Energy saving opportunities in the refrigerated transport sector through Phase Change Materials (PCMs) application

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Abstract. Transportation of food products at controlled temperature is a critical task in the transport sector. In fact, whilst there is a need of ensuring both food quality and safety to the global population, its impact in terms of energy consumption and related CO₂ emissions into the atmosphere is becoming increasingly evident. In this regard, Thermal Energy Storage (TES) using Phase Change Materials (PCMs) can be considered as a potential way of reducing the cooling load, energy consumption and related greenhouse gas emissions in refrigerated transport sector. In this paper two different PCM applications are investigated. Specifically, in the first study a PCM (35 °C melting temperature) layer was added to the external side of a refrigerated enclosure wall with the aim of managing the cooling peak (shifting and reducing) and reducing the daily energy rate. Outdoor experimental results showed that the added PCM layer helps to reduce (between 5.55% and 8.57%) and delay (between 4.30 h and 3.30 h) the peak load of incoming heat compared to the reference one. In the second study, the energy performance of a refrigerated chamber with an air heat exchanger containing PCM (5°C melting temperature) was investigated. The study purpose was to reduce the cooling energy consumption during steady state operating conditions and the rate of temperature increase throughout the course of a power failure event. Test results showed that using a PCM air heat exchanger addition, up to 16% of energy can be saved.

Keywords: phase change materials; PCM; refrigerated transport, energy conservation; air heat exchanger

1. Introduction

Globalization of the food system has led to an increase of volume and variety of refrigerated food traded globally. At the same time, during the carriage of perishable foodstuffs it is important to guarantee a constant temperature throughout the entire journey, which determines a high energy consumption and related CO₂ emissions into the atmosphere [1]. It is well known that maintenance of the refrigerated compartment below the ambient air temperature represents a driving force for heat flow towards the refrigerated compartment from the external environment [2]. In this regard the total heat gain, which generally affects a refrigerated system, is determined by the surrounding environment (heat conducted through the insulated envelope), door openings (infiltration load), and product loading (heat that has to be removed from stored products) process. The latter in conjunction with a low efficiency-refrigerating unit, results in an increased energy consumption. Therefore, a solution to this problem could be the use of Thermal Energy Storage (TES) with the addition of Phase Change
Materials (PCMs) [3]. PCM is a substance characterized by a high heat of fusion, capable of storing and releasing large amounts of energy, thereby producing the cooling effect necessary to maintain a constant temperature throughout the journey. As shown in the next section (2. Study background), several authors have investigated various promising applications based on the use of PCM in the refrigeration sector. The main purpose of the paper is to describe two different PCM applications over refrigerated transport systems. The first experimental investigation focused on the addition of PCM to the external compartment walls of a refrigerated container stacked in a container terminal. The aim of this technology is the decrease and phase displacement of the incoming heat load with a consequent reduction of the cooling energy required to maintain the internal temperature at a constant level. The second experimental investigation focused on PCM air heat exchanger addition near the evaporator of a refrigerated enclosure.

