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Experimental testing and numerical modelling of masonry wall solution with PCM incorporation: A passive construction solution

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ABSTRACT

Presently the essential research trend for sustainable buildings is the use of renewable energy sources and the development of new techniques of energy storage. Phase change materials (PCMs) may store latent heat energy in addition to the typical sensible energy capacity of current building materials, allowing to store significantly more energy during the phase change process (solid to liquid and vice versa). The incorporation of PCMs into building envelope solutions takes advantage of solar energy, contributing to the overall reduction of energy consumption associated to use of the air conditioning systems.

This paper presents and discusses research developed in two main components: experimental testing and numerical simulation of a building component with PCM incorporation. The main goal of the experimental testing carried out was to evaluate the effect of the incorporation of PCM macro encapsulated into a typical Portuguese clay brick masonry enclosure wall. It is evaluated the influence of the phase change process of the PCM over the attenuation and time delay of the temperature fluctuations for indoor spaces. The experimental results allowed the calibration and validation of the numerical model, enabling to carry out parametric studies with different PCMs quantity analysing consequent temperature damping and time delay.

1. Introduction

In the last years, despite the improvement of the thermal insulation levels of buildings, the use of mechanical equipment to improve the expected thermal comfort of buildings has also steadily increased, consequently leading to the increase in energy consumption. Due to this exaggerated and increased consumption of energy [1] the European Union (EU) has been working on new and more complex legislation and is arguably broader that it has ever been [2]. The Energy Service Directive proposes a 9% savings of energy by 2016 as a main goal of the National Energy Efficiency Action Plans (NEEAP) of EU member states, while the proposed Renewables Directive aims for 20% of all energies to come from renewable energy sources by 2020 [2]. The building sector represents 27.1% of total energy consumption and figures as one of the major energy consumers [3,4], expecting in 2035 this sector will be the fourth largest CO_2 emitter [4].

To minimize the energy consumption, research on passive cooling/heating strategies, as well as the development of new materials and building components with smaller environmental impact are essential [5]. This is the case of PCMs that can be incorporated into building components (windows, enclosure and partition walls, ceilings and floors, etc.) [6,7]. As Zhu et al. [3] suggested thermal energy storage systems using PCMs have been recognized as one of the advanced energy technologies in enhancing energy efficiency and sustainability of buildings. The most interesting feature of incorporating PCMs into building components and structure is that they can store latent heat energy as well as sensible energy. The storage of thermal energy as latent heat has attractive features over that of sensible heat due to its high storage density. Comparatively to the common construction materials, the PCM can storage more energy with less layer thickness. For example, comparatively to the brick material, the phase change material can store eighteen times more energy [8].

As Kuznik et al. [9] explain, when the temperature of PCM increases the material changes phase from solid to liquid. As this physical reaction is endothermic, the PCM absorbs heat. When the temperature decreases the material changes phase from liquid to solid. As this reaction is exothermic the PCM releases heat.

Many numerical and experimental studies have been carried out to evaluate the potential of PCM incorporation into more energy efficient buildings. Three main research areas have been identified: (i) the potential of incorporating PCMs into latent heat thermal energy storage systems (higher inertia); (ii) the potential of PCMs as

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Nomenclature

C_p	specific heat (J/(kg K))
L_f	latent heat (J/kg)
T_l	liquids temperature (K)
m	mass (kg)
T_s	solidus temperature (K)
T_i	interior air temperature (K)
T_e	exterior air temperature (K)
T_{eq}	equivalent temperature (K)
S	total solar radiation to south facades (W/m^2)
h_e	exterior convection heat transfer coefficient (W/(m^2 K))
h_i	interior convection heat transfer coefficient (W/(m^2 K))

Greek symbols

λ	thermal conductivity (W/(m K))
ρ	mass density (kg/m^3)
μ	dynamic viscosity (kg/(m s))
υ	kinematic viscosity (m^2/s)
α	solar absorption coefficient
φ	time delay (s)
ΔQ	stored heat (J)
Δh	phase change enthalpy (J/kg)

Subscript

e_{caps}	capsule wall thickness (mm)
PCM	phase change material
e_{PCM}	PCM thickness (mm)
CC1	climatic chamber 1
CC2	climatic chamber 2
R.H.	relative humidity (%)
PT	PT100 probe
K_i	thermocouple

envelope insulation material; (iii) the potential of PCMs for indoor thermal regulation purposes (increased comfort). For a review, see Sharma et al. [10], Tyagi and Buddhi [11] and Zhu et al. [3].

