Universitat de Lleida

Thermal energy storage in buildings through phase change materials (PCM) incorporation for heating and cooling purposes

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PhD Thesis

Thermal energy storage in buildings through phase change materials (PCM) incorporation for heating and cooling purposes

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Thesis submitted to qualify for the degree of Doctor of Philosophy at the University of Lleida (PhD Program in Engineering and Information Technologies)

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Thermal energy storage in buildings through phase change materials (PCM) incorporation for heating and cooling purposes

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CERTIFIQUEN:

Que la memòria “Thermal energy storage in buildings through phase change materials (PCM) incorporation for heating and cooling purposes” presentada per Lidia Navarro Farré per optar al grau de Doctor s’ha realitzat sota la seva supervisió.

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Resum

El sistemes de calefacció i refrigeració representen dos terços del consum final d'energia en els edificis de la Unió Europea, per tant la reducció del consum energètic d'aquests sistemes és un repte fonamental a assolir. Durant aquests últims anys, els edificis d'energia nul·la i quasi nul·la s'estan popularitzant en el sector de l'edificació amb la corresponent aparició de noves tecnologies moltes d'elles centrades en diferents aplicacions d'emmagatzematge d'energia tèrmica.

L'emmagatzematge d'energia tèrmica en edificis es pot implementar com un sistema passiu en l'envolvent dels edificis, o com una unitat d'emmagatzematge actiu acoblat a sistemes de climatització. Un dels objectius d'aquesta tesi doctoral és revisar les aplicacions passives i actives d'emmagatzematge d'energia que es troben en la literatura, especialment aquelles que aprofiten la calor latent a través de l'ús de materials de canvi de fase (PCM).

Quant a les aplicacions passives d'emmagatzematge d'energia tèrmica, l'ús de materials de canvi de fase (PCM) en l'envolvent de l'edifici ha estat àmpliament estudiat. No obstant, en la majoria d'estudis, els requeriments de confort i les condicions climàtiques són els principals paràmetres que es tenen en compte. Per aquest motiu s'estudia experimentalment la influència de les càrregues internes en el comportament de tancaments amb PCM.

D'altra banda, en relació als sistemes actius d'emmagatzematge tèrmic, es presenta un sistema innovador que consisteix en un forjat alveolar de formigó prefabricat amb PCM dins dels seus alvèols. El forjat es presenta com una unitat d'emmagatzematge tèrmic i a la vegada un sistema de calefacció i refrigeració. El rendiment tèrmic d'aquest sistema s'analitza teòricament i posteriorment es testeja sota condicions reals. A més, s'avalua el potencial que té el sistema per reduir el consum d'energia de calefacció i refrigeració gràcies al sistema de forjat actiu.

Resumen

Los sistemas de calefacción y refrigeración representan dos tercios del consumo final de energía en los edificios de la Unión Europea, por lo que la reducción de su consumo energético es un reto fundamental. Durante estos últimos años, los edificios de energía nula y casi nula se están popularizando en la edificación, con la aparición de nuevas tecnologías centradas en diferentes aplicaciones de almacenamiento de energía térmica. El almacenamiento en edificios se puede implementar como un sistema pasivo en el envolvente de los edificios, o como una unidad de almacenamiento activo acoplado a sistemas de climatización. Uno de los objetivos de esta tesis doctoral es revisar las aplicaciones pasivas y activas de almacenamiento de energía térmica, especialmente aquellas que aprovechan el calor latente a través del uso de materiales de cambio de fase (PCM).

En cuanto a las aplicaciones pasivas de almacenamiento de energía térmica, el uso de PCM en la envolvente del edificio ha sido ampliamente estudiado. Sin embargo, en la mayoría de estudios, únicamente se tienen en cuenta los requerimientos de confort y las condiciones climáticas. Por este motivo se estudia experimentalmente la influencia de las cargas internas en el comportamiento de cerramientos con PCM.

Por otro lado, en relación a los sistemas activos de almacenamiento térmico, se presenta un sistema innovador que consiste en un forjado alveolar de hormigón prefabricado con PCM dentro de sus alveolos. El forjado se presenta como una unidad de almacenamiento térmico y a su vez un sistema de calefacción y refrigeración. El rendimiento térmico de este sistema se analiza teóricamente y posteriormente se testea bajo condiciones reales. Además, se evalúa el potencial que tiene el sistema para reducir el consumo de energía de calefacción y refrigeración gracias al sistema de forjado activo.

