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EXPERIMENTAL STUDY OF ACTIVE SLAB WITH PCM DURING SUMMER PERIOD

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Abstract

Energy consumption in buildings has become an important part of the global energy consumed in Europe and it is mainly related to HVAC systems. Moreover, the implementation of cooling systems is increasing which causes problems in the electricity grid. Therefore, it is crucial to reduce the energy consumption which can be achieved by decreasing the energy demand or/and improving the efficiency of the cooling systems. In this study, an innovative technology for heating and cooling application in buildings is presented. The experimental set-up of Puigverd de Lleida (Spain) allocates two house-like cubicles, one with a conventional slab and the other one with an active slab. The target is to use the internal slab as a storage unit by incorporating phase change material in order to increase the heat storage capacity. The operational summer mode consists of solidifying the PCM with the outer cool air during the night-time. Then the cold is stored inside the slab for covering a later cooling demand. Moreover, a solar air collector has been installed in the South facade of the cubicle to act as a heat source during winter season. The hot air provided by the air collector is directly pumped to the inside of the slab in order to melt the PCM. Thus, the slab becomes a heat storage component and when heat supply is required, the heat stored is used to cover the demand. Experimental analysis will demonstrate the potential of the technology for heating and cooling purposes and the need of a control strategy to optimize the operational principle.

Key-words: phase change material, cooling system, heating system, hollow core slab, experimental study.

1. Introduction

It is well known that energy consumed by the HVAC systems in buildings represents an important part of the global energy consumed in Europe. That is the reason why the Horizon 2020 European framework reflects the necessity of a reduction on the energetic consumption and consequently, the greenhouse gas emissions. Moreover, the comfort parameters are becoming stricter because of the high requirements from the users, especially in summer. According to the Energy Performance of Buildings Directive (2010/31/EU), the installation of air-conditioning systems has increased significantly in the European countries. That causes problems at peak load times such as, increasing the cost of electricity, and disrupting the energy balance.

Latent heat storage has been widely studied for its potential in many applications for building energy management, thermal energy storage and thermal inertia enhancement (Cabeza et al. 2011). Many researchers have focused their studies on the energy demand reduction improving the building envelope with the addition of phase change materials (PCM). Using passive solutions such as increasing the thermal inertia of the constructive systems could provide more stable internal conditions to the whole building and therefore, a reduction on heating and cooling demand (Zhou et al. 2012, Zalba et al. 2003). On the other hand, improvements on HVAC systems efficiency have been also studied in order to achieve a direct reduction on the final energy consumption.

Moreover, new technologies that have an active charge and passive discharge have been incorporated in last decades in public or offices buildings as substitution of the conventional HVAC systems. The TermoDeck system (Barton et al. 2002) and the thermally activated building systems (Pomianowski et al. 2012) are some examples of these alternative systems. The common property of these systems is the active charge of a

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building component (wall, floor, and ceiling) for a later passive discharge which gives stable comfort conditions to the building.

The new technology presented in this paper is designed to cover completely or partially the cooling and heating demand of a building. A structural component of the building is used as a storage unit with an active charge and discharge process for covering the energy demand of the building. The novelty of the system is the inclusion of phase change materials (PCM) inside the storage unit in order to increase the heat storage capacity.

2. Experimental set-up

In the experimental set-up located in Puigverd de Lleida (Spain) several house-like cubicles were built to study different constructive systems and materials. One of these cubicles has an internal slab separation with a prefabricated concrete plate of 30 cm thickness where the PCM is incorporated inside its hollows.

2.2. Description of the active slab

In order to distribute the air throw the internal channels of the slab, an air duct installation is implemented as shown in Figure 1. Depending on the operational mode, six gates are actuating to take air from outdoors or indoors which gives versatility to the system.