2. Study background

Many technical options based on PCM have been developed in order to improve the energy performance of refrigerated transport systems. For example Tassou et al. [4] reported a road transport refrigeration technology consisting of hollow tubes, filled with a eutectic solution, positioned inside the refrigerated compartment. Specifically the operating principle of this equipment is based on the use of latent heat storage capacity of the phase change material. In fact all the cold energy stored during the night by power supply, can be progressively released during the truck journey, thus providing the cooling effect necessary for a specific duration of time. Moreover this technology can be useful in contrasting the infiltration heat load due to door openings of refrigerated vans. Another technology consisting of a PCM application in a typical refrigerated truck compartment was numerically analyzed by Simard and Lacroix [5]. Specifically the latent heat cold storage unit involves parallel plates, filled with an aqueous-glycol mixture, with the purpose of absorbing the incoming heat load and keeping the internal temperature below -8.15 °C for almost 8 consecutive hours. The authors explored all the operational and design parameters that could have a negative effect on the performance of the whole system. Specifically, it was found that a too wide or too narrow plate spacing can result in a reduced heat transfer coefficient and in a complete obstruction of the air flow passage respectively. Still regarding the refrigerated transport sector, a novel refrigeration system for trucks was proposed by Liu et al. [6]. This technology is based on a phase change thermal storage unit (PCTSU), which can be charged with cold energy when the truck is parked and discharged during working hours. Moreover, the authors developed a new and economical PCM with a phase change temperature compatible with the study object. The obtained results demonstrated that the energy cost was 86.4 % lower when the PCTSU was applied to the refrigerated transport system. Another aspect to be taken into account is the capability of PCM in improving the thermal inertia of refrigerated compartment walls. In this way a reduction of cooling energy required to break down the heat load deriving from the external environment can be achieved. This is what the study by Ahmed et al. [7] is based on. Substantially, the authors modified the conventional method of insulation of refrigerated wall enclosure by using PCMs. By comparing two test truck trailer simulators, it was found that the inclusion of copper pipes containing paraffin, allowed an average daily heat flow reduction inside the refrigerated compartment equal to 16.3%. Moreover, for individual walls the peak heat transfer rate reduction was found to range between 11.3% - 43.8%. Glouannec et al. [8] numerically and experimentally analyzed three different multilayer insulation walls of a refrigerated van. They aimed to study the effect of the external environment such as solar irradiation and temperature over energy consumption and thermal behavior. It was found that the wall made with reflective multi-foil insulation and aero gel decreased the external surface temperature by about 9 °C, highlighting its high insulating capacity compared to the reference. On the other hand, considering the wall made with microencapsulated paraffin, thanks to PCM thermal inertia the energy consumption decreased by about 25 % when compared to the standard insulation wall. Moreover a significant decrease in the external surface temperature due to the melting of paraffin was observed. Finally, Tinti et al. [9] using experimental approach, evaluated the incorporation of microencapsulated phase change material into
standard polyurethane foam walls designed to improve the thermal performance of refrigerated vehicles. This technology resulted more useful in contrasting all the thermal loads which could occur during the journey of the vehicle such as refrigeration system blackout, compartment doors opening and varying solar irradiation. As proposed in the present study, a PCM air heat exchanger addition near the evaporator of a refrigerated enclosure can lead to an improvement of energy efficiency. In fact in accordance with Chatzidakis and Chatzidakis [10] the low efficiency of a cooling unit can be determined by higher condenser temperature (more than 32 °C) which generally characterizes the Mediterranean climatic context. This is even truer for refrigerated enclosures which are on the ground or in a ship. Therefore, the aim of this study was the reduction of cooling energy required to run a low efficiency refrigeration unit operating during the summer season.

3. Proposed technologies in refrigerated transport sector

The reduction of energy consumption and environmental impact of refrigerated transport systems can be achieved by the increase of insulation enclosure performance and energy efficiency of the refrigeration units. In the following paragraphs the development of two technologies easily implementable in refrigerated transport systems was investigated.

3.1. PCM thermal shield

3.1.1. Thermal behaviour. The most commonly used insulation material for refrigerated transport systems is polyurethane foam. In fact, its use allows a suitable thermal resistance against the external heat load due to a reduced global heat transfer coefficient. However, an improvement of lightweight wall energy performance can be achieved by increasing its thermal inertia. This goal is currently being realized by adding PCMs. In fact, thanks to their high heat storage capacity, PCMs are able to reduce and delay the heat load determined by solar irradiation and temperature difference between the external and internal environment. Specifically, the term “heat load delay” is intended as the time shift at which the highest external surface temperature and the internal surface temperature values occur. A heat load delay of about eight hours allows the refrigeration unit to work at a higher performance (due to lower environmental temperature) and reduced energy costs. At the same time, a reduction of the peak heat load can be translated into a lower cooling energy amount required to maintain a constant temperature inside the refrigerated compartment.

3.1.2. Technological development. When selecting a PCM there are three main requirements to be considered: a suitable phase change temperature, a large latent heat of fusion and a proper amount, Orò et al. [11]. Specifically the selection of a PCM that properly matches all the above requirements, represents a delicate phase in the refrigerated transport sector. In fact when considering a PCM applied to the external refrigerated compartment walls, it should be compatible with the varying environmental conditions during the journey. In fact a too high or too low phase change temperature could determine a partial exploitation of the PCM’s latent heat storage capacity. Strictly linked to the phase change temperature, the latent heat of fusion is another important factor to be considered when selecting a PCM. This latter expresses the amount of energy that a PCM can store or release per unit mass during its phase change process. Therefore the selection of a PCM with a large latent heat of fusion can be translated in a reduced material quantity. This aspect is crucial in the refrigerated transport system. In fact, the optimization of PCM thickness that has to be applied to insulated walls, results in a limited weight to be added at the transportation system. Therefore considering all these advantageous characteristics and in accordance with a previous study [12] the three centimetres thick paraffin wax RT35HC (www.rubitherm.de) was selected Table 1. Moreover, due to the PCM’s solid-liquid transition it was encapsulated in polyethylene containers (with dimensions of 0.6 x 0.6 x 0.03) internally divided into 81 small square tanks. The latter, filled by paraffin in liquid phase, were then hermetically closed (three bars of pressure, 170°C) using a thin multilayer film. This packaging system configuration allows a good thermal contact between all the stratigraphic components and a flexibility necessary to contain
the PCM volume expansion during its melting phase. Finally the PCM layer was then added to all the external surfaces of a cold room using a wood frame and closed by a metal sheet layer (Figure 1).

