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Characterization of panels containing micro-encapsulated Phase Change Materials

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ABSTRACT

A solution to increase passively the thermal inertia of lightweight wallboard for building envelopes is to incorporate a Phase Change Material (PCM). The thermal mass and thermal conductivity of the panels establish the thermal inertia of the envelope, which causes a damping and time lag of the temperature peaks inside the buildings. The knowledge of the thermal properties of the wallboard is the base of the modeling of buildings, a target uncertainty can be calculated from the modeling purposes. This paper is devoted to the characterization of a panel containing PCM for its thermal properties. Particular attention is devoted to the calculation of the uncertainty of the thermal properties. Commercial microencapsulated paraffin-based PCMs and specific binders have been used to prepare panels. PCMs have been characterized by granulometric and thermo-gravimetric analysis and the porosity of each panel has been determined experimentally by mercury porosimetry. The microstructure of the panels has been observed by SEM analysis in order to recognize the nature of the porous structure. The theoretical effective thermal conductivity of the PCM embedded in the polyurethane resin has been predicted by different models; especially the Maxwell–Eucken and the EMT (Effective Medium Theory) equations just on the basis of the volume fractions and the thermal conductivities of the components. The thermal conductivity estimated with the EMT model closely followed the experimental data measured by thermofluximeter method and the accuracy of the prediction has been analyzed evaluating the uncertainty budget with respect to all the variables of the model. The accuracy of the method resulted to be acceptable for modeling the thermal performance of a building.

1. Introduction

The thermal efficiency of buildings is not only related to the insulation from external environment but also to the indoor temperature variability. The combination of sun radiations and thermal behavior of the building may result in a wide variability of indoor temperature. If the temperature variability exceeds the comfort range, it stresses the environment active conditioning and the power consumption increases causing a lower efficiency of the building and increasing the expenditure of conventional energy.

Energy storage in greenhouses has been studied since the 1980s in order to achieve the environmental thermal comfort passively reducing thermal dispersion and temperature fluctuations inside the building space. Phase Change Materials (PCMs) are capable to store and release large amounts of energy by melting and solidifying at a certain temperature and are characterized by their transition temperature range, their transition related enthalpies, i.e., a measure of the internal energy storage, and their conductivity, i.e., related to the energy transfer rate. That is the reason why PCMs have been recently embedded in building materials and components to reduce the peaks of temperature inside the building spaces, leading to a room climate, more indoor comfort and a major energy saving [1].

A more interesting way to smooth the temperature variations within a space is by using wallboards impregnated with PCMs, or underfloor heating with latent heat storage. Gypsum wallboard impregnated with PCM could be directly installed in place of ordinary wallboard [2,3] or innovative concretes containing PCM could be used [4]. PCMs are also useful for both energy storage and humidity control in greenhouses, promoting energy management [5]. Many works have been done over the past two decades using PCMs as thermal energy storage to enhance the energy efficiency of the buildings, attracting growing attention due to the concomitant energy conservation and thermal comfort [6,7]. Both full scale experimental investigations and numerical simulations of buildings with PCMs has been the subject of many studies in order to evaluate their behavior in buildings [8,9].

Many PCMs are available, like paraffin waxes, hydrated salts, fatty acids, eutectics of organic and non-organic compounds, with

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a wide range of melting temperatures. The practical temperature range of operation identifies the set of PCMs suitable for the specific application by their transition temperature range. PCMs have also to be chemically stable, cheap, not toxic and not corrosive. The encapsulation is a way to prevent PCMs from dispersion in case of damages, to reduce interaction with the outside environment and with others constituents and to decrease the change of volume during phase transformation but, it reduces active mass for heat storage and creates voids inside bed particles which decreases the thermal conductivity of the system. Pure paraffin waxes are very expensive and most manufacturers use technical grade paraffin, essentially paraffin mixture(s), having a wide range of melting temperatures to reduce costs. The main disadvantage of the paraffin waxes is the low thermal conductivity in their solid state [10].

The determination of the thermal conductivity of systems containing granulate PCMs is very complex because they contain two or more components and are probably porous materials. In this case, the thermal conductivity is a function of the composition, the porosity and the bulk thermal conductivity of each component and it could also depend on the microstructure of the material, i.e., the spatial distribution of each component, the shape and size of the individual pore and particle and the extent of contact between pores and particles [11].

The mechanism of heat transfer in porous materials depends mainly on the volume fraction. It is necessary to differentiate two type of porosity: the external porosity, typical of a granular material in which the void volume is occupied by a gaseous phase which forms continuous conduction pathways, and the internal porosity, in which bubbles or pores filled with a gaseous phase are dispersed in a continuous solid matrix and are not interconnected [12]; in this case the condensed phase forms continuous conduction pathways. For instance, due to the differences in structure, foam and particulate materials may not have the same effective thermal conductivities, even if they have identical void fractions and thermal conductivities of the components [13].