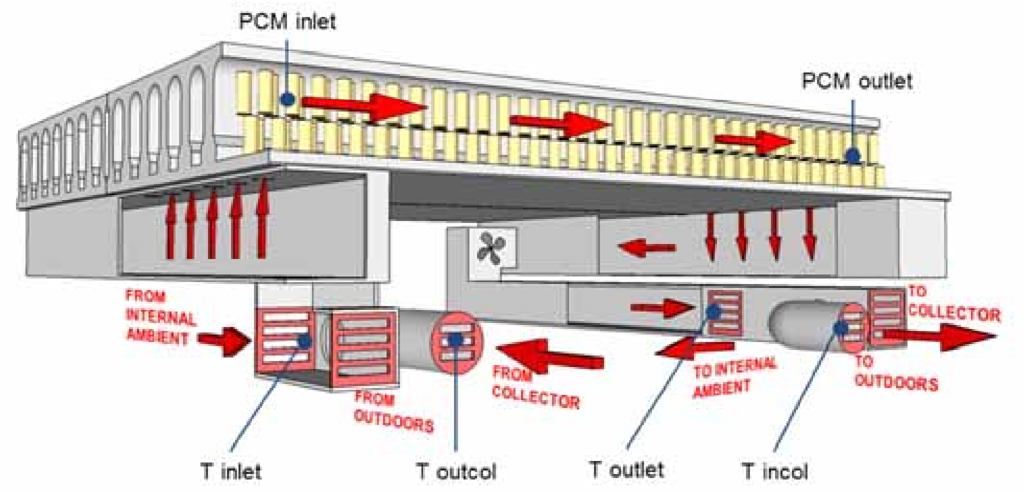

Fig. 1: Scheme of active slab operation

The PCM used in this application is commercial paraffin, RT-21, macro-encapsulated in aluminium tubes of 115 mm of height and 25 mm of diameter (Figure 2). A total amount of 52 kg of PCM is placed in a mesh of these tubes. The cross flow distribution of the tubes enhances the heat transfer between the PCM and the air.

Fig. 2: Incorporation of PCM macro-encapsulated in aluminium tubs inside concrete slab

3. Operational principle

3.1. Winter mode

In the winter season (Figure 3), in order to melt the PCM, a solar air collector is installed in the South facade of the cubicle, where the outside air is heated by the solar radiation and then injected to the inside of the slab. The system works as a heating supply having stored the solar energy from the solar air collector. During the day time, when a heating demand is needed, the air of the internal ambient is pumped through the hollows of the slab and the heat exchange with the PCM provides the heat needed to cover the demand.

Due to the versatility of the system, the heat can be supplied either during the melting process, taking advantage of the temperature of the air at the outlet of the slab, or in later hours using the storage capacity of the PCM in the slab. Furthermore, several cycles of charging and discharging of the PCM could be done during the same day and, therefore, increasing the storage potential of the system.

Moreover, a recirculation mode could be programmed to inject the air coming from the outlet of the slab to the air collector. Thus, the air could achieve a higher temperature and it could provide a good solution for days with low solar radiation values.

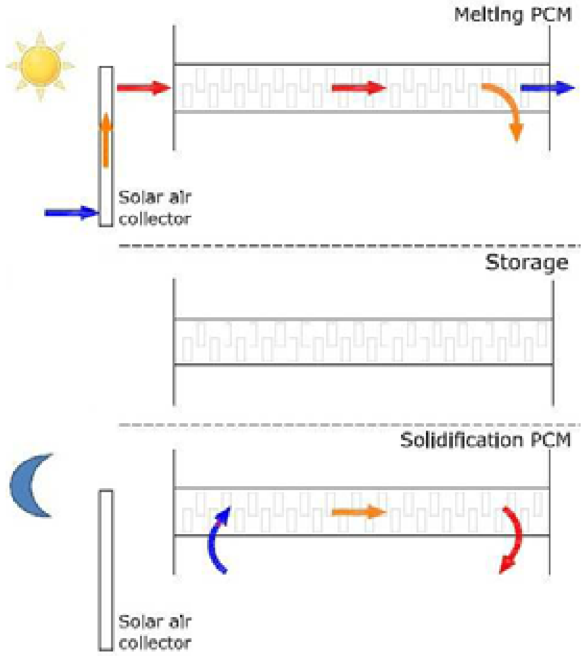

Fig. 3: Operational principle of the active slab during winter period

3.2. Summer mode

On the other hand, the operational mode in the summer season (Figure 4) is based on night free cooling. When the external temperatures are below the phase change temperature (20 ºC) the outside air is injected inside the slab and the PCM is solidified. The storage period starts when the temperatures start to rise up and the PCM is completely solidified. During the day, when a cooling demand is needed, the internal ambient air from the cubicle is pumped through the slab and cooled down till 20 ºC due to the heat exchange with the PCM, covering part of the cooling loads.

