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A simple model to predict the thermal performance of a ventilated facade with phase change materials

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ABSTRACT

Appropriate design and control strategies are crucial for the implementation of certain complex active systems in the building sector. Suitable and user-friendly numerical tools have to be available to architects and engineers, so they can incorporate innovative active systems in their building designs. The thermal response of a ventilated facade with phase change material in its air chamber for cooling applications is studied in this paper. The system makes use of low temperatures at night to solidify the phase change material, and store it solid for a later cooling supply to the interior of the building. This active technology is very sensitive to the weather conditions as well as to the defined operational schedule (charge, storage and discharge periods definition). Two different numerical approaches have been developed to better understand this system and to define different control strategies, as well as to determine their potential to reduce the energy consumption in the building for cooling purposes. First, a finite control volume approach was applied to describe the ventilated facade with latent heat storage. The important computational cost and complexity of this numerical methodology leaded the authors to develop a simple numerical model based on the assumption that the exchange between the air and phase change material inside the ventilated facade occurs at isothermal conditions. Both models were validated against experimental data, and even though the isothermal model presented slightly higher deviation from the experimental results than the finite control volume one, it is presented as a suitable numerical tool for architects and engineers because of its light computational cost and versatility.

1. Introduction

It is well known that the high energy demand of HVAC (Heat, Ventilated and Air Conditioned) systems used in the building sector and its reduction is considered a key aspect in energy, economical and sustainable point of view. Numerous energy policies have been recently implemented worldwide to achieve this goal, such as the European directive 2010/31/EU [1]. According to the ETP 2012 [2], the building sector consumes approximately 32% of global final energy use, making it responsible for almost 15% of total direct energy-related CO_2 emissions from final energy consumers. Several studies showed that thermal energy storage (TES) systems can be efficiently applied in building design as passive or active systems to reduce the energy required by HVAC systems [3–5].

Within this context, the incorporation of latent heat thermal energy storage (LHTES) systems based on the use of phase change materials (PCM) in both passive and active buildings systems [6,7] has been a big topic of interest because of the high energy density that these materials can provide. However, these technologies have to overcome some important barriers before being widely implemented in the building sector. Apart from the economics, one of the main important technical barriers is the complexity of these systems to be implemented in the building design [8]. In order to better understand and optimize the design of these systems, the use of numerical tools is required. Even though several numerical models are available in the literature (both for passive [9,10] and active [11,12] systems), they are developed for specific applications, are non-user-friendly, and require high computational costs as well as very specific knowledge of the numerical models. These drawbacks strongly limit their use in the building sector and hence, discard the possible implementation of LHTES systems in the building design.

In this paper, a simple numerical tool is developed and presented to describe the performance of a ventilated facade with PCM panels in its air chamber for cooling purposes. The simple tool (isothermal model from here on) is based on the assumption that the heat exchange process between the air flowing through the ventilated

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Nomenclature

A_{conv}	area air-PCM heat transfer [m^2]
A_{out}	area heat losses [m^2]
C_p	heat capacity [$\mathrm{J\,g^{-1}\,K^{-1}}$]
h	heat transfer coefficient [$\mathrm{W\,m^{-2}\,K^{-1}}$]
L	enthalpy of fusion [$\mathrm{J\,g^{-1}}$]
$\dot{m}$	air mass flow rate [$\mathrm{kg\,s^{-1}}$]
m_{PCM}	mass of PCM [kg]
$Q_{n\rightarrow n+1=}$	energy absorbed or released [J]
$\dot{Q}^n$	power of charge or discharge [W]
U	thermal transmittance [$\mathrm{W\,m^{-2}\,K^{-1}}$]
t	time [s]
T_{ext}	outdoor temperature [K]
T_{inlet}	inlet temperature [K]
T_{PCM}	average PCM temperature [K]
T_{outlet}	outlet temperature [K]

Greek symbols

Δx	absolute error of variable (x)
δx	relative error of variable (x)

facade cavity and the PCM panels occurs in isothermal conditions. Even though the model is here presented for such specific application, it can be easily adaptable to any active system containing air-PCM heat exchange.

The isothermal model is compared against a finite control volume approach (control volume model from here on) and both numerical models are validated against experimental measurements. Moreover, some key aspects, such as the treatment of the inlet temperature in the active system, are also discussed.

Fig. 1. Experimental set-up. Prototype of the VDSF with PCM.

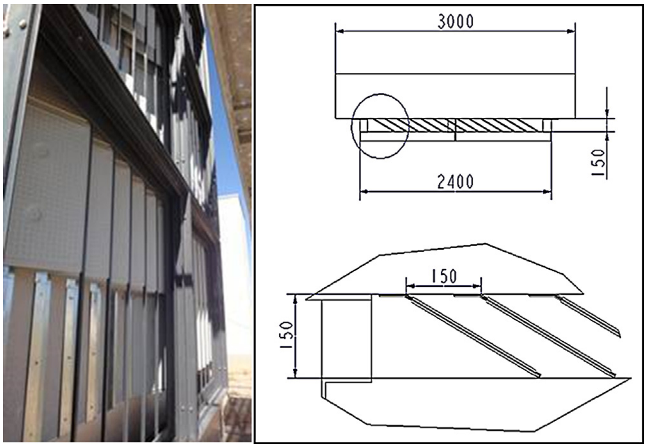

Fig. 2. PCM panels distribution inside the air cavity of the VDSF.

2. Methodology

2.1. Description of the system

A versatile ventilated double skin facade (VDSF) with PCM panels in its air channel was tested experimentally to provide energy benefits both for heating [13] and cooling [14]. Fig. 1 shows the prototype tested in the experimental set-up located in Puigverd de Lleida (Spain).

In the air cavity between the two skins of the VDSF, 112 PCM panels (RT21 macro-encapsulated CSM panels from Rubitherm Technologies GmbH [15]) are installed creating 14 channels, as it can be seen in Fig. 2. Six automatized gates were installed at the different openings of the channel in order to control the operational mode of the facade. Moreover, three fans with variable power output (ranging between 17 W and 120 W each) were placed at the inlet of the air channel to provide mechanical ventilation when needed.

The ventilated facade operates as a cold storage system, since it uses the low temperature at night to solidify the PCM. During the peak load hours, when there is a cooling demand, the air is cooled down by the PCM providing a cooling supply. The operational principle of the system is summarized in Fig. 3. The cold storage sequence is based on a charge process (Fig. 3a), a storage period (Fig. 3b), and a cooling discharge (Fig. 3c). It is important to notice that both charge and discharge processes are driven by mechanical ventilation; hence, an appropriate control strategy is mandatory for the use of this system in order to ensure that the electrical energy consumption by the fans is minimized and net energy benefits can be achieved. Within this context, the necessity of a simple and computationally light numerical tool is reaffirmed, since such a tool could be implemented in any basic control system at building scale or used for the development of control strategies.

A full description of the sensors used in the experimental facility is given in de Gracia et al. [13]. The sensors used for experimental validation purposes were the following:

- Indoor and outdoor air temperature (at a height of 1.5 m and 4.5 m) measured with ELEKTRONIK EE21.
- Air temperature of the cavity at different heights and locations (10 Pt-100 with an irradiative cover).
- Temperature of the PCM at three different heights (3 Thermocouples Type T, 0.5 mm thick inserted in the PCM panels).
- Horizontal and vertical global solar radiation measured with two Middleton Solar pyranometers SK08.