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A numerical study on the thermal performance of night ventilated hollow core slabs cast with micro-encapsulated PCM concrete

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ABSTRACT

This paper presents a numerical procedure for predicting the thermal performance of ventilated hollow core slabs (VHCS). The proposed approach is validated against experimental measurements available in the literature and then applied to study the effects of incorporating micro-encapsulated phase change materials (mPCM) in VHCSs for the cooling of office buildings. In particular, the impact of mPCM content, mPCM type (i.e. phase change temperature) and hollow core ventilation rates u_{in} on the slab's cooling potential is evaluated under two ideal room temperature cases. The first case reflects the behaviour of a high thermal mass building in which the high thermal mass enforces room temperature variations to be negligible. The second case imitates a low thermal mass building in which the room temperature is significantly affected by external temperature variations. It is assumed that the temperature responses within typical offices would fall between these two scenarios. The results indicate that, with the VHCS placed in a high thermal mass building, the use of the mPCM with a phase changing temperature of 20 °C (denoted by mPCM20) improves the cooling potential of the slab, regardless of the mPCM content (up to 20% incorporation) and the ventilation rate (up to u_{in} = 5 m/s). However in the low thermal mass building case, the best performing mPCM type depends on the ventilation rate (i.e. mPCM20 when $u_{in} \leq 2$ m/s, and mPCM19 – the mPCM with a phase changing temperature of 19 °C when u_{in} = 5 m/s) and is independent of the mPCM content.

1. Introduction

Under hot climatic conditions, mechanical cooling systems are widely used in buildings to maintain thermal comfort. The energy demand of such systems can be reduced drastically if the day time heat gain is removed by ventilating the building naturally using cold air at night [1,2]. The effectiveness of this strategy, often termed as night ventilation (NV), is largely dependent on the building's thermal mass structure or its thermal storage capacity [3].

Advanced fabric energy storage methods, such as ventilated hollow core slabs (VHCS), enhance the use of building thermal mass by increasing the contact between the ventilation air and the structure [4–7]. Recent studies show that phase change materials (PCM) also have the potential to increase building thermal mass with minimal impact on structural weight [8–12]. Since the application of these two technologies in buildings have proven to reduce energy requirements in cooling and heating applications, scope largely exists in quantifying and comparing the effect of integrating VHCSs with different PCM types and PCM content, on the system's overall thermal interaction with the ambience.

The concept of VHCS was proposed in the 1970s by Swedish engineers through a development called the TermoDeck system [13]. They identified that the parallel hollow cores in pre-cast structural hollow core slabs, when adjoined orthogonally at the ends, represented an ideal path for ventilation air flow, simultaneously aiding in the thermal coupling between the ventilation air and the concrete mass. In summer, night ventilation through the hollow cores significantly facilitates slab cooling, enabling it to act as a heat sink during daytime. Air supply to VHCSs typically involves a fan-assisted system to force external air through the hollow cores at speeds that ensure turbulence, in which case, heat storages between 10 and 40 W/m^2 of floor area can be attained [14,15]. The primary advantage of VHCSs is that it can make use of low operating temperatures to activate large amounts of thermal mass (concrete in this case), that would otherwise be unutilised in buildings, even though concrete responds rather slowly to internal cooling needs.

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Quicker thermal responses can be achieved with concrete elements when they are cast with PCMs such as organic paraffin waxes and fatty acids, which have substantially high latent heat values as they absorb (or release) large amounts of energy from (or to) the ambience during melting (or freezing) [16]. Direct integration of PCMs in concrete is achieved by micro-encapsulating them (referred to as mPCMs in this paper) in polymer shells that remain physically and chemically stable when the PCM undergoes phase change [11,17]. Since the thermal capacities of PCMs are variable over a range of temperatures (peaking at phase change), PCM integrated building elements tend to exhibit a dynamic thermal behaviour, and have the potential to improve the thermal stability of interiors under variable climatic conditions.

Several studies have been reported in the literature on direct integration of PCMs in concrete and cement mortars [8,9,18–20]. Based on experimental measurements, Hunger at al. [8] reported that integration of micro-encapsulated paraffin up to 5% by mass of self-compacting concrete increased the specific heat capacity of the resulting concrete by up to 350%, within the melting temperature range 23–26 °C, when compared to that of the reference concrete containing no paraffin. Using the mix designs of Hunger at al. [8], Entrop et al. [9] built concrete cubicles with paraffin integrated floors exposed to solar irradiation. The use of paraffin reduced the internal temperature fluctuations while decreasing the maximum floor temperatures by up to 16%. Gomez et al. [18] arrived at similar conclusions based on computational fluid dynamics (CFD) simulation of a concrete cubicle with PCM concrete walls exposed to environment. Pomianowski et al. [19] implemented a two-dimensional (2D) model of a thermally activated building system (TABS) element with a PCM concrete layer at the bottom surface in COMSOL Multi-physics program to evaluate the impact of using experimentally and theoretically determined thermal properties (of PCM concrete) on the slab's thermal performance. Given that the experimentally obtained properties were much lower than the theoretical predictions, significantly lower performance was observed when using experimental properties.