At night and during the solidification process of the PCM, the air could also be used to cool down the internal temperature of the cubicle. Unlike in winter mode, during the summer season the PCM can only provide one cycle of cold storage a day.

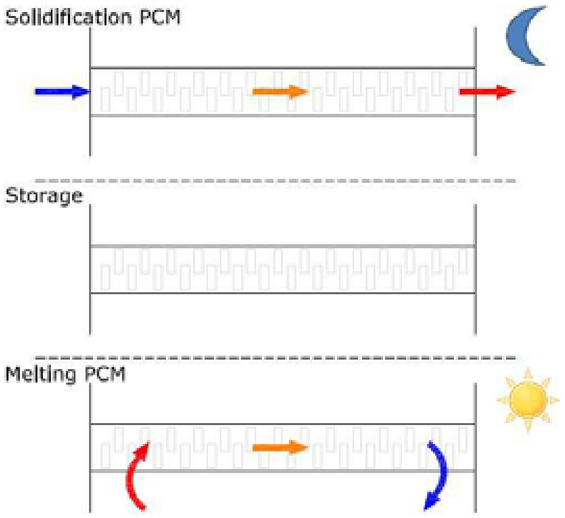

Fig. 4: Operational principle of the active slab during summer period

4. Methodology

The experiments presented in this paper were designed to test the system concept as well as to analyse the melting and solidification process of the PCM. For this reason, the system operates under the following operational schedule during winter period:

- Winter charging period: From 10:00 to 18:00. Air circulates through the solar air collector in order to absorb heat from solar radiation. The hot air is pumped through the inside of the concrete slab and returned again into the collector. During this period the PCM is melted.
- Winter discharging period: From 18:00 to 10:00. Once there is no incident solar radiation, air is circulated from indoors to indoors. The system discharges the stored heat in order to provide a heat supply to the inner environment.

On the other hand, in the experiments performed under summer conditions the active slab had the schedule described below:

- Summer charging period: From 00:00 to 07:00. Outside air circulates through the hollows of the slab, in order to solidify the PCM.
- Summer storage period: From 07:00 to 11:00. Active slab is not working actively. Outside temperatures are not low enough to charge the PCM and no cooling supply is needed.
- Summer discharging period: From 11:00 to 18:00. During daytime, when temperatures are higher, air is circulated from indoors to indoors. The cold stored in the slab is discharged to the internal environment providing a cooling supply. During this process the PCM is melted.

In order to quantify the amount of energy stored and released from the system, an energy balance between inlet and outlet temperatures is performed. Two different parameters have been described to evaluate the efficiency of the technology during charging and discharging processes. The charge efficiency (εcharge) for winter conditions is described in Eq. (1) as the ratio between the energy injected by the collector (Qcol) and the energy received by the slab (Qcharge):

$$\varepsilon_{charge} = \frac{Q_{charge}}{Q_{col}} \qquad \text{(eq. 1)}$$

where,

$$Q_{charge} = A_{duct} \cdot \rho_{air} \cdot Cp_{air} \cdot \int_{t_{i.ch}}^{t_{e.ch}} v_{air} \cdot \left(T_{inlet} - T_{outlet}\right) \cdot dt \qquad \text{(eq. 2)}$$

$$Q_{col} = A_{duct} \cdot \rho_{air} \cdot Cp_{air} \cdot \int_{t_{i.ch}}^{t_{e.ch}} v_{air} \cdot \left(T_{incol} - T_{outcol}\right) \cdot dt \qquad \text{(eq. 3)}$$

Moreover, the discharge process is also analysed by the parameter (εdischarge) defined in Eq. (4). This parameter is used to define a performance coefficient of the technology during winter and summer periods, and is defined by the amount of energy used to cover the heating/cooling demand (Qdischarge) and the energy that has been charged to the slab (Qcharge):

$$\varepsilon_{discharge} = \frac{Q_{discharge}}{Q_{charge}} \qquad \text{(eq. 4)}$$

where,

$$Q_{discharge} = A_{duct} \cdot \rho_{air} \cdot cp_{air} \cdot \int_{t_{i.dis}}^{t_{e.dis}} v_{air} \cdot \left(T_{outlet} - T_{inlet}\right) \cdot dt \qquad \text{(eq. 5)}$$

5. Results

The operating principle of the active slab system was tested under winter and summer mode in order to evaluate its performance under real conditions.