Summary

Space heating and cooling in the building sector account for two thirds of the final energy consumption in the European Union (EU). Therefore, the energy reduction of the HVAC systems is critical to achieve the Horizon 2020 agreement. Last decades, zero and nearly zero energy buildings are becoming popular in the building sector, hence new technologies are emerging to achieve energy savings, especially different thermal energy storage (TES) applications.

TES in buildings can be applied as a passive system in building envelopes to reduce the energy demand or as an active storage unit coupled to heating ventilating and air conditioning (HVAC) systems, ventilation equipment or domestic hot water (DHW) facilities. One of the objectives of this PhD thesis is to review the passive and active TES applications found in the literature, especially the ones that take advantage of the latent heat storage by the use phase change materials (PCM).

Regarding the passive TES applications, the use of phase change materials in the building envelope has been widely studied. However, the comfort requirements and the weather conditions are mostly the main parameters that are taken into account in the research studies. In this PhD thesis the internal heat loads parameter is taken into account to see the influence in the PCM performance through experimental study.

On the other hand, concerning to active TES systems, an innovative system of concrete slab with PCM inside its hollows is presented as a storage unit and a heating and cooling supply. The thermal performance of this system is theoretically analysed and experimentally studied under real conditions. Also, the potential in reducing the energy consumption for heating and cooling of the active slab is evaluated.

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Nomenclature

A_{col}	Area of the solar air collector [m^2]
A_{duct}	Sectional area of the air duct [m^2]
A_{hollow}	Area of the hollow of the concrete slab in contact with the air [m^2]
Bi	Biot number $\left(=\frac{h \cdot r_0}{k_s}\right)$
cp_{air}	Air heat capacity [$J \cdot kg^{-1} \cdot K^{-1}$]
cp_s	Specific heat capacity PCM (solid phase) [$J \cdot kg^{-1} \cdot K^{-1}$]
DHW	Domestic hot water
DSF	Double skin facade
h	Heat transfer coefficient [$W \cdot m^{-2} \cdot K^{-1}$]
HVAC	Heating ventilation and air conditioning
I	Daily irradiance [$W \cdot m^{-2}$]
k_s	Thermal conductivity (solid phase) [W/m·K]
L_{pcm}	Latent heat of fusion [$J \cdot kg^{-1}$]
$m_{concrete}$	Total concrete mass [kg]
m_{pcm}	Total PCM mass [kg]
$\dot{m}$	Mass flow rate [$kg \cdot s^{-1}$]
$P_{available}$	Daily available power achieved from temperatures below 21 ºC [W]
$P_{concrete}$	Discharge power of the concrete slab [W]
$P_{required}$	Daily required power to solidify the PCM [W]
PCM	Phase change materials
$Q_{available}$	Energy available in the solar air collector [kWh]
Q_{charge}	Total stored heat in the active slab [J]
Q_{col}	Total injected heat supplied from the solar air collector [J]
$Q_{concrete}$	Energy stored by the concrete slab [Wh]

$Q_{discharge}$	Total provided heat by the active slab [J]
$Q_{loss.col}$	Energy losses during the charging period [J]
$Q_{loss.passive}$	Energy losses during the discharging period [J]
$Q_{required}$	Energy required to melt the total amount of PCM [kWh]
Q_{sol}	Total solar energy incident in the solar air collector [J]
$\dot{Q}_{glob\_rad}$	Incident vertical global solar irradiance [W·m^{-2}]
r_0	Cylinder radius [m]
Ste	Stefan number $\left(= \frac{cp_s \cdot \left(T_{i.pcm} - T_{\infty}\right)}{L} \right)$
$T_{av.out}$	Average outside temperature below 21 ºC [K]
$T_{e.concrete}$	Final temperature of the concrete [K]
$T_{e.air}$	Mean temperature of the air at the outlet of the hollow [K]
$T_{i.concrete}$	Initial average temperature of the concrete [K]
$T_{i.pcm}$	Initial temperature of the PCM