is formed when components A and B are reacted together forming the the component C. During this formation, energy is stored. High storage density, low heat loss, long storage period and long-distance transport possibility are the advantage of thermochemical storage method. $FeCO_3$ and $CaCO_3$ are candidate materials for this method [15]..

2.3. Latent heat storage method

LHS is based on storing and releasing heat during phase change of a substance at a nearly constant temperature. Usual phase change is between solid and liquid states. During charging process (melting), heat is released with phase change from solid to liquid. Material that has this characteristic is called phase change material. The amount of heat stored can be determined by the following equation:

$$Q = \int_{T_i}^{T_m} mC_p dT + mL_f + \int_{T_m}^{T_f} mC_p dT \tag{3}$$

LHS has the advantage of having high storage density in a nearly constant phase change temperature. Compared with SHS, for a specific amount of energy, LHS requires less volume and amount of material. For instance, the mass required to store 10^6 kJ energy for water as SHS material is 16000 kg while for organic PCMs as LHS is 5300 kg [15].

3. Latent heat thermal energy storage (LHTES) systems with PCM

3.1. Selection criteria

Besides having proper phase change temperature and high latent heat of fusion, PCMs need to have some other appropriate properties for better utilization in LHTES systems. These properties are classified and showed in figure 2. If figure or graphs are duplicated from other reference, a citation should be appearing at the end of caption.

Besides their advantage, PCM have some disadvantages that should be considered in their selection for the desired application. These disadvantages besides each PCM category are brought in next section.

3.2. PCM category

Phase change material as a medium in latent heat thermal energy storage systems are classified in three main Groups named organic, inorganic and eutectics. In fact, each group does not have all the advantages that one system needs; and one needs to select suitable material

Table 1. Advantage and disadvantages of different PCMs

	Eutectic Material	Organic Material	Inorganic Material
Example	• Inorganic-organic • Inorganic-organic • Organic-organic	• Paraffin • Fatty acid • Alcohol • Ester • Polyethylene glycol	• Salt hydrate • Metallic
Advantage	• Wide range of phase change temperature • Good chemical and thermal stability • High heat capacity • No or little supercooling	• Non-corrosive • Good chemical and thermal stability • No supercooling • High heat of fusion • Low vapor pressure • Nontoxic	• Nonflammable • Inexpensive • High heat of fusion • Good thermal conductivity
Disadvantage	• Leakage during the phase transition • Low thermal conductivity	• Low thermal conductivity • Low phase change enthalpy • High changes in volumes during the phase transition	• Corrosion • Phase decomposition • High supercooling effect • Loss of hydrate throughout the process • Insufficient thermal stability • Weight problem

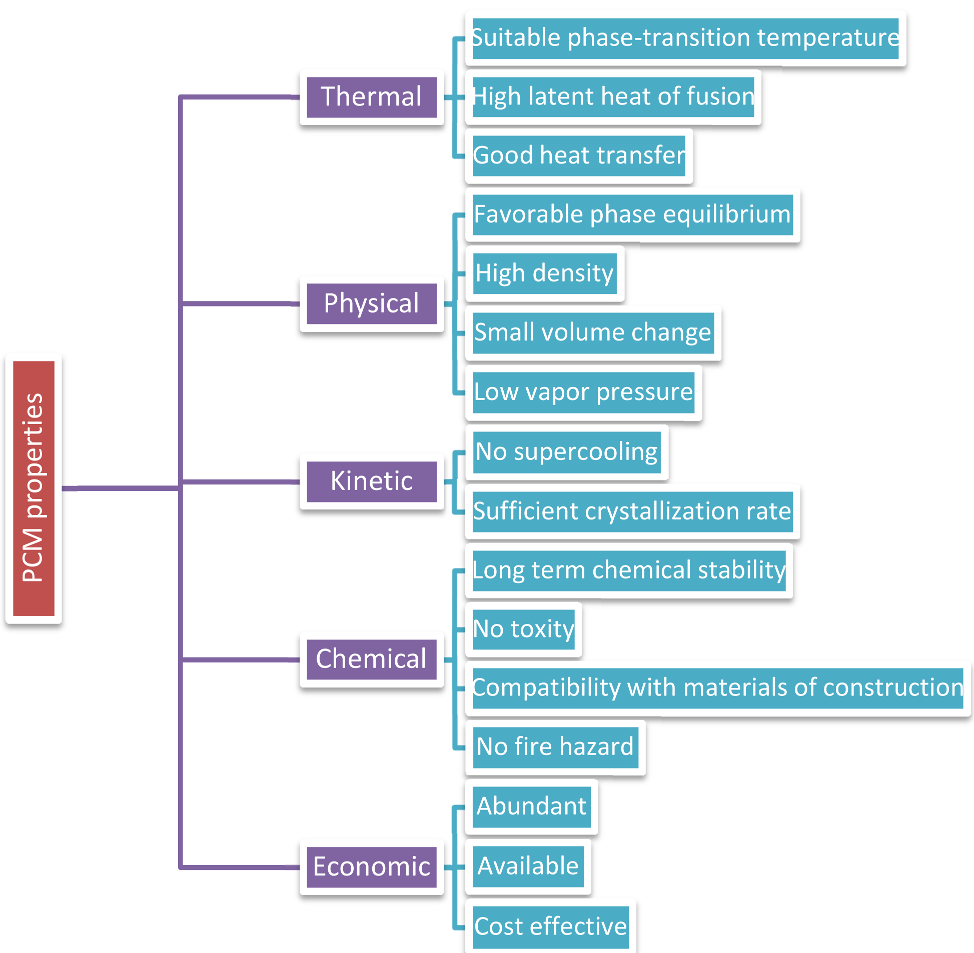

Figure 1. Desired PCM properties.

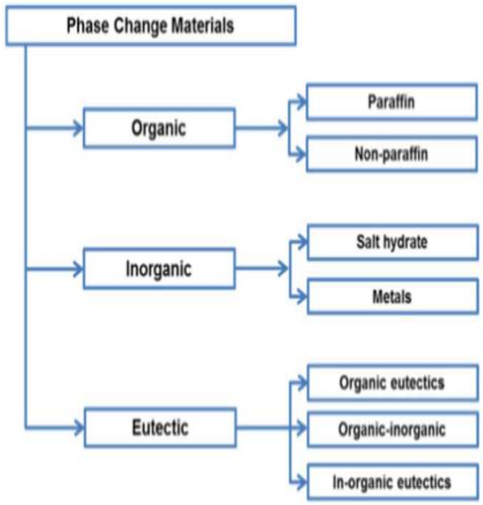

Figure 2. General classification of phase change materials [15].

with regarding the advantage and disadvantage of each group and material. In selecting proper phase change material for each system, major important parameters are the phase change temperature of chosen material and the latent heat of fusion. Figure 1 shows different PCM categories used in LHTES systems.