3.2. PCM air heat exchanger

3.2.1. Thermal behaviour. The reduction of temperature fluctuations and the enhancement of energy performance of the refrigerated transport system, led to the development of technologies involving the use of PCM inside a refrigerated chamber [13]. In this study a PCM air heat exchanger was applied close to the evaporator of a cold room. Due to the high latent heat, the integration of PCM near the evaporator could determine a prolonged ON-OFF compressor time and could also act as a cooling unit during power failure. In fact, as shown in Figure 2, during the compressor OFF time period, due to the PCM melting phase, the heat load transmitted through the insulated envelope is absorbed by the PCM air heat exchanger, determining a reduction of the rate of compartment air temperature increase. Conversely, during the compressor ON time period, due to the PCM freezing phase, heat is released to the evaporator outgoing air determining a reduction of the rate of compartment air temperature. Therefore as a result, an extension of the ON-OFF compressor time and a reduction of the ON-OFF cycles can be achieved over time. This means that the refrigerating unit energy efficiency can be increased together with a reduction of electric power consumption.

| Table 1. Thermophysical properties of PCM used for “thermal shield” proposal. |
|---------------------------------------------------------------|
| Value                                                                 |
| PCM commercial name                                           | Rubitherm RT35HC |
| Phase change temperature                                      | 35 [°C]         |
| Heat storage capacity                                          | 220000 [J/kg]   |
| Specific heat capacity                                         | 2000 [J/kg K]   |
| Heat conductivity                                              | 0.2 [W/m K]     |
| Volume expansion                                               | 12 %            |

Figure 1. PCM layer addition procedure.

3.2.2. Technological development. The technology developed in this work is based on an air heat exchanger made up of six PCM container units assembled in pairs and located in a polystyrene channel near the evaporator of a refrigerated enclosure Figure 2. Each PCM container unit is characterized by an anodized aluminium and finned surface with internal dimensions of 1.00 m x 0.03 m x 0.14 m (length x height x width), equal to a 4.2•10-3 m³ in volume. The exchange surface area is equal to 1.44 m² per meter of length. Moreover in order to obtain a better heat exchange between the evaporator outgoing air
and the PCM air heat exchanger a fan system (electric power of 20 W) was added on the outlet section of the channel. In this study the paraffin wax RT5HC was selected (Table 2). In fact, in accordance with Joybari et al. [14] the selection of PCM with a phase change temperature close to the operating temperature (5 °C), was found to be the most effective choice in terms of improving the energy performance of a refrigerated system and maintaining the compartment air temperature at the desired thermal conditions. After selecting a proper phase change temperature, the next phase consists in choosing the correct amount of PCM. It is well known that thinner of thicker PCM can result in reduced thermal effectiveness. Therefore in this study 19.15 kg of RT5HC were used. This amount of PCM could be useful in contrasting all the heat load transmitted through the insulated envelope during 12 hours of a power failure event. Even if not all the PCM thickness underwent a phase change during steady state operating conditions, an extension of the compressor ON-OFF time and a reduction of start/stop compressor cycle over time were achieved.

**Table 2.** Thermophysical properties of PCM used for “air heat exchanger” proposal.

| Value                          | Rubitherm RT5HC |
|-------------------------------|-----------------|
| PCM commercial name           | Rubitherm RT5HC |
| Phase change temperature      | 5 [°C]          |
| Heat storage capacity         | 240000 [J/kg]   |
| Specific heat capacity        | 2000 [J/kg K]   |
| Heat conductivity             | 0.2 [W/m K]     |
| Volume expansion              | 13 %            |

**Figure 2.** PCM air heat exchanger operating principle: 1) Fan 2) Evaporator 3) PCM air heat exchanger 4) Additional fan system.

