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Thermographic analysis of polyurethane foams integrated with phase change materials designed for dynamic thermal insulation in refrigerated transport

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HIGHLIGHTS

- A phase change material (PCM) was incorporated into a rigid polyurethane (PU) foam.
- PCM micro-capsules were thermally stable in the temperature interval of interest.
- The dispersion process led to a homogeneous distribution of PCM into the PU matrix.
- The higher the PCM content the lower the heat flow transmitted by the hybrid foam.

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ABSTRACT

The dispersion process of a micro-encapsulated phase change material (n-tetradecane) into a polyurethane foam was studied in order to develop a micro-composite insulating material with both low thermal conductivity and latent heat storage properties. The maximum weight content of micro-capsules added to the cellular matrix was 13.5%. Dynamic thermal properties of hybrid foams were investigated by means of a thermographic analysis. This was found to be a very effective diagnostic technique in detecting the change in heat transfer rate across the micro-composite foam in an indirect way, i.e. by measuring how the surface temperature changes over time under heat irradiation. Such a material would be of interest in the field of transport of perishable goods, particularly those requiring a controlled regime of carriage/storage temperatures.

1. Introduction

Transport refrigeration systems, mainly vapor compression units, are required to operate reliably in harsh working environments. Moreover, due to the wide range of operating conditions and constraints imposed by available space and weight, transport refrigeration systems have quite low COPs (coefficient of performance). This, together with increasing use of refrigerated transport, are driving the industry toward the goal of reducing the related energy consumption. The reduction in energy consumption, however, cannot compromise the temperature control of the transported products which is governed by legislation [1]. By way of example, the transport of perishable foodstuffs and the equipment used for the carriage of these products is governed by the ATP agreement [2], whose aim is to facilitate international traffic by setting common internationally recognized standards for temperature controlled transport vehicles. Moreover, the regulation EC No. 852/2004 on the hygiene of foodstuffs [3] requires manufacturers to have suitable temperature controlled handling and storage facilities that can maintain food at appropriate temperatures and enable these temperatures to be monitored, controlled and recorded.

Traditional insulation materials such as expanded polystyrene (EPS), extruded polystyrene (XPS), polyurethane (PU) foams, etc., are typically used in thick or multiple layers in order to achieve higher thermal resistances in the insulating structures of vehicles [4]. At the same time, in the last years a further solution gained interest for the purpose of heat transfer management, that is the use of phase change materials (PCMs) as thermal energy storage system [5,6].

In the particular field of refrigerated transport, a branch of the current research relies in the possibility to lower the heat transfer rate from the outside environment to the inside of the vehicle via the integration of a phase change material to the standard vehicle walls.

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List of acronyms

ATP	Agreement on the International Carriage of Perishable Foodstuffs and on the Special Equipment to be used for such Carriage
COP	coefficient of performance (dimensionless)
DSC	differential scanning calorimetry
EE	enthalpy efficiency (dimensionless)
EPS	expanded polystyrene
HFC	hydrofluorocarbons
MF	melamine-formaldehyde
MME	measured melting enthalpy (J/g)
PCM	phase changing material
PU	polyurethane
RS	reduced compressive strength (kPa m^3/kg)
S	compressive strength (kPa)
TGA	thermogravimetric analysis
TME	theoretical melting enthalpy (J/g)
XPS	extruded polystyrene

The properties of insulation are generally expressed in static terms as the thermal resistance or thermal transmittance of the exterior vehicle envelope, by taking into account the heat flow for a static temperature difference between two faces. Such static properties can be extended by introducing a dynamic term, the index of inertia $I = (\lambda \rho c)^{1/2}$ where λ is the thermal conductivity [W m^{-1} K^{-1}], ρ is the density [kg m^{-3}] and c is the specific heat capacity [J kg^{-1} K^{-1}]. The index of inertia expresses the ability of a substance to store heat in the form of internal energy, thus smoothing the temperature fluctuations arising from a periodical heat flow wave. Phase change materials (PCMs) have been widely studied with the aim to provide a high index of inertia and, as a consequence, to lower the energy consumption needed to operate a temperature controlled environment.

A PCM is a substance with a high latent heat of fusion (i.e. melting enthalpy) so that, during the solid-to-liquid phase change and vice versa, it is able to absorb/release a great amount of energy.

