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Thermal behavior of building material containing microencapsulated PCM

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ABSTRACT

The application of phase change materials (PCMs) for building applications has received considerable attention in recent years due to the large storage capacity and isothermal nature of the storage process. This paper summarizes the results of a physical model and analysis of thermal energy storage and temperature control achieved using mortar incorporating microencapsulated PCM. The validity of the numerical code used is ascertained by comparing our results with previously published results. The effect of different parameters such as the heating/cooling rate and the mass fraction of the PCM on the thermal behavior of the mortar is also analyzed.

1. Introduction

Building is one of the leading sectors of the energy consumption. In the year of 2009, around 40% of the total fossil energy was consumed in building sector in the United States and European Union [1]. Furthermore the energy consumption of heating, ventilation and air conditioning systems is still increasing with the increasing demand for thermal comfort. Under this circumstance, the integration of phase change materials (PCMs) into conventional construction materials has gained more and more attention as a potential technology for minimizing energy consumption in buildings [2,3]. The high energy storage capacity per unit volume at a nearly constant temperature characterizes and distinguishes them from conventional building materials. In a given day, when the ambient temperature rises enough to reach the solid-liquid transition temperature, the PCM, incorporated in a construction material, changes from solid to liquid with endothermic behavior thus limiting the flow of heat towards the interior of the building. Conversely, upon an environmental temperature decreases, the PCM, that is now in the liquid state, may reach the liquid–solid transition temperature again and shift to solid state, with energy liberation (exothermic process), thus delaying the cooling tendency inside the building. The permanence at a known melting temperature range will stabilize interior ambient temperatures thus influencing the thermal comfort sensation. The material used in building envelopes must be well chosen depending on the weather and environmental conditions. Therefore, it is very important to specify and compare during the design phase of the building, the thermal properties of the different possible construction systems, such as thermal transmittance in steady state, the contact thermal resistance between the layers, the heat storage capacity of the envelope and its dynamic thermal response under different environmental conditions. Several researchers have investigated methods for impregnating gypsum wallboard and other architectural materials with PCMs [4–6]. Khudhair and Farid [7] summarize the investigation of thermal energy storage systems incorporating PCM for use in building applications. The PCM must be encapsulated so that it does not adversely affect the function of the construction material. Encapsulation allows the PCMs to be incorporated simply and economically into conventional construction materials, this has been studied by several researchers [8–10] and developed by companies like BASF [11] and Dupont [12,13]. Concerning the use of PCM in building materials, a methodology for choosing a PCM has been developed by Peippo et al. [14] for passive solar heating and criteria of choice were given by Gu et al. [15] for thermal energy recovery with air-conditioning systems.

Characterization of the phase changing behavior of the construction materials is an important issue for design and optimization of these materials. Storage density and phase change temperatures are very important parameters since they decide the storage system capacity, size and application range. Moreover, accurate estimation of PCM enthalpy variation in the working temperature range is essential for correct mathematical modeling of the storage system. Of the number of apparatus/tests required for complete characterization, one notices that the test based on differential thermal analysis (DTA) and differential scanning calorimetry (DSC) devices

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Nomenclature

A	superficial capsule area per unit mortar volume (m^{-1})
c	specific heat ($J\,kg^{-1}\,K^{-1}$)
d	diameter (m)
f	PCM liquid mass fraction
L_f	latent heat of PCM ($J\,kg^{-1}$)
Q	total stored energy (J)
t	time (s)
T	temperature (K)
U	heat transfer coefficient ($W\,m^{-2}\,K^{-1}$)
x	axial coordinate (m)

Greek symbols

β	heating/cooling rate ($^{\circ}C\,min^{-1}$)
ε	volume fraction
λ	heat conductivity ($W\,m^{-1}\,K^{-1}$)
ϕ	heat flux ($W\,m^{-2}$)

Subscripts, superscripts

m	melting
Mr	mortar
i	initial
PCM	phase change material
p	imposed temperature

generally require very small samples [16,17], so that they become inappropriate for testing heterogeneous materials with large size representative volumes.

