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A refrigerated container envelope with a PCM (Phase Change Material) layer: Experimental and theoretical investigation in a representative town in Central Italy

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In this paper, a novel technology to improve the thermal performance of reefer container envelopes using a Phase Change Material (PCM) has been investigated. To that end, an external PCM layer was integrated with an insulated sandwich panel, in order to reduce and displace the heat flux phase caused by the external climatic conditions. The proposed technology was evaluated using an experimental and numerical design study. Specifically, during the experimental activities, a prototype panel was first tested inside a climatic test room and subsequently assembled on mini cold rooms and evaluated under real summer environmental conditions in Ancona (Italy). Finally, the numerical analysis was carried out using Finite Element Method (FEM) software in order to simulate a two-dimensional unsteady-state heat transfer with PCM. The calculation results were compared with the experimental values in order to validate the mathematical model, achieving a high reliability (correlation coefficient equal to 0.95).

1. Introduction

Nowadays, there is a growing consumer demand for chilled or frozen products and refrigerated containers carry many of these products over long distances. In fact, due to the considerable latitudinal extension and complex morphology characterising the Italian peninsula, containers often have to travel for more than 1100 km to reach their destination. Therefore, the total heat load during transport by rail, road and ship using containers is subject to high oscillation due to the changing external climatic conditions. At the same time, the maintenance of suitable storage conditions during refrigerated cargoes transport represents a compelling food industry concern mainly due to the relevant economic value behind the entire agricultural and food chain. It is well known that, compared with frozen food, chilled products, which include fruits and vegetables, are more liable to temperature abuse. All fresh fruits and vegetables are characterised by metabolic activity and the rate at which they ripen is determined by temperature. As a secondary effect, the ripening of fruits and vegetables produces a heat emission that depends on temperature and time [1]. Therefore maintaining the optimum carriage temperature determines slow transpiration and extended storage life, thereby forestalling the problem of the cargo being deemed unfit for consumption.

According to Hartmann [2] during different transportation ways (train, ship and truck) or terminal stacking, reefer containers require external power supply. Moreover, especially throughout loading and unloading phases containers undergo different duration power failure. Therefore, depending on the external climatic conditions, the quality of the refrigerated cargo could be affected by the internal operative temperature oscillations caused by the lightweight envelopes.

For those reasons, this study focuses on the thermal effectiveness of a Phase Change Material (PCM) layer application to the external side of a container envelope. In fact, thanks to their high value of thermal inertia, PCMs act as heat transfer rate reduction technology. Indeed, since PCMs are characterised by high latent heat of fusion, they are able to absorb and delay the heat loads from the environment, maintaining the internal temperature in an acceptable range [3]. In this regard, a Thermal Energy Storage (TES) system by using PCMs offers a high thermal storage density enhancing the energy efficiency of cold storage and transportation systems [4].

In recent years, various methods regarding the PCM applications to various cold storage and transportation systems have been investigated. As an example, Cheng et al. [5] adopted a shape-stabilised phase change material to construct a heat storage condenser in order to improve the overall heat-transfer performance

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Nomenclature

C_{eff}	effective heat capacity (J/(kg K))	I	solar irradiation (W/m^2)
C_S	sensible heat capacity (J/(kg K))	h	surface convective coefficient (W/(m^2 K))
C_L	latent heat of fusion (J/kg)	α	absorption coefficient
T	temperature (°C)	λ	conductivity (W/(m K))
T_m	melting temperature (°C)	ρ	density (kg/m^3)
T_{amb}	ambient temperature (°C)		
t	time (s)		