4. **Measurement and test conditions**

The experimental set-up consists of a walk-in temperature controlled mini cold room equipped with a refrigeration unit (1140 W of cooling capacity). The maximum and the minimum operating temperature values of the cold room are equal to 8 °C and 0 °C respectively. The cold room walls are made of galvanized metal sheet, insulated by polyurethane foam which determines a total panel thickness of 10 cm.
4.1. Cold room with PCM thermal shield
Both the novel and the reference cold rooms were tested during a typical Italian summer (August-September 2014, Ancona, Italy) in order to verify the thermal improvement deriving from PCM addition to the refrigerated enclosure envelope. A monitoring system was developed and the real time data were acquired by using Datataker DT500, set to one reading every 5 min. In Figure 3 the location of the Thermal Resistance Detectors (RTDs) “PT100” with a four-wire connection through the cross section of the new and reference composite walls are shown ($T_n$). Moreover, a fluxmeter (Hukseflux HP01) ($Q_1$) was used to measure the heat flux passing through the south oriented wall which represented the most affected wall by solar irradiation. Finally, in order to measure the external climatic conditions a meteorological station was employed.

![Figure 3](image)

**Figure 3.** Monitoring system developed for PCM thermal shield experimental tests. ($T_n$ = Sensors of temperature; $Q_1$ = Heat flux meter sensor).

4.2. Cold room with PCM air heat exchanger
In this experiment both the novel and the reference cold room were tested in a laboratory room kept at 32 °C. The aim was to study the thermal improvement deriving from this technology considering the refrigeration unit operating at steady state conditions under high environmental temperature. Therefore, a monitoring system was developed in order to measure the thermal parameters characterizing the PCM air heat exchanger behaviour and its influence over the internal conditions of the refrigerated compartment. Power consumption was tested (wattmeter Christ Elektronik CAC 140). Also in this case data were acquired using Datataker DT500 linked to a computer for monitoring experimental real time data. In Figure 4 the location of the Thermal Resistance Detectors (RTDs) “PT100 with a four-wire connection over the novel and the reference cold room is shown ($T_n$).
5. Results and discussion

5.1. PCM thermal shield

In this section the main monitoring data of the reference and the novel cold room, referred to one test day, are reported and discussed. Meteorological parameters such as solar irradiation and external environmental temperature affecting the refrigerated enclosure, are also analysed. In Figure 5 it is possible to appreciate that the highest values of solar irradiation (almost 800 W/m²) and outdoor temperature (almost 28 °C) occurring during the daily midday hours, determine a high thermal heat load and a consequent reduction of refrigeration unit energy efficiency. This means that the maintenance of a constant temperature inside the refrigerated enclosure leads to a high energy consumption as well. Figure 7 and Figure 6 show the comparison of measured heat flux and temperature through the cross section of the novel and reference south oriented wall respectively. Specifically in Figure 6 the time shift of almost five hours is evident, which occurs between the highest value of the external surface (R4_PCM) and the PCM surface (R5_PCM) temperature. This thermal behaviour is due to the increase of the compartment wall thermal inertia, determined by PCM addition. In fact thanks to the PCM high heat storage capacity it is able to store all the incoming heat load at a relatively constant temperature (during its melting phase), determining a reduction and phase displacement of the incoming heat load. Moreover, by comparing the external surface temperature of the reference cold room (R4_REF) with the PCM surface temperature (R5_PCM), it is evident that the PCM heat load storage process leads to a reduction in the maximum temperature value (33 °C instead of 44 °C). Finally Figure 7 shows a reduction and a phase displacement of the heat flux coming into the refrigerated compartment. In fact, as can be observed, the heat transfer rate of the reference cold room peaked at 4:30 PM while the heat flux in the novel cold room peaked at 9:00 PM. This means that a peak delay of almost 4.30 h was achieved. Moreover, the thermal inertia compartment wall improvement determined a thermal heat flux peak reduction equal to 5.55%. In fact, PCM acting as an energy storage medium can absorb and displace the incoming heat flux during its melting phase. This means that the reduced heat load stored during the day reaches the internal refrigerated environment during the night, which is characterised by high refrigeration system performance (due to lower environmental temperature) and reduced energy costs. In this way a reduction in energy or fuel consumption by the refrigeration unit, especially in the daytime, characterised by high external temperatures, can be achieved.
Figure 5. Meteorological parameters such as solar irradiation and external environmental temperature detected during the experimental campaign.

Figure 6. Measured temperature trend through the cross section of the novel and reference cold room south oriented wall.