Organic materials are classified in two main subgroups named paraffins and non-paraffins. Paraffins, with chemical formula of C_nH_{2n+2} known as n-alkanes. The more the carbon in the chain, the higher the melting temperature of the paraffin [17-18]. Non-paraffins are grouped as fatty acids, sugar alcohols and glycols.

Inorganic PCMs are salt hydrates and metallic. They have high latent heat of fusion pre unit mass, higher thermal conductivity and also lower cost.

Eutectics are composition of two or more PCMs like inorganic with inorganic, organic with inorganic and organic with organic. They have the advantage of having specific phase change temperature by combination of different proportion of components.

As discussed in section 3.1 each PCM has its own advantage and disadvantage that there is no single PCM can obtain the whole required properties. These properties are brough in Table 1.

3.3 PCM cotainers

After choosing the main material of LHTES system with proper phase change temperature and latent heat, another important parameter that affects the goal of using this system is selecting proper container according to the system application. PCMs commonly placed in cylindrical containers, rectangular containers and long thin heat pipes. In cylindrical containers which are so-called shell and tube, are consistent of heat transfer fluid and phase change material [19]. HTF can flow through inner tube, outer tube or in multitubes used in the system [20]. Rectangular containers are common in cooling in heat sink systems [21]. Figure 3 shows different PCM containers used in LHTES systems.

4. LHTES systems in refrigerated appliances

Maintaining the quality of perishable foods can be achieved using refrigerated units. For different temperature ranges, this application can be divided in different groups such as refrigerator and freezer, refrigerated display cabinets, refrigerated truck trailers, ice cream freezers and other. Among this, refrigerators and freezers used in domestic places are more populated, however others are benefited in their own field. Thus, maintaining the inside temperature of these food preserve appliances are in attention to preserve the quality of its inside contents. One approach to this goal is using phase change material as heat or cold storage device to achieve desired level of temperature. The subsequent section will present comprehensive study on utilizing PCMs in cool storage devices as grouped above.

4.1. Domestic refrigerators and freezers

Domestic refrigerators and freezers are mainly used to store perishable food contents in a desired temperature. Refrigerators and freezers are almost operated between 2-5 ℃ and -18 ℃, respectively. Almost all refrigerators are composed of compressor, condenser, evaporator and capillary tube, thus improving the performance of each part can improve the performance of the whole cycle. Table 2 briefs the work done on different parts of the domestic refrigerators and freezers.

Due to the wide range application of this appliance, more researches are focused on optimizing the performance of domestic refrigerators and freezers.

With the goal of maintaining inside temperature of refrigerator at 265K, Simard and Lacroix [22] studied using PCM at frosting conditions. They used PCM contained in parallel plates to absorb heat from warm moist air. They recommended PCM thickness of 50×10-3 m and distance between PCM plates of 30×10-3 m.

In a comprehensive study, Marques et al. [2] studied the performance of domestic refrigerators in different operational conditions with thermal storage, Figure 7. Firstly, they analyzed single speed compressor for different displacements (compressor size). They used RS+3 tool program developed by Danfoss for predicting performance data and CoolPack software for calculating compressor isentropic efficiency. They concluded that, for a single speed compressor, increasing compressor size from 4 to 8 cm^3, leads to 50% increase in isentropic efficiency, namely from 0.4 to 0.6. This 8 cm^3 was the optimal size in which the isentropic efficiency stayed the same or decreased for higher compressor displacements. Also 19.5% decrease in energy consumption and reduction of 22% to 10% in run time was reported. however more start and stop for compressor would affect the refrigerator performance. For thermal storage experiments numeric study, they used water as PCM where the top surface of

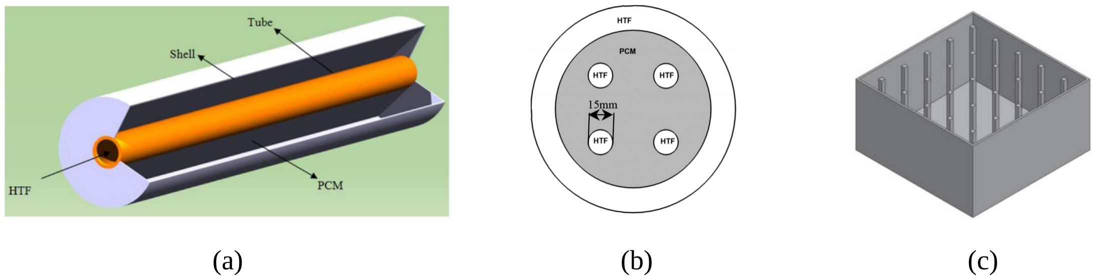

Figure 3. Different PCM containers used in LHTES systems (a) shell and tube (b) multitube (c) rectangular.

Table 2. Summary of works done in domestic refrigerators and freezers.

Reference	Topic	Method	PCM kind / Phase change temperature	Refrigerator & Freezer/ PCM placement	Parameters investigated	Outcome
Gin and Farid [21]	Using PCM for improving frozen food keeping conditions	Experimental	Eutectic (water+Amon iom chloride)/ -15.4˚C	Vertical freezer/ Cabin	Measuring meat drip loss ice crystal size	Reduction in meat drip loss and ice crystal size using PCM
Marques et al. [2]	Improving performance of domestic refrigerator sing thermal storage	Experimental & Numerical	Water (0˚C)	Manufactured	Compressor displacement PCM thickness Ambient temperature Evaporation temperature	3-5 hours continues operation during power loss Larger compressor is effective
Azzouz et al. [22]	Performance enhancement of domestic refrigerator using thermal storage	Experimental & Numerical	Eutectic with phase change temperatures of -1,-3,-5,-7 and -9 ˚C	Refrigerator/ Rear the evaporator	Phase change temperature PCM thickness thermal load (ambient temperature, door opening)	5-15% COP improvement Reducing the start/stop of compressor Choosing the PCM is dependent on thermal load
Azzouz et al. [23]	Performance enhancement of domestic refrigerator using thermal storage	Experimental	Water (0˚C) and eutectic (-3˚C)	Refrigerator/ Rear the evaporator	Phase change temperature PCM thickness Thermal load	Depending the results on thermal load 5-9 hour continues operation during power loss 10-30% COP improvement
Visek et al. [24]	Sequential dual evaporator Refrigerator-freezer system energy optimization using PCM	Experimental	Water (0˚C)	Refrigerator-freezer/ Rear the roll-band evaporator	Energy consumption Evaporator kind	8.4 ˚C increase in evaporator temperature 19.9% energy consumption reduction