of a household refrigerator condenser. The experimental results showed lower energy consumption for the PCM-added system (about 12% energy savings). In addition, as a result of PCM application, a higher evaporator temperature (3 °C) and a higher COP (coefficient of performance) were obtained. In a recent study, Yuan and Cheng [6] proposed a novel multi-objective optimization method, with the aim to minimize the total cost and energy consumption of an ordinary household refrigerator. This novel method, which combines refrigerator dynamic model and Genetic algorithm NSGA-II, leads to an overall performance optimization of both novel and reference household refrigerators. However, by comparing the main optimization findings obtained for the ordinary and novel household refrigerators, the authors stated large energy and cost saving in the PCM added system. Chen et al. [7] developed a novel composite PCM for cold TES, obtained with an alkane hydrocarbon (dodecane) stabilised with hydrophobic fumed silica. Thanks to its low thermal conductivity value, this composite PCM proved to be favourable in cold TES applications. Moreover, the authors experimentally investigated the thermal performance of composite PCMs with different dodecane percentage mass (100%, 85%, 80% and 75%) in a real cold storage system. Thanks to good storage performance and high shape stability, the dodecane/ hydrophobic fumed silica composite PCM with 85 wt% of dodecane performed well in the cold storage system. A good agreement between the experimental and numerical data was found also. Gin et al. [8] demonstrated that through the application of PCM panels against the internal walls of a freezer, a reduction in temperature variations in case of heat loads (such as opening of door, defrosting and loss of electrical power) can be achieved. The energy consumption tests showed that the addition of PCM can reduce energy consumption during the defrost cycle and door opening by 8% and 7% respectively. Azzouz et al. [9–11] studied the inclusion of a thick PCM slab on the back of a household refrigerator evaporator both numerically and experimentally with the aim to improve its energy efficiency and to keep the refrigeration system at constant temperature during power failure. Encouraging results were obtained by the authors. The PCM integration allows 5–9 h of continuous operation without the electrical supply and a 10–30% increase in the coefficient of performance. Orò et al. [12] numerically and experimentally demonstrated the improvement in the thermal performance of a chilly bin due to the inclusion of a PCM layer. Specifically, the numerical model demonstrated the PCM's capacity to maintain product temperature constant for a longer period. Wang et al. [13] investigated the use of PCM heat exchangers in various positions inside a refrigeration system. The phase change material was located between the condenser and the compressor, between the condenser and the thermal static expansion valve, and between the evaporator and compressor. The results showed that locating PCMs in different positions could increase the COP (coefficient of performance) by up to 8%. Tassou et al. [14] revised different technologies aimed at reducing the refrigerated food transport environmental impact. The authors found that transport system could be based on tubes filled with a eutectic solution. This technology based on PCM provides the cooling effect required to keep the refrigerated trucks at a chosen internal temperature. In their study Simard and Lacroix [15] validated a numerical model for simulating thermal behaviour of a parallel plates (filled with an aqueous-glycol mixture) operating in a typical refrigerated truck. The results highlighted that the latent cold storage unit helped to maintain the refrigerated compartment internal temperature below −8.15 °C for 8 h. Liu et al. [16] developed an advanced cooling system incorporating a PCM with the aim to keep refrigerated vans at the required thermal conditions during their journey. The special feature characterising the proposed technology is that the van does not have the cooling system on-board. In fact the phase change thermal storage unit, charged by a refrigeration unit located off the vehicle, provides cooling when the truck is in service. In this way, a reduced energy consumption and lower greenhouse gas emission can be achieved. Following the promising thermal results obtained in lowering and shifting the peak heat load across building walls [17–21] and roofs [22] to off peak electricity demand, there has been a developing attention in the addition of PCMs in standard vehicle walls. Ahmed et al. [23] proposed a novel method for reducing heat transmission through the envelope of a refrigerated truck trailer by adding PCMs. This technology, based on the inclusion of copper pipes containing paraffin in standard vehicle walls, 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% and 43.8%. Tinti et al. [24] thermo-graphically analysed polyurethane foam integrated with phase change material designed for thermal insulation in refrigerated transport. The developed hybrid insulation panel would be considered as an advanced technology on contrasting all events in which a temperature transient occurs, especially during the vehicle journey. Glouannec et al. [25] presented a numerical and experimental investigation of three different configuration walls of a refrigerated van. The reference wall thermal behaviour was compared, in turn, with two different multilayer insulation walls containing: a first case with reflective multi-foil insulation and aerogel while a second case with the insertion of PCM (microencapsulated paraffin). Compared to the reference wall the authors found that for the RMS-aerogel wall, the heat flux density peak and the energy consumption were decreased by 27% and 36% respectively. Although during eight hours test a complete material melting and freezing was not reach, good results were obtained by increasing the wall thermal inertia using a PCM layer. Globally, during the daytime period, the energy consumption decreased by 25% compared with the reference wall.

In this context, the purpose of this study is to investigate the effect of the addition of a PCM layer to a reefer enclosure, ideally stacked in the container terminal, in order to reduce and shift the cooling load in comparison with a conventional enclosure. To that end, a theoretical and experimental investigation was conducted. The aim of the experimental analysis was to study the thermal behaviour of a prototype panel inside a climatic test room and