5.1. Winter experiments

Four consecutive experiments are presented to show the performance of the slab during mild winter conditions. During these four days outside temperatures fluctuated between 1 ºC and 20 ºC. The daily global radiation incident on the vertical surface was around 25 MJ/m^2.

Figure 5 shows temperature evolution of a sunny day experiment. During the charge period, temperature (T inlet) of the air at the inlet of the slab which comes from the solar air collector has a thermal evolution dependent on the solar radiation. Moreover, PCM temperatures plotted in Figure 5 belong to two different points of the slab (inlet and outlet), hence, the melting rate shows different behaviour. While PCM located at the inlet part is fully melted, the one at the outlet is just inside the phase change range at the end of the charge period. In addition, air temperature (T outlet) supplied was over 18 ºC during all the discharge period, which resulted in having an internal ambient temperature above 18ºC almost during 12 hours.

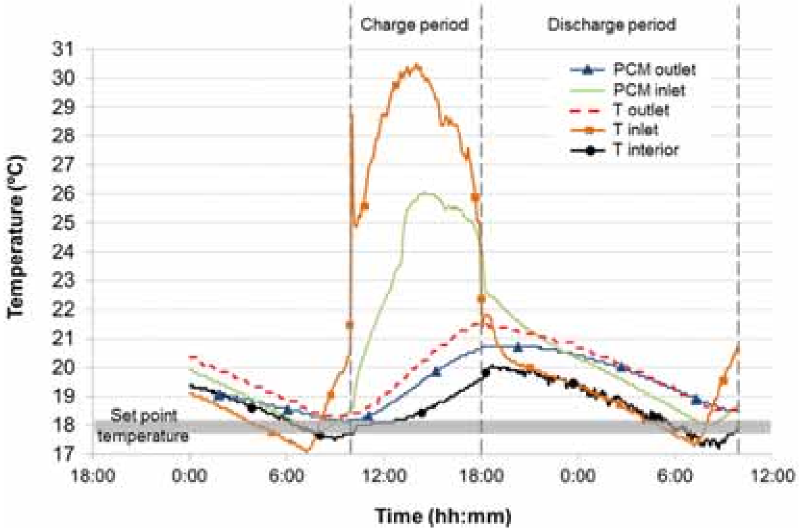

Fig. 5: Daily temperature evolution (winter day 2, March 2014) of the active slab

On the other hand, Figure 6 presents an experiment with cloudy conditions if compared to the one presented before. This fact is reflected in the air inlet temperature during the charge period however, PCM inlet was melted but again PCM outlet did not. In spite of this, the heating supply provides energy to keep the internal ambient temperature above 18 ºC during 9 hours of the discharge period.

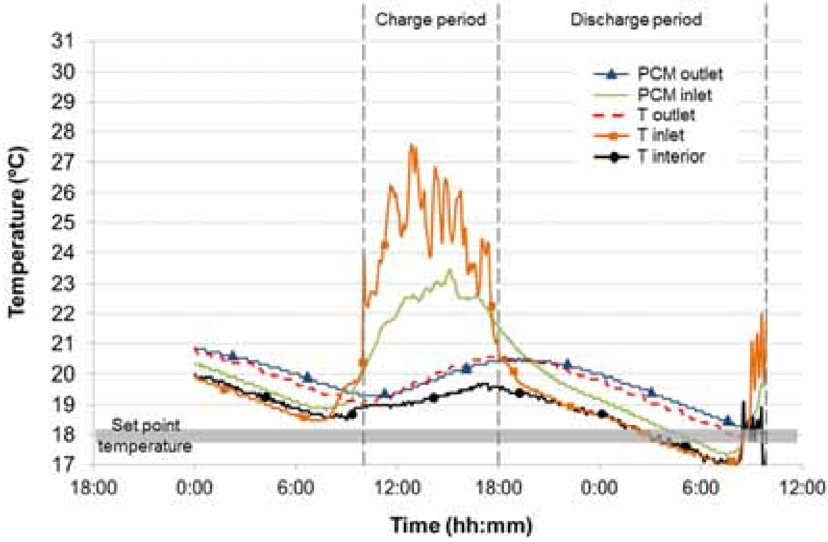

Fig. 6: Daily temperature evolution (winter day 4, March 2014) of the active slab