Elarem et al. [25]	Performance enhancement of household refrigerator using PCM	Experimental & Numerical	Plus-Ice (4˚C)	Refrigerator and freezer/ Cabin	Different arrangements of PCM	12% energy consumption reduction 8% COP improvement, stabilizing Homogenizing temperature
Khan et al. [26]	Effect of PCM on performance of a household refrigerator	Experimental	Water (0 ˚C)/ Eutectic solution (-5˚C)	Refrigerator-freezer/ Around the freezer	Phase change temperature Thermal load PCM mass	Depending the results on thermal load Eutectic is better than water 20-27% COP improvement
Oro et al. [27]	Thermal performance improvement of freezers using PCM	Experimental	Climsel (-18˚C)	Freezer/ Cabin	Door opening Electrical power loss	Keeping the cabin temperature 4-6 ˚C lower during 3 hour power loss
Oro et al. [1]	Thermal analysis of low temperature storage unit using PCM without refrigeration cycle	Experimental	Climsel (-18 ˚C) & CRISTOPIA (-21˚C)	Freezer/ Cabin	Phase change temperature Electrical power loss	Keeping the compartment and air temperature in a desired range during power loss CRISTOPIA is better than Cimsel for keeping the temperature lower
Yusufoglu et al. [28]	Improving Performance of Household Refrigerators by Incorporating PCMs	Experimental	Five different PCMs (0-10˚C)	Refrigerator/ Evaporator tube	Phase change temperature Increasing condenser surface area Environmental and economical analysis	9.4% energy saving PCM is cost effective Increasing evaporator and condenser temperature
Zarajabad and Ahmadi [29]	Employing finned PCM container in a household refrigerator	Experimental & Numerical	Water (0˚C)	Refrigerator & Freezer/ Bottom of evaporator	Effect of using fin Energy consumption	Increasing standard temperature time from 30 to 60 min 17.4% energy saving
Cofre-Toledo et al. [30]	Evaluating household refrigerators evaporator using two eutectic PCMs	Experimental	PLUSICEE-10 & 19.5wt% NH_4Cl	Refrigerator/ Evaporator	Phase change temperature	Decreasing average temperature in fresh-food and fast-cooling compartment 1.74 and 5.81% energy saving using two eutectics

Cheng et al. [3]	Using shape-stabilized PCM heat storage condenser	Experimental	paraffin, high density polyethylene and expanded graphite (25-60˚C)	Refrigerator & Freezer/ Condenser	Condenser/evaporator temperature Energy consumption	Lower condensation temperature Higher evaporation temperature Lower energy consumption More compressor start/stop
Cheng et al. [31]	Performance analysis of household refrigerator with PCM at both evaporator and condenser	Numerical	-26˚C (at evaporator) & 50 ˚C (at condenser)	Condenser & Evaporator	Effect of PCM presence on condenser and evaporator conditions	Best performance on using PCM at both condenser and evaporator 32% energy saving
Sonnenrein et al. [32]	Reducing the energy consumption of household refrigerator using PCM at wire-and-tube condenser	Experimental	Water (0˚C) & paraffin/copolymer compound (34˚C)	Refrigerator/ Condenser	Phase change temperature	Lower condensation temperature Reducing power consumption up to 10%
Wang et al. [33]	Using PCM at different locations in refrigeration cycle: Experimental investigation	Experimental	Eutectic (21 & 8 ˚C)	Refrigerator/ Different locations	Effect of using PCM at different locations	Improving COP by 6-8% Temperature stability Reducing superheat
Wang et al. [34]	Using PCM at different locations in refrigeration cycle: Dynamic simulation	Dynamic simulation	Eutectic (21 & 8 ˚C)	Refrigerator/ Different locations	Effect of using PCM at different locations	Good agreement between dynamic model and experimental results
Wang et al. [35]	Using PCM at different locations in refrigeration cycle: PCM for control and energy savings	Numerical	Eutectic (21 & 8 ˚C)	Refrigerator/ Different locations	Effect of using PCM at different locations	COP improvement by 8% through lowering the subcooling System stabilization
Marques et al. [36]	Theoretical modelling and experimental investigation of a thermal energy storage refrigerator	Experimental & Theoretical modelling	Water (0˚C) & Eutectic (-2, -6˚C)	Household refrigerator/ Cabin	PCM orientation Phase change temperature Refrigerator kind	Lower compartment temperature at horizontal orientation Eutectic is better than for temperature control
Gin et al. [37]	Effect of door opening and defrost cycle	Experimental	Aqueous ammonium	Freezer/	Door opening Defrosting	Reducing temperature variation

	on a freezer with phase change panels		chloride solution (-15.4˚C)	Cabin	Power loss	Reducing temperature increase during door opening and defrosting Reducing energy consumption
Liu et al. [38]	Performance study on air-cooled household refrigerator with cold storage phase change materials	Experimental	-0.41˚C (at refrigerator) & -18.98˚C (at freezer)	Refrigerator & freezer/ Cabin	Compartment temperature Energy consumption Compressor ON time	18.6% energy consumption reduction 13.6% reduction in compressor ON time
Ezan et al. [39]	Prolonging compressor off time in a beverage cooler using PCM	Numerical	Water (0˚C)	Beverage cooler/ Evaporator	PCM thickness	Reducing compressor ON time Longer standard temperature limit
Maderic et al. [40]	Energy efficiency of a beverage cooler with the latent heat storage	Experimental	Ice bank	Beverage cooler	Effect of ice bank presence	15% energy consumption reduction Need to optimizing the ice bank mass
Pavithran et al. [41]	PCM incorporation in refrigerator at different arrangements	Numerical	Not specified	Compartment	PCM arrangement	Maintaining the temperature during compressor off-mode
Abdolmaleki et al. [42]	Using PCM for efficiency enhancement of household freezers	Experimental	Eutectic mixture of polyethylene glycol	Freezer	System operation with and without PCM	energy savings of 8.37% with 1.5 kg of PCM Reduction of temperature fluctuations up to 40.59%
Pirvaram et al. [43]	Using PCM for efficiency enhancement of household freezers	Experimental	Eutectic mixture of polyethylene glycol	Condenser	System operation with and without PCM	Decreasing the condenser surface temperature Decreasing the compressor work time and energy consumption
Berdja et al. [44]	Effect of PCM and frost on heat transfer and thermal performance of conventional refrigerator	Experimental & Analytical	Not specified	Evaporator	PCM thickness Frost effect	COP increase Energy consumption decrease