Ibanez et al. [14] developed a methodology that allowed the simulation of the thermal effect of PCMs in the building as a whole by a quasi-steady simulation model as base tool. Furthermore simulation of the transient heat process inside wallboard containing PCM requires the pre-determination of the effective thermal conductivity of the heterogeneous multi-component material forming the wall.

Various methods have been proposed to predict the effective thermal conductivity of porous heterogeneous systems. Much of them are purely empirical and are specific to a given material, others are theoretically based models and have a wider range of applications. Theoretical models are, generally, based on simplified or idealized microscopic configurations. They limit the analysis to steady-state conduction heat transfer and to materials that may be considered isotropic at the macroscopic scale, and the thermal conductivity is determined only as a function of the porosity and the thermal conductivity of each phase. Some general models have been formulated by introducing an empirical parameter into the original theoretical model in order to describe better the microscopic configuration of each material [15], but their convenience of use is limited by the inclusion of parameters whose values must be determined. An extensive list of theoretical models are proposed by Carson et al. [16], including the experimental procedure to determine the empirical parameters but no model or prediction procedure is universally valid [12].

Series and Parallel models bounds the thermal conductivity predictions for both external and internal porosity materials: the first one is the upper limit for the internal porosity materials, while the latter is the lower limit for the external porosity materials [12]. They are therefore the boundaries for the effective thermal conductivity of any heterogenous material provided that conduction is the only mechanism of heat transfer involved. The most often models used to predict thermal conductivities are the Maxwell–Eucken equations for both gas phase dispersed and continuous together with the Kopelman Series and Isotropic models, the Hill, Levy, Geometric and EMT equations [16]. These models gives large discrepancies between the values and therefore it is important to select rigorously the accurate equation for the prediction of the thermal conductivity of the system.

In the case of porous materials in which the two phases are distributed randomly, with neither phase being necessarily continuous or dispersed, the effective conductivity is well modeled by the Effective Medium Theory (EMT) equation [17,18]. The EMT equation is a two-component model in which either component may forms continuous heat conduction pathways, depending on the relative amounts of the components and the internal contact. The model assumes that the effect of local distortions due to the temperature distribution caused by the individual inclusions could be averaged [12]. The optimal heat transfer pathways are strongly affected by the extent/quality of thermal contact between solid particles, i.e. the phase with the highest thermal conductivity, because the heat conduction could be inhibited by the low proportion of surface area that is in intimate contact.

Since thermal contact is dependent on the shape and packing arrangement of the particles, there is a great level of randomness involved [16], and the uncertainty in predicting the thermal conductivity has to be determined.

In the present paper, several composites have been prepared by embedding two different microencapsulated paraffin-based PCMs in different polymeric matrices (acrylic, epoxy and polyurethane resins) in order to obtain light panels with different microstructures, using thermal and UV at room temperature as curing processes. Granulometric analysis of the PCMs have been carried out in order to select the optimal distribution curve, i.e. the distribution which allows to obtain a packaging of the particles with a minor porosity, a major amount of capacitive mass per unit volume and a good thermal contact between particles. The porosity of the samples has been determined experimentally by mercury porosimetry and their microstructures have been observed by SEM analysis.

The effective thermal conductivity has been measured by thermofluximeter method. The value has been verified by using all the models cited above. The accuracy of the different equations has been evaluated by calculating the uncertainty budget with respect to all the variables of the model.

The objective of this paper is to prepare panels containing PCM by different curing processes (both thermal and UV). The influence of different parameters such as the granulometric distribution and nature of the PCM, the resin for binder and the thermal properties of the panels have been studied. A simulation has been performed on small-scale building for the most compromising panel and its efficiency on the softening of temperature peaks has been evaluated. The thermal conductivity of the panel has been calculated using different models available in literature and has been compared to the experimental data. Particular attention is devoted to uncertainty calculation, the ISO guide for uncertainty calculation [19] is here applied.

2. Experimental setup

2.1. Characterization of the Phase Change Materials

Two commercial encapsulated PCMs have been considered. PCM1 is a mixture of paraffin waxes in powder form encapsulated in poly-methyl-methacrylate (PMMA) microcapsules; its melting point is around 23 °C. PCM2 is composed by a mixture of paraffin waxes in powder form encapsulated in silicon dioxide; its melting point is around 27 °C. Both have been used in order to prepare com-