Table 1 shows the energy values of the charge and discharge processes, as well as the energy received by solar radiation in the solar air collector surface and the energy injected in the slab. The charge efficiency (ε_{charge}) of the first three experiments is around 73% while the last experiment has an efficiency of 64%. This ratio indicates the energy stored by the slab and also the energy lost (28% - 36%), both through the air ducts when the air is flowing from the collector to the slab and from the slab itself to the cubicle. In this case, a part of the energy losses become direct passive energy gains since the duct installation is located inside the cubicle and most of the heat losses from the slab are also to the internal ambient air, contributing to its heating.

Table 1. Charge and discharge energy of the Active slab.

March	Solar Radiation Energy (MJ)	Energy Injected (MJ)	Energy Charged (MJ)	Energy Discharged (MJ)	ε_{charge} (%)	$\varepsilon_{discharge}$ (%)
Winter day 1	34.86	16.34	11.99	8.80	73.4	73.4
Winter day 2	35.64	18.36	13.56	8.99	73.9	66.3
Winter day 3	32.45	15.96	11.42	8.03	71.6	70.3
Winter day 4	26.65	10.02	6.43	8.97	64.2	139.5

5.2. Summer experiments

Preliminary results have been analysed from the experimental campaign of summer 2014. Maximum outside temperatures during these experiments were between 36 ºC and 32 ºC, while minimum temperature were around 14 ºC. Solar global horizontal radiation had maximum values around 950 W/m2.

Temperature evolution of the slab during a daily experiment is presented in Figure 7. Air inlet temperature drops to 16 ºC at the end of the charging period providing cold for the PCM solidification process. At this point, PCM at the inlet is completely solidified, but the one at the outlet did not. During the storage period (from 07h to 11h) PCM inlet temperature rises up 1 ºC which means there is absorption of heat (losses of cold energy stored). Nevertheless, the heat absorbed comes from the internal ambient due to the integration of the slab inside the building, providing a passive cooling supply. This fact is reflected in the interior temperature which decreases during the storage period.

Moreover, once the PCM inlet is fully melted in the discharge period, the air at the outlet of the slab (T outlet) is not able to cool down the internal ambient (T interior). In spite of this, internal ambient temperature was kept under 26 ºC during all day without any conventional cooling system, just with the active slab supply.