First, when the ambient temperature rises, the solid warms by absorbing heat, behaving as a sensible heat reservoir. Once the melting point is reached, the intermolecular bonds of the material break up whereby the material changes from solid to liquid. This phase change is an endothermic process and as a result the PCM continues to absorb heat at constant temperature until the melting process is completed. As the ambient temperature drops again, the PCM returns to the solid state and gives off the absorbed heat.

This cycle would stabilize the interior temperature and cuts off-peak cooling loads, not by affecting the thermal resistance of the vehicle envelope but by influencing the surface temperatures.

The main advantage of latent heat storage is the high storage density, i.e. storage capacity per unit volume, in small temperature intervals.

The use of PCMs in transportation refrigeration systems has attracted far less attention than in its building counterpart [7–10]. The inclusion of PCM in a chilly bin used to store cold or hot food was studied experimentally and numerically by Oró et al. [11] proving the efficiency of the use of PCM in these systems. Liu et al. [12] proposed a novel refrigeration system incorporating a PCM to maintain refrigerated trucks at the desired thermal conditions, with the charging being done by a refrigeration unit off the vehicle. Ahmed et al. [13] suggested a practical arrangement to incorporate a PCM within the standard insulated walls of a refrigerated truck trailer. A paraffin-based PCM (melting point +7 °C, compared to the +4 °C inside trailer temperature) was selected to fill a number of copper pipes, in turn inserted into conventional polyurethane sheets to manufacture in-house a set of insulating panels. Finally, a small-scale simulator of the trailer loading compartment was built and also equipped with the cooling system. Measurements, on a daily basis, of heat flux across the walls of the 'PCM simulator' showed a significant reduction in both peak heat transfer rate and total heat flow in respect to a twin 'control simulator' (without PCM). This can potentially translate into smaller refrigeration units as well as lower usage of fuel to power the refrigeration units. These requirements would be very crucial as an integral part of the so-called cold chain.

This last study describes an example of the so-called macro-encapsulation of PCMs, that is encapsulation in containers usually larger than 1 cm in diameter. On the other hand, micro-encapsulation is a recently developed new form of PCM encapsulation and consists of particles smaller than 1 mm in diameter. In the latter case the larger surface-to-volume ratio improves the heat transfer to the surrounding [5,7].

Such a characteristic makes micro-encapsulation particularly promising for the aim of this study. The idea was to produce a dispersion of PCM micro-capsules (MicroPCM) within a standard polyurethane foam during the production process itself, i.e. directly at the mixing stage of the liquid reaction components. In this way a micro-composite material was obtained that combines the thermal insulating properties of the foam with the ability of PCM to store heat at constant temperature. A PCM with a melting point in the range of temperatures typical for the carriage of "fresh" foodstuffs was selected, i.e. a positive temperature of few Celsius degrees.

A similar study, although in a different temperature interval, was recently conducted by You et al. [14–17]: they demonstrated the feasibility of the incorporation process and optimized the synthesis parameters. Conversely, other authors experimented the process of post-impregnation of already consolidated polyurethane sheets by adsorption from a PCM solution. The main disadvantage of this procedure was the partial leakage of PCM from the foam, that caused the change over time of acquired dynamic insulation properties [18].

With respect to the aforementioned work of You et al., in the present study a non contact thermographic analysis of PCM-integrated polyurethane foams was developed and it was proven to be an excellent mean to properly characterize the dynamic behavior of latent heat storage in PCMs.

2. Experimental

2.1. Materials

A dual component polyurethane system formulated to produce rigid foams for thermal insulation was supplied by TIOXIDE EUROPE S.r.l. with the trade name of Daltofoam® TP 42202, for the polyol mixture, and Suprasec® 5025 for the isocyanate. The mix ratio reported in the technical data sheet is 100:160 by weight of polyol to isocyanate.

This system was selected because it does not contain neither flame retardants nor physical blowing agents (e.g. HFC) and so it allows a more controllable reactivity and safety issues less severe, characteristics well suited to an experimental activity on a laboratory scale. Material foaming occurs chemically thanks to the carbon dioxide produced by the reaction between isocyanate and water present in the polyol.

MicroPCM was purchased from Microtek Laboratories Inc. (Ohio, USA). They are dual component particles consisting of a core material – the PCM – and an outer shell. The product form is that of a