Karthikeyan et al. [44]	Effect of different PCMs on vapor compression systems	Experimental	OM32 & OM 29	Freezer Fridge Condenser	Phase Change temperature PCM location	Improving the system efficiency at three different PCM locations
Ko et al. [45]	Cascaded CO2 refrigeration system using PCM	Experimental	Not specified	Storage compartment	System operation with and without PCM	Energy consumption reduction by using PCM

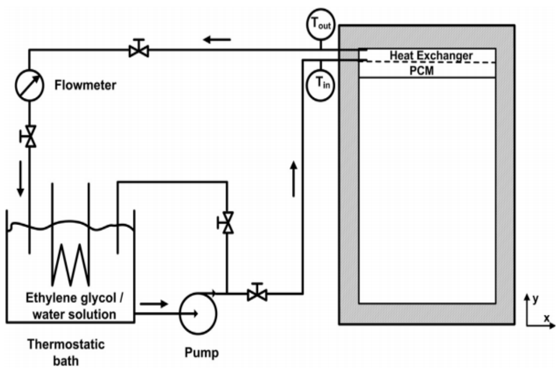

Figure 7. Schematic view of experimental setup [2].

Figure 8. Freezer used in the work of Oro et al. [23].

water container was in contact with the refrigerator evaporator and the bottom surface was in subjected to natural convection from the refrigerator compartment. The numerical study was to analyze the parametric conditions (PCM thickness, ambient temperature, evaporating temperature) affecting the performance of refrigerator in the presence of PCM heat exchanger. Their results indicated that the integration of a 5 mm PCM slab into the refrigerator would allow 3-5 h of continuous operation without power supply depending on the ambient conditions. Also, they concluded that by increasing evaporating temperature from -10 to -15, freezing time of PCM increases, however the influence is on increasing COP.

Oro et al. [23] investigated the application of PCMs in commercial vertical freezers under door opening and electrical power failure. They used climsel-18 as PCM in a 10mm stainless steel panels placed at different heights in the freezer, Figure 8. For better comparison, they used empty plates and filled one with PCM with same numbers in all experiments. For simulating thermal mass of food, they used M-packs with 76.42wt% water, 23.0wt% oxyethylmethylcellulose, 5.0wt% sodium chloride, and 0.08wt% parachlorometacresol with melting point of -5℃. The measured parameters for their experiments were air temperature inside the freezer, product temperature (M-pack), PCM temperature and ambient temperature. Their results indicated that with the presence of PCM, inside temperature remained lower while this effect diminishes in filling the inside with M-packs due to high thermal mass of M-packs. They also reported that during 3-hour power failure, the freezer temperature remains 4-6 ℃ lower and allows M-packs to stay at lower temperature.

Also in another study with the same application (commercial vertical freezer), Oro et al. [1] studied using PCMs for food transportation systems in non-refrigerated trucks or vans. Two different PCMs, Climsel-18 from CLIMATOR and E-21 from CRISTOPIA with melting temperatures of -18 and -21 ℃ were used. The authors defined a parameter called period factor as ratio between the period that the system is under a specific temperature without PCM to the same temperature with the presence of PCM. The higher the period factor, the better performance with the PCM; they reported that this amount is higher for E-21 according to C-18 because of lower temperature of E-21. They indicated that loading and unloading the system with M-packs, the time that system remains at lower temperature for E-21 and C-18 is about 13 times and 7 times more than the systems unloaded with these PCMs.

Fuqiao Wang et al. [33] thoroughly investigated using PCMs in different places of refrigeration cycle. Their experimental setup was incorporating PCM heat exchangers between condenser and compressor (PCMA, melting point 21 ℃), between condenser and thermal expansion valve (PCMB, melting point 21℃) and between evaporator and compressor (PCMC, melting point 8 ℃), Figure 9. All the results are compared with basic system without PCM heat exchanger. For PCMA, due to lower condensing pressure and higher subcooling rate, 6%

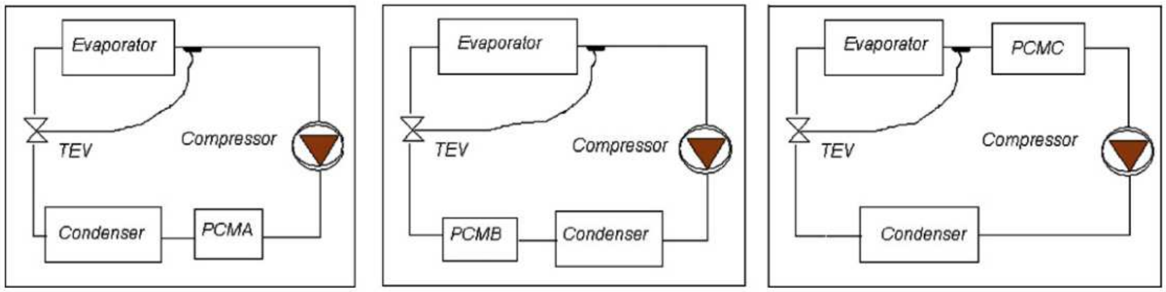

Figure 9. PCM heat exchanger integrated into refrigeration system [24-26].

higher COP was achieved compared with the basic system. In this part, PCMA acted as extra condenser. For PCMB, COP increased 8% due to reduced temperature before the TEV. For PCMC, no improvements in COP was observed due to increased pressure drop, while more temperature stabilization and lower superheat are benefited the system performance [24].

In second part of their work, Wang et al.[25], dynamically simulated the whole refrigeration cycle using three PCM heat exchangers, PCMA, PCMB and PCMC. The model used was lumped-parameter method and considered three different states for condenser and evaporator side, divided as superheat region, a two-phase region and a sub-cooled region. Adiabatic process was considered for modelling compressor and isenthalpic process was assumed for thermal expansion valve. For better understanding of different parameters, they analyzed parameters such as 10 refrigerants, variable speed compressor and unsteady one-dimensional phase change process.