Figure 7. Comparison of thermal flux through the south-oriented wall of novel and reference cold room.
5.2. **PCM air heat exchanger**

The thermal behaviour of both the novel and reference cold room under steady state operating conditions was studied during a 24 h test. To make the results clear and readable 2h test results are reported and discussed. In Figure 8 the reference and novel cold room compartment air temperature are shown. Moreover both the reference evaporator ($T_{\text{OUT-REF}}$) and PCM air heat exchanger ($T_{\text{OUT-OUT-PCM}}$) outgoing air temperature are reported. For the ordinary cold room the average compartment air temperature was equal to 3.68 °C. For the novel cold room it was equal to 5 °C. As can be seen from the graph, the number of fluctuations over time was significantly reduced in the PCM added system. These results suggest that the PCM air heat exchanger application, close to the evaporator of refrigeration unit, allowed the increase and stabilization of air temperature leaving the evaporator. In fact, during the compressor OFF time period the heat gain, transmitted through the insulated walls, was absorbed by PCM (thanks to its high storage capacity) avoiding a rapid rise in the compartment air temperature. Moreover, during the compressor ON time period the evaporator outgoing air passing through the PCM air heat exchanger, was heated as a result of PCM freezing process. Consequently, the air temperature leaving the heat exchanger ($T_{\text{OUT-OUT-PCM}}$) increased. This means that the lowest value of the Tout out PCM was 2.9 °C higher than the lowest value of the reference evaporator outgoing air temperature ($T_{\text{OUT-REF}}$). In this way, the destructive effect of evaporator freezing temperature over fresh products could be avoided [13]. Figure 9 shows the comparison of the compressor power between the reference and the novel cold room. Moreover PCM air heat exchanger surface temperature was reported. From the graph it is immediately evident that thanks to the PCM solid/liquid transition, an increase of the compressor ON/OFF cycle time and a reduction of compressor START/STOP over time was achieved. In fact, during the OFF period, the warmed air passing through the air heat exchanger, released heat at PCM, which changed its state (melted). In this way, thanks to the PCM melting process the compressor STOP period increased by about 7.75 min compared to the reference. In the same way during the ON period, the evaporator outlet air passing through the PCM air heat exchanger absorbed heat from the PCM, which changed its state (solidified). Thanks to the PCM freezing process the compressor START period increased by about 3.17 min compared to the reference. This means that the number of the ON/OFF compressor cycles over time was also reduced (six cycles instead of thirteen). Overall the total electric power consumption of the novel cold room, during 2 h of stable operating conditions, was reduced by about 16% compared to the reference.

![Figure 8](image-url)  
*Figure 8. Compartment air temperature with/without PCM, evaporator outgoing air temperature without PCM ($T_{\text{OUT-OUT-PCM}}$) and temperature of air leaving the air heat exchanger ($T_{\text{OUT-REF}}$).*
6. Conclusion

Nowadays, refrigerated transport plays an essential role in the food industry, preserving the quality of foodstuffs and satisfying an increasingly wide range of consumer needs. However, it is well known that the maintenance of a proper temperature along the entire journey determines a high-energy consumption and related greenhouse gas (GHGs) emissions into the atmosphere. Even small improvements in energy performance of refrigerated transport systems can lead to an interesting reduction in overall energy impact on an already high-tech sector. Considering the main heat loads affecting a refrigerated compartment, the application of PCM on two different thermal energy storage systems were assessed. The first analysis was focused on the reduction of cooling energy required to break down the heat load deriving from the external environment (e.g. heat conducted through the insulated envelope). In this context, a PCM layer was added to the external side of a refrigerated container envelope. Afterwards, an experimental campaign was aimed at reducing cooling energy required to run a low efficiency-refrigerating unit. In this way, an air heat exchanger containing PCM was positioned close to the evaporator of a cold room. Results underline that improvement of the envelope thermal inertia, after adding the PCM layer, led to a consistent reduction (5.55%) and phase displacement (between 4.30) of the daily heat load. This means that the refrigeration unit operated with high efficiency due to a reduced temperature gradient between the external and the internal environment therefore requiring a lower amount of energy. Results obtained by positioning a PCM air heat exchanger close to the evaporator highlighted a lower number of compressor ON-OFF cycles (6 cycles instead of 13 cycles in 2 hours) and in an increase of their length. In this way, the refrigerating unit energy efficiency increased and the electric power consumption decreased (about 16%). Finally, it is also worth noting that the technologies presented here can be easily applied to other compartments involved in refrigerated transport systems and should not be considered alternative to each other. In fact, considering a possible research development, it would be interesting to study a refrigerated compartment (travelling by rail, ship or road) which is fully integrated with all the described technologies. The development of energetically “independent” refrigerated compartments able to meet the required cooling energy in different environmental conditions should be strongly considered.

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