The improvement of the thermal performance of the building through the incorporation of PCMs into the building envelope system depends on many factors: (i) climate conditions, mainly on the solar radiation and ambient temperature, (ii) thermal physical properties of the materials and, (iii) design parameters such as shading, configuration and orientation of the system (PCM localization versus insulation material localization). However, the quantity and type of PCMs is an important factor to be considered.

Solar energy resources are abundant in the winter season in the Mediterranean climates. As Soares et al. [12] suggests this is of great advantage, from the point of view of energy-saving, for the integration into building construction of systems using this reusable energy source. The authors are particularly driven by the problem of how to effectively store the extra solar thermal energy during the day and release throughout the night, when the demand to reduce the energy consumption in air conditioning and heating is essential. As Kuznik et al. [9] suggests the volume of PCM must be optimized because if it is too large the time needed for the heat to penetrate the PCM becomes larger than the total number of available sunshine hours and the storage process cannot be complete during a day.

Due to low thermal conductivity of the PCM, these systems have an inherent disadvantage of slow heat transfer during the charging and discharging process. This could be an advantage if one considers the potential of the use of PCM as an insulation material due to its high thermal resistance. However, if the main goal is to enhance the storage and the release thermal capacity of the system during a typical winter day cycle, the time needed to complete all the charging and discharging process is crucial to the high performance of the system [8–11,13,14].

The problem of predicting the behaviour of phase change is difficult due to its nonlinear nature at the moving interface, and in addition, to the fact that the two phases have different thermo physical properties. One of the methods to solve the moving boundary problem is the enthalpy formulation proposed and studied by various authors: Swaminathan and Voller [15], Costa et al. [16], Brousseau and Lacroix [17], Chen and Sharma [18], Sharma et al. [19], Chen et al. [20]. According to Costa et al. [16] and Chen et al. [20] by introducing an enthalpy formulation, the phase change problem becomes simpler.

The aim of the present research is to reveal the PCM potential as a passive solution, by decreasing the internal temperatures fluctuations and the internal temperature peak, and increasing the time delay between the external and the internal conditions. This type of results are a clearly synonymous of thermal efficiency of buildings, by contributing to the reduction of the energy consumption associated to active systems and or using more efficiently the available energy sources.

2. Methodology

Considering the historical climatic data available for some Mediterranean cities [21] the imposed conditions were defined for the numerical models and experimental campaign, as well as the PCM material characteristics. To incorporate PCM into a typical commonly built clay brick wall, it was necessary to select the metal and the shape of the capsules for compatibility purposes to brick horizontal voids. Secondly, the clay brick wall specimens were built and tested with the selected climatic conditions.

Finally the results attained from the experimental campaign aided the validation and calibration of a numerical model, allowing further on to carry out optimization studies for different boundary conditions, PCM quantities and positioning in the wall.

The work methodology is structured into three main steps: (i) climatic conditions and definition of material properties; (ii) wall specimen construction and experimental testing; and (iii) numerical modelling and validation. The work developed follows the flowchart shown in Fig. 1.

3. System description

3.1. System configuration

To construct the wall specimen, typical horizontally hollowed clay bricks (30 cm × 20 cm × 15 cm format) were used as the principal masonry unit and all-purpose mortar for horizontal and vertical mortar joints. To incorporate PCM into the brick wall, steel macro capsules (30 cm × 17 cm × 2.8 cm and 0.75 mm mean thickness) were filled with PCM and inserted into the middle brick voids. The wall specimen geometry and constitution is shown in Fig. 2.

3.2. Materials properties

According to Sharma et al. [10] PCMs can be classified into three main groups: organic, inorganic and eutectic mixtures. For this research project it was chosen an organic paraffin, designated as RT18 (fusion temperature 18 °C), and their main properties are shown in Table 1. The main advantage to use an organic PCM is because they are chemically inert, not corrosive and they are compatible with the majority of current construction materials.