In third part [26], they discussed about control and energy saving aspects of PCMs in refrigeration cycle. According to their previous study, i.e. reference [25], using mathematical model, the authors showed 8% increase can be achieved with lowering the sub-cooling effect. Also, in thermal expansion valve and orifice system, up to 4% and 7% improvement can be observed because of minimized superheat.

Condensers are responsible for rejecting heat from high temperature refrigerant exiting from compressor. Sonnenrein et al. [27] experimentally studied incorporating latent heat storage materials in condenser (wire and tube condenser) side of built-in off-the-shelf cooling device with energy efficiency class of A++. In addition to using the standard heat storage materials such as water, paraffin and PE-HD foil and aluminum-compound film, they developed enhanced material with high capacity with the basis of a block polymer fixed organic paraffin derivative. Thermal conductivity of this new material was increased by adding graphite compound to it. Their results indicated that using PCMs in condenser side would reduce the condenser temperature in inlet and outlet side. They reported that this effect accompanying

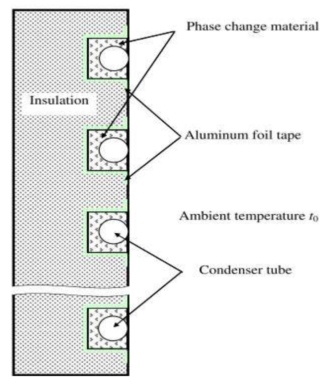

Figure 10. Schematic representation of the heat storage condenser with HCE-SSPCM [3].

with lower refrigerant pressure lead to an increase in refrigerators COP. Regarding the low thermal conductivity of PCMs, new developed material by Sonnenrein et al. [27] showed that higher thermal conductivity can homogenize the temperature in condenser. They also reported that power consumption of refrigerator decreases using PCMs up to 10%. This effect is much pronounced by leading only 25% surface of condenser, power consumption reduction of 4% can be achieved.

Azzouz et al. [28] numerically studied and experimentally validated adding PCM on the outside surface of a refrigerator evaporator. Various phase change temperatures, various PCM thicknesses and various thermal loads are applied to refrigerator cycle for parametric study. They classified the results for three different categories: partial melt (high thermal load), complete melt and partial freeze (low thermal load). They reported that the performance of the cycle is dependent on thermal load inserted to system in which, higher thermal load needs higher energy extract from PCM. Their model predicted 5-14% enhance in COP and reduced starts and stops of the compressor. They also indicated that depending on thermal load, between 4 to 8 hours without power supply can achieve for food preservation.

In an attempt to improve the efficiency and providing heat storage capacity in power failure times, Azzouz et al.

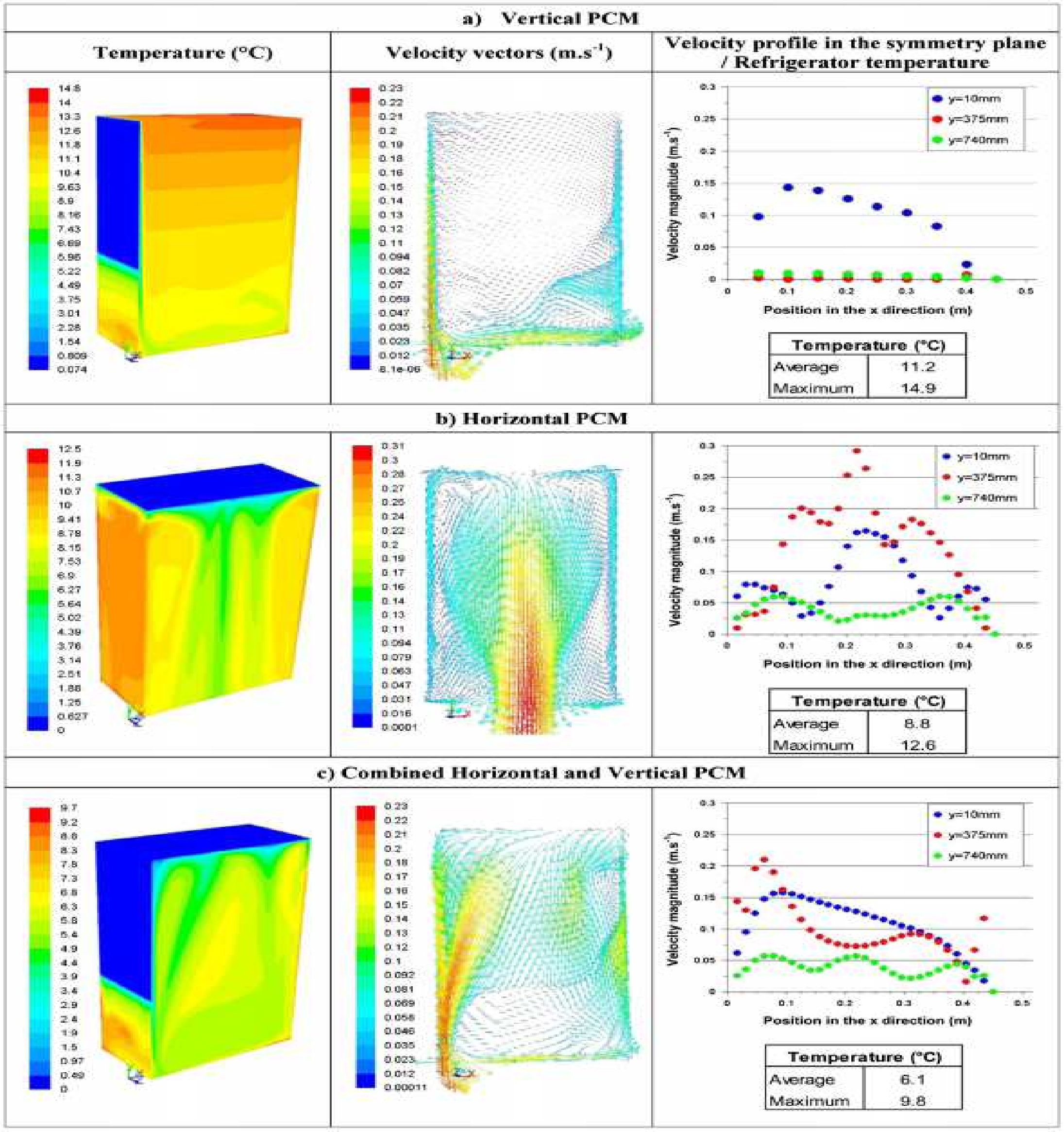

Figure 11. Simulation comparison between PCM orientation [30].

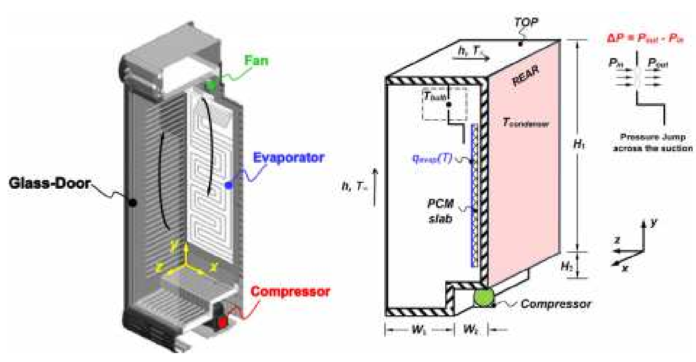

Figure 12. Cooler geometry and mathematical model for [36].

[29] studied locating PCM panels to the outer side of the evaporator. They used two PCMs with different melting temperatures, water and eutectic mixture (freezing point -3℃) for a range of operating conditions (PCM thickness, ambient temperature, thermal load). They concluded that the cool storage capacity of the system is slightly smaller with a eutectic aqueous solution than with water as a PCM, but the advantage of the eutectic solution is the ability to maintain the air in the refrigerated cell at proper temperature values recommended for the refrigerator.

With new shape-stabilized PCM at condenser side, Cheng et al. [3] studied performance of household refrigerator, figure 10. They constructed new type PCM with paraffin, high density polyethylene and expanded graphite called HCE-SSPCM. The new type PCM was placed in aluminum foil tape surrounding the condenser tube. Their configuration allowed the continues heat dissipation of the refrigerator even in compressor off-time. Their results showed lower condensation temperature, higher evaporation temperature and more subcooling degree at the condenser outlet. They stated that despite more frequent starts and stops of the compressor, due to short on-time of cycle to total cycle time, systems energy consumption lowered.

Airflow and temperature distribution using CFD software in a natural convection thermal energy storage refrigerator with different PCMs (water and eutectic) was investigated by Marquez et al. [30]. Their goal was to understand the effect of PCM orientation and PCM temperature. Their results showed lower compartment temperature using horizontal PCM than vertical one, while combining these two types with full height, results in a better performance, figure 11. In addition, for keeping inside temperature below 0 ℃, PCM with lower temperature should be chosen, i.e., eutectic one.

In an experimental study, Maderic et al. [31] studied the impact of using ice bank in a beverage cooler on energy consumption and energy efficiency of the system. They showed that by replacing thermostatic system with ice bank storage, energy consumption reduces up to 15% and also start and stops of the compressor reduces too.

In another study, Pavithrun et al. [32] numerically studied the incorporation of PCM in a refrigerator at different locations. Their results showed that using PCM can control the temperature fluctuations in the compartment during the compressor OFF time and consequently lowering the energy consumption.

Experimental investigation on the effect of different heat loads such as door openings, defrosting and loss of electrical power on product and air temperature inside a domestic freezer with and without PCM was done by Gin et al. [33]. An aqueous ammonium chloride solution (phase change temperature of -15.4℃) with 2.2 kg mass was used as the phase change material (PCM) with anodized aluminum container for better thermal conductivity.

Their results indicated that during defrost cycle, energy consumption of system with PCM decreases about 6% (21% without PCM and 15% with PCM). This effect is also obvious for door opening with 17% higher energy consumption without PCM and 11% with PCM. They reached 2.9 ℃ and 1 ℃ lower peak air and product temperature with PCM presence.

With the same setup and the goal of understanding the PCM effect on drip loss and ice crystal size, Gin et al. [34], analyzed repeated power loss every 24 h for a 2 week period. They used 1×1 cm cubes of bovine muscle for drip loss analyzes (centrifuging samples and weighting them) and 1 L block of vanilla ice cream for ice crystal size (microscopy and image analyze tool). They found lower drip loss and smaller ice crystal size with PCM compared to simple freezer without PCM.

Using PCM in direct contact with evaporator coil and cabinet box was done by Khan et al. [35]. They used water and eutectic solution with phase change temperature of -5℃ as PCM with different thermal loads. Depending on PCM type and the thermal load, they reported up to 20-27% COP improvement. Also, average compressor running time was reduced about 2-36% in different conditions.

A transient three-dimensional numerical study on the effect of PCM slab inside a vertical beverage cooler was done by Ezan et al. [36], figure 12. They studied energy consumption, thermal stability and air flow characteristics inside the cooler and used water as PCM in rear side of the evaporator with five different thicknesses. Their results showed enhanced performance by prolonged compressor off-time and desired temperature limit with PCM. They also showed that increasing the PCM slab thickness, increases the pressure drop within the cooler and decreases the air speed.

Using PCM on evaporator side of refrigerator was done by Yusufoglu et al. [37]. They used five different PCMs with melting temperature between 0 ℃ and 10 ℃. They achieved 9.4% energy saving. They also showed that increasing 20% in surface area of condenser enhances the effect of PCM. their economic and environmental analyses showed that PCM incorporated in refrigerators is beneficial for end-users, national economies, and for the global environment.

Experimental study on the effect of using PCM in air-cooled frost free refrigerator was done by Liu et al. [38]. Their test results showed that using PCM slows down the rate of increasing inside temperature and keeps it around 8℃. They also reported that the compressor ON-time ratio and energy consumption was reduced about 18.6 % and 13.6 % respectively.

Elarem et al. [39] experimentally and numerically investigated new PCM heat exchanger design incorporation on household refrigerator. They used U-type tube covering the evaporator with Plus-Ice PCM of phase change temperature 4 ℃. They measured power supply, energy consumption and the refrigerator temperature. In the numerical part, they defined four different cases with the aim of finding best case which rapidly stabilizes the temperature inside the refrigerator. They showed higher evaporator temperature, lower condensation temperature and less energy consumption and also reduced compressor running time per cycle. They showed that increasing PCM coverage in the racks more than 75% does not lead to any significant reduction in time to achieve the uniform temperature.

Contemporaneous use of thermal storage on evaporator and compressor side of household refrigerator was done by Cheng et al. [40]. They dynamically simulated heat storage condenser (HSC), cold storage evaporator (CSE) and dual energy storage (DES) refrigerator for their analysis. the DES refrigerator combines the advantage of HSC refrigerator and CSE refrigerator, it has more balanced operational cycle and higher evaporation pressure and temperature. They also reported that in comparison with two other cases, DES refrigerator has 32% energy saving and 4.3 off-time to on-time ratio.

Visek et al. [41] experimentally studied sequential dual evaporator refrigeration system by using PCM in direct contact with roll-band evaporator. The authors asserted that with this system heat absorption in the cycle is continues and natural convection will role the heat transfer in refrigeration compartment (RC). They reported that evaporation temperature can increase by 8.4 K and also after implementing condenser fan overall energy consumption will decrease by 5.6%.

With a novel design, Visek et al. [41] investigated using dual evaporator domestic refrigerator with the aim of system energy optimization. They used alternating mode for extracting heat from refrigerator compartment (RC) and freezer compartment (FC) in different times and used 2.2L of water in a plastic bag for preventing the leakage. They reported that 8.4˚C maximization in RC temperature can be achieved and installing the compressor fan reduces the overall energy consumption by 5.6%.

In an experimental study, Abdolmaleki et al. [42] studied the effect of using PCM in a freezer with the goal of finding optimum mass and phase change temperature of selected eutectic PCM. They tested the freezer under ISIRI 13700 condition and the PCM is placed in each tray of the freezer. They found out that by using 2kg PCM with phase change temperature of -20˚C, fluctuation of temperature can be decreased up to 40.59%. They also showed that using 1.5kg can save the energy up to 8.37%.

In another study, Pirvaram et al. [43] studied the incorporation of two eutectic PCMs in a cascaded mode in the back-side of a wire-and-tube condenser of a household refrigerator. Two PCMs were placed in decreasing order of their melting temperatures along the refrigerant flow direction. They indicated that the new system can significantly decrease the condenser surface temperature and consequently increasing the COP of the system. They also stated that in comparison with single PCM that reduces the energy consumption by about 8%, the new two PCM mode can decrease the energy consumption up to 13%.

Theoretically and experimentally, Berdja et al. [44] studied the effect of using PCM in a domestic refrigerator with flat plate evaporator. They stated that the phase change temperature of PCM should be close to the evaporator's temperature. They also showed the COP increase and reduction in daily energy consumption and indicated that frost affects heat transfer more significantly than PCM during the off cycle.

In a vapor compression refrigeration system, Karthikeyan et al. [45] placed PCMs at different locations such as freezer, fridge and condenser. They used four PCMs with different melting temperatures related to the location it placed. The slab PCM is located in freezer and fridge and PCM covered by aluminum foil with descending order of melting temperature is placed in the condenser. They compared their results with no-PCM refrigerator and concluded that implementing PCM in each section can considerably control the temperature fluctuations.

Ko et al. [46] studied the using of PCM in a cascaded refrigeration system using CO_2. They dynamically validated their model in a Simscape ™/MATLAB for an R-744 vapor compression system. They placed PCM in storage compartment as a thermal buffer and its impact on On-time ratio and energy consumption are studied. In comparison with system without PCM, the new proposed system showed 12.3% decrease in energy consumption. Finally, they indicated that for low temperature refrigeration applications using R-744, using PCM has a positive impact on power saving goal.

In a comprehensive study, Maiorino et al. [47-48] studied the effect of using PCM in the cabinet of a refrigerator and its impact on temperature and compressor operation. Their results showed that using PCM n the refrigerators cabinet can reduce the temperature fluctuation and extend the compressor OFF time. Also in another study, Maiorino et al. [47] studied the controlling of an operation of a cabinet refrigerator equipped with PCM attached to a bare tube evaporator with an optimization algorithm. Their goal was to minimize the overall running cost over the pre-defined time. They showed that higher is the difference between the peak and off-peak electricity cost; more significant is the economic benefits reached by their proposed method.

4.2 Refrigerated trucks

Liu et al. [49] developed new refrigerated truck using phase change materials. The charging of PCM was during the off usage of vehicle in a stationary state. They used PCM with phase change of -26.7 ℃. Their novel system showed lower energy consumption and lower local greenhouse gas emmision production.

In another study, Liu et al. [50] studied using PCM with TRNSYS for a mobile refrigeration system. Their results showed that for no door opening and 20 door opening during the transportation, a total of 250 kg and 390 kg of PCM needed for maintaining the product temperature at -18 ℃ for 10 hours.

Also Ahmed et al. [51] modified conventional insulation of refrigerated truck trailers using PCMs. They

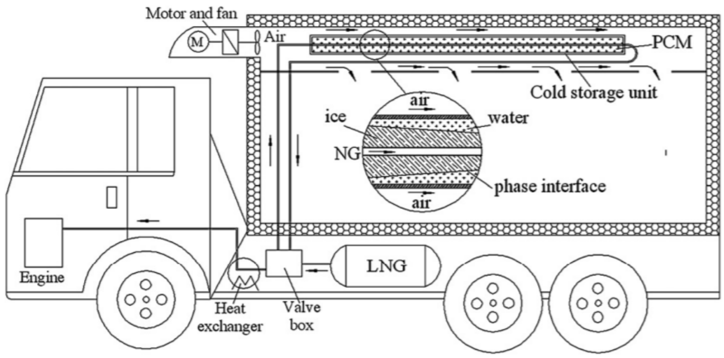

Figure 13. The schematic diagram of LNG refrigerated vehicle and the cold storage unit [53].

observed 11.3-43.8% heat transfer reduction across the walls using PCM depending on the wall orientation. Using this method they achieved energy saving, refrigeration equipment size reduction, pollution reduction and extended rquipment operational life.

In another experimental study, Nie et al. [52] investigated the effect of using PCM in a rail carriage air conditioner system with dynamic exergy analysis. Their results showed that by dropping the charging temperature from 15 to 11 °C and increasing the inlet air velocity from 0.70 to 1.20 m/s the charging time can be reduced by 49% and 28%. They also concluded that the designed conficuration optimal charging depth increases with the rise of inlet air temperature.