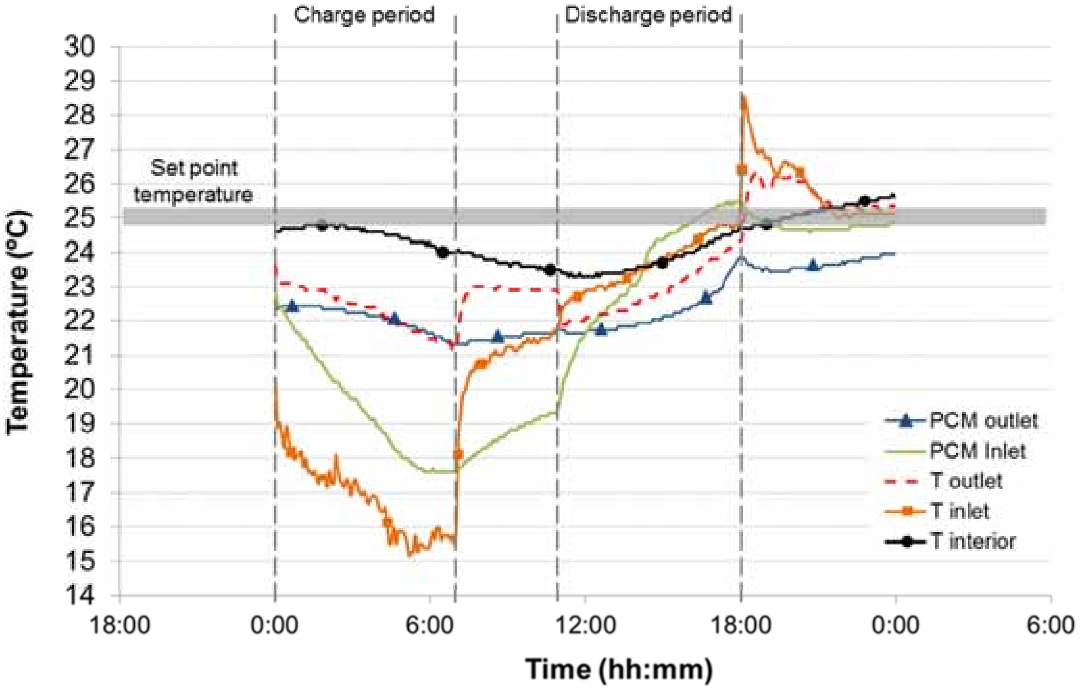

Fig. 7: Daily temperature evolution (summer day 1, June 2014) of the active slab

Energy values during the charge and discharge period are presented in Table 2. During these experiments, discharge efficiency values are quite low, oscillating from 17% to 6%. An important part of the energy charged during night time is lost in the storage period. However, as it was previously mentioned, since the storage system is located inside the building cold losses are contributing to cool down the internal ambient and the storage period becomes a passive cooling period.

Table 2. Charge and discharge energy of the active slab.

June	Energy Charged (MJ)	Energy Discharged (MJ)	$\varepsilon_{discharge}$ (%)
Summer day 1	9.00	1.39	15.5
Summer day 2	8.83	1.49	16.9
Summer day 3	10.50	1.03	9.8
Summer day 4	7.73	0.44	5.7

6. Conclusions

An innovative active slab system consisting of a concrete slab with PCM inside its hollows was presented in this paper. The technology design allows the use of the slab as a thermal storage system integrated inside the building structure as well as a heating and cooling supply. A prototype was installed in a house-like cubicle at the experimental set-up of Puigverd the Lleida (Spain) where first tests were carried out under real conditions. The concept was tested under winter and summer conditions, where the charging and discharging processes were analysed.

During winter period, the active slab is able to charge 70% of the energy injected by the solar air collector. Moreover, the discharge efficiency varies between 66% and 73% which means an injection of energy between 8 MJ/day and 8.9 MJ/day for space heating.

On the other hand, summer experiments showed low discharge efficiencies. Even though the amount of energy charged were around 8 MJ to 10 MJ per day, the discharge efficiency values did not overcome 15%.

In both winter and summer mode energy losses were registered during charge or storage periods. An important part of the energy lost through air ducts or convection in the same slab, became direct energy gains (heating or cooling) to the internal ambient, since the system is integrated in the building.

The potential of the system to store and provide heating and cooling supply has been demonstrated. However, it should be taken into account that the operational profile of these experiments was designed to assess its potential. The charge and discharge processes should be well determined in order to maximize the efficiency of the technology. A control unit is programmed for further experiments to control the system depending on the weather and the energetic requirements.

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Nomenclature

A_{duct}	Sectional area of the air duct [m^2]
Cp_{air}	Air heat capacity [$J \cdot kg^{-1} \cdot K^{-1}$]
Q_{charge}	Total stored heat in the active slab [J]
Q_{col}	Total injected heat supplied from the solar air collector [J]
$Q_{discharge}$	Total provided heat by the active slab [J]
T_{inlet}	Temperature at the inlet of active slab [K]
T_{outlet}	Temperature at the outlet of active slab [K]
T_{incol}	Temperature at the inlet of the solar air collector [K]
T_{outcol}	Temperature at the outlet of the solar air collector [K]
$t_{i.ch}$	Time start of charge process [s]
$t_{e.ch}$	Time end of charge process [s]
$t_{i.dis}$	Time start of discharge process [s]
$t_{e.dis}$	Time end of discharge process [s]
v_{air}	Air velocity [$m \cdot s^{-1}$]

Greek symbols

ρ_{air}	Air density [$kg \cdot m^{-3}$]
ε_{charge}	Charge efficiency
$\varepsilon_{discharge}$	Discharge efficiency