It is also common to integrate PCMs with building structures, for example covering building components with PCM layers or PCM wall boards [21–25]. Among these, Ascione et al. [22] performed dynamic energy simulations using EnergyPlus to determine the potential cooling energy savings associated with the addition of PCM plaster on the inner side of a building envelope subjected to Mediterranean climatic conditions. They found out that in reference to a case with no PCM, the addition of a 30-mm thick PCM plaster (melting at 29 °C) doubled the time period during which the internal temperatures remained within the desired comfort range. Biswas et al. [23] showed, through numerical simulations, that the use of nano-PCM wallboards can potentially reduce the heat gains and losses through a building envelope and result in reduced electricity consumption. On the other hand, Ling et al. [24] successfully applied PCM wall boards to improve the indoor thermal environment of greenhouses. Using the building simulation software EnergyPlus, Lei et al. [25] investigated the energy performance of a concrete cubicle with its walls layered with PCMs for cooling load reduction under the typical hot climatic conditions of Singapore. It was concluded that better performances are provided when PCMs are applied on the exterior wall surfaces than on the interior surfaces.

Other means of utilising PCMs in buildings include their incorporation in ventilated facades [26] as well as cross [27] and parallel [28] flow ventilation systems. Using a 2D CFD model of a ventilated façade that includes PCM inside its outer layer, Diarce et al. [26] found that the RNG k-ε model provides the best prediction of the air and PCM temperatures at turbulent air flow rates. Navarro et al. [27] built a two storey cubicle with its upper and lower spaces separated by a VHCS, with its cores consisting of PCM filled aluminium tubes. This allowed direct cross-flow heat exchange between the inlet air from outdoor and the PCM such that the air exiting the hollow cores could be used to condition room spaces. It was found that, during a summer day when the slab inlet air temperature exceeded 28 °C, the temperature within the bottom space remained below 25 °C when the space was conditioned with the air exiting the hollow cores. Borderon et al. [28] used the energy simulation software TRNSYS and Matlab to model a house unit installed with a PCM/air system, consisting of 16 horizontal PCM layers (15 mm each) placed at air gaps of 10 mm for parallel flow ventilation under French climatic conditions. With this arrangement, the percentage of hours during which the room temperature exceeded 26 °C in the summer dropped to as low as 2.6%, while without the PCM/air system, this percentage exceeded 11.5%.

Over the past decades, a large body of research has been carried out to quantify the potential of VHCSs for improving indoor thermal comfort under hot climatic conditions [29–32,7]. Through a thermal model (called CBS-MASS), Zmeureanu & Fazio [29] showed that the peak indoor temperature in a Montreal office was 3 °C lower when VHCSs were used, compared to a case with conventional direct ventilation. Winwood et al. [30] used PHOENICS (a CFD program) to model a cooled VHCS with a sinusoidal inlet air temperature cycle. It was reported that the peak outlet air temperature was 3.5 °C lower than the peak temperature at the inlet. Through a dynamic thermal balance model implemented in Simulink, Corgnati & Kindinis [31] showed that the coupling of night ventilation with VHCSs could significantly reduce summer cooling loads while improving thermal comfort in Mediterranean climates. Gunay et al. [32] carried out a numerical study on the thermal responses of a room segment consisting of a VHCS. They found that the inclusion of mPCMs in the VHCS by 10% of the concrete weight allowed the thickness of the slab to be halved (from 300 mm to 150 mm) without significantly affecting the reduction and phase shift of the peak room temperature achieved with the original VHCS (i.e. with no mPCM). Using a 2D finite difference model of VHCSs embedded in a building envelope, Park & Krarti [7] carried out a parametric study to evaluate the performance of the slabs under various design and operating conditions. It was found that, in cooling operations, the average heat transfer rate on the slab surface showed a negative correlation to both the inlet air temperature and the depth of hollow core embedment, while a positive correlation was observed to both the air mass flow rate and the contact area of the hollow cores. Despite the cooling advantages associated with VHCS, substantial work is still needed to enhance the thermal performance of VHCSs in order to significantly reduce energy bills under hot weather conditions, as also pointed out recently by Xu et al. [33].

While the above literature study indicates that both VHCSs and mPCMs have the potential to reduce the internal cooling energy requirements in buildings, past studies have generally considered the individual applications of these two technologies. As such, scope exists towards the combination of these two technologies to further improve the energy performance in buildings under hot climatic conditions. In this context, this paper aims to study the possibility of improving the thermal performance of VHCSs with the use of PCMs. The VHCS application strategy assumed here involves the cooling of VHCSs via night ventilation with cold air (through the hollow cores) such that the nightly cooled slabs can act as heat sinks for the room spaces during the day time when the hollow core ventilation is switched off. In this study, a numerical procedure suitable for modelling the thermal performance of a complete three-dimensional (3D) VHCS unit is described. The turbulence within the hollow cores is modelled using the Standard k-ε model [34] (as implemented in the CFD code ANSYS Fluent 14). The numerical approach is validated against experimental measurements available in the literature and then applied to study the effects of incorporating micro-encapsulated phase change materi-