The present work aims to contribute to the solution of these problems by introducing the use of heat flux sensors (or fluxmeters) to study the thermal behavior of building material containing microencapsulated PCM. The heat flux sensor utilizes the principle of the differential thermocouple and most commercial models are conceived as thin flat sensors, comprising a serial array of miniature thermocouples forming a thermopile. Thermocouple junctions are embedded in a sample and are symmetrically distributed along both surface of the sample. When attached to the surface of a material that exchanges heat with the environment, the fluxmeters allow the measurement of the instantaneous heat flux traversing its surface, which is proportional to the temperature difference between the opposite surfaces of the sensor. Signal acquisition is possible using microvolt meters and heat flux ($W\,m^{-2}$) is calculated directly from the sensitivity of the sensor. High sensitivity values are possible due to the weak internal electrical resistance and to summing effect of each individual junction tension. All heat transfer mechanisms can be studied with the aid of fluxmeters. The heat flux measured by a flux sensor is the sum of the heat absorbed by the instrument. Different fields, like building, aeronautics, soil and food thermal research processing employ this kind of instrument. Recently, different experimental devices using fluxmeter instrument were developed to study the effect of melting and solidification of the PCM on the thermal behavior of the construction materials [18,19]. These devices are based on the measurement of temperatures and heat fluxes exchanged between the two lateral sides of the PCM samples, providing the total heat stored during the phase change process. To obtain overall one-dimensional heat transfer [19] in these devices, the lateral faces or edges of the sample are insulated. Detailed discussion of these devices is provided in Refs. [8,18].

In this paper numerical model has been developed to investigate the temperature regulation effects resulting from the incorporation of microencapsulated phase change materials in cement based mortar and to enable more accurate interpretation of the measured data provided by the fluxmeter instrument.

2. Mathematical formulation

For the integrated PCM-building materials, the assumption of homogeneous mixture is crucial for the simulation of thermal performance [20]. Because the PCM and the building material have different thermal properties, the interaction between the two might affect the overall thermal behavior. Thus, the ideal model is to simulate the two discretized domains.

To facilitate the formulation, the following assumptions are adopted:

- The PCM material is pure, homogeneous and isotropic.
- The thermophysical properties of the PCM and the mortar are temperature independent.
- Heat transfer is caused by heat conduction and is one-dimensional.

Based on the preceding assumptions, the energy equations for the mortar can be written as:

$$(1-\varepsilon)(\rho c)_{\mathrm{Mr}}\frac{\partial T_{\mathrm{Mr}}}{\partial t} = \frac{\partial}{\partial x}\left((1-\varepsilon)\lambda_{\mathrm{Mr}}\frac{\partial T_{\mathrm{Mr}}}{\partial x}\right) + UA(T_{\mathrm{PCM}} - T_{\mathrm{Mr}}) \quad (1)$$

During sensible heat storage, when the PCM is completely solid or liquid, the corresponding governing equation can be written in this form:

$$\varepsilon(\rho c)_{\mathrm{PCM}}\frac{\partial T_{\mathrm{PCM}}}{\partial t} = \frac{\partial}{\partial x}\left(\varepsilon\lambda_{\mathrm{PCM}}\frac{\partial T_{\mathrm{PCM}}}{\partial x}\right) + UA(T_{\mathrm{Mr}} - T_{\mathrm{PCM}}) \quad (2)$$

where ρ_{Mr} and c_{Mr} are, respectively the density and the specific heat capacity of mortar, U is the overall constant heat transfer coefficient and ε is the volume fraction of the PCM in the mortar.

The superficial capsule area per unit mortar volume A is classically expressed as a function of the volume fraction of the PCM in the mortar ε and of the capsule diameter d, namely:

$$A = \frac{6.\varepsilon}{d} \quad (3)$$

In the latent-heat storage, when the PCM is changing phase, the corresponding model takes this form:

$$\frac{\partial f}{\partial t} = \frac{AU}{\varepsilon\rho_{\mathrm{PCM}}L_{\mathrm{F}}}(T_{\mathrm{Mr}} - T_{\mathrm{m}}) + \frac{\lambda_{\mathrm{PCM}}}{\rho_{\mathrm{PCM}}L_{\mathrm{F}}}\frac{\partial^2 T_{\mathrm{PCM}}}{\partial x^2} \quad (4)$$

where λ_{PCM} is the thermal conductivity of the PCM, ρ_{PCM} its density and c_{PCM} its specific heat capacity, f is the liquid fraction of PCM, T_{m} is the melting temperature of the PCM and L_{F} is the latent heat of the PCM.

The temperature on each side of the sample (see Fig. 1) is programmed to be a linear function:

$$T_{\mathrm{p}} = \beta t + T_{\mathrm{i}} \quad (5)$$

At $t = 0$ the initial condition is $T_{\mathrm{Mt}}(x, 0) = T_{\mathrm{PCM}}(x, 0) = T_{\mathrm{i}}$.

3. Numerical solution

The governing differential equation subjected to the initial and boundary conditions shown in Eqs. (1), (2) and (4) has been solved numerically by using the control volume finite difference technique. The physical model is divided into contiguous control volumes, where the grid points are placed at the geometric centers of these control volumes. The differential equation is integrated over each control volume and over the time step. Piecewise profiles expressing the variation of the dependent variable between the nodal point and the neighboring grid points are used to evaluate the