Tan et al. [53] experimetally studied water phase change for cold energy recovery of Liquified Natural Gas (LNG) in a refrigerated vehicle, figure 13. The cooling was achieved using cryogenic nitrogen gas and water was used as a PCM for solid-liquid phase change outside the heat transfer tube. To overcome the thermal resistance of gaseous heat transfer fluid inner the tube, they substituted the smooth tube with wave-like internally finned tubes and showed that the current enhancement technique efficiently can improve the gas-side heat transfer and the solidification process.

In a real application, Mousazadeh et al. [54] studied the effect of using sub-zero PCMs in a 6-ton refrigerated truck. They used eutectic PCMs of E-26, E-29, and E-32. The tests were carried out in a constant distance of 466 km length and different truck speeds of 80 to 110 km h^{-1}. They showed that for the moving trucks, the E-26 PCM had the highest melting time of 17200 s at the truck speed of 81 km h^{-1}.

4.3 Refrigerated display cabinets

Open type refrigerated display cabints are oftenly used in supermarkets for chilling and display food which allows the customer for easier food accessibility and food cooling is by convective heat transfer. In a novel design, Lu et al. [55] implemented heat pipes and PCMs (de-ionized water added with borax) in shelf of a refrigerated diplay cabinet,

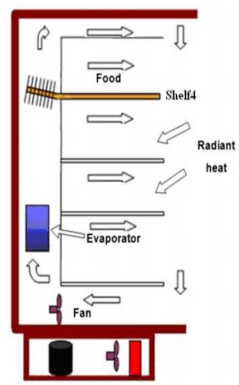

Figure 14. A typical multi-deck type display cabinet with heat pipe.

figure 14. Their experiments was done in two sections: one with heat pipe and one with combined heat pipes and PCMs and compared the results with original refrigerator.

Their results showed that using the heat pipes with inclined condenser could decrease the food temperature by 3.0 to 5.5˚C. They also showed 1.5˚C reduction in temperature rise by using the combined heat pipe and PCM.

In an experimental study, Yilmaz et al. [56] studied the effect of PCM location in a closed display cabinet. The PCMs are located on the backside and the shelves of the cabinet and its influence on air temperature and compressor power consumption are studied during charging, running and power failure periods. Their results indicated that using PCM on the shelves can save the energy to 4.4% but implementing it on the backside can increase the energy to about 8%.

Lu and Tassou [57] studied candidate phase change materials for application in chilled food refrigerated cabinets for temperature ranges between 0-5˚C.

Comparison with water based PCMs. Also due to their low thermal conductivity, paraffins need longer periods for complete solidification and melting. But water based prducts have higher latent heat but they undergo supercooling during the solidification. Author have stated that adding nucleat agents like silver iodine (AgI) cn help to decrease the degree of supercooling which makes water-based PCMs as a suitable choice for the application in chilled food refrigerated cabinets.

In an experimental study, Alzuwaid et al. [58] investigated the performance of a refrigerated open-type multi-deck display cabinet with integrated phase change material (PCM). They carried out their experiments with or without PCM integration and stated that by installing the PCM radiators, up to 5% of energy savings and lower cabinet temperatures could be achieved.

XueHong et al. [59] investigated performance study of vertical open refrigerated display cabinets using the combination of heat pipes and cold storage materials. Their results showed better heat transfer between food and the shelf, food core temperature reduction, temperature fluctuation decrease during the defrosting period.

4.4 Refrigerated container envelope

Refrigerated container envelopes often used for storing sensitive products for long carrying distances. During the transportation these sensitive products may expose to heat loads and climate fluctuations, thus controlling their temperature may be a crucial issue. The container is always surrounded by PCM to store and release energy during the heat loads. In an experimental and numerical study, Fioretti et al. [60] investigated incorporating external PCM layer to reefer container enclosure to reduce the heat flux applied by climate changes. They tested their prototype panel in a test room and a real summer climate condition. Their results showed that in a test room condition and the applied heat load, the PCM layer can reduce the internal temperature about 1-2˚C lower in comparison with container without PCM. Also, in real test condition in two days of summer, the proposed PCM container showed up to 8.57% reduced peak heat transfer rate.

In another experimental and theoretical study, Kozak et al. [61] investigated thermal performance of transported insulated cold storage packages. Also, in another study, Leducq et al. [62] studied the effect of packaging ice cream with PCM and comparing it with usual packaging technique, polystyrene packaging configuration. Their results showed by the new technique, the ice cream temperature stays stable and the temperature fluctuations inside the envelope decreases significantly. Du et al. [63] studied the cooling performance of a portable box integrated with PCM as a cold thermal storage. The effect of different parameters such as PCM location, phase change temperature and insulation material on temperature and charging/discharging processes. They indicated that the configuration of PCM with 20 % located at the top and 20 % on each of the side walls, with the melting point at 2 °C and the vacuum insulated panel (VIP) gave the longest duration time.

Xiaofeng and Xuelai [64] proposed a multi-temperature insulation box with different phase change materials (PCMs) for cold storage purposes. Their results showed that the new proposed boxes can keep the temperature 7-9 ˚C for about 13h and -2-0 ˚C for about 14h.

5. Conclusion

Perishable food products need to be kept in special condition which is available by refrigeration cycle and refrigerated devices. Despite their advantage in keeping the food products in suitable conditions, these devices are high energy consumer and different conditions affect their performance. Defrosting process, thermal loads (door opening, ambient temperature) and power loss are the conditions that influence the performance of refrigeration cycle. Latent heat thermal energy storage using phase change materials is a promising option in refrigeration cycle for energy savings and temperature control targets. Using PCM in refrigeration cycle at different locations, condenser, evaporator and cabin somehow helps to improve the ability of the refrigerator. This review studies different PCM kinds, PCM containers, their enhancement techniques and specially their application in refrigeration cycle such as refrigerators and freezers, refrigerated truck trailers and open-type refrigerated display cabinets. Using PCM in condenser leads to lowering the condenser temperature and using it in evaporator can increase the evaporation temperature. Also applying them inside the cabin helps to stabilize and homogenize the temperature. The effect of using the PCM in other refrigeration application leads to the same results like the refrigerator and freezer in lower energy consumption and better temperature conditions.

Nomenclature

C_p	Specific heat (kJ/kg)
L_f	Latent heat (kJ/kg))
m	Mass (kg)
Q	Total heat (kJ)
T	Temperature (K)
T_f	Final temperature (K)
T_i	Initial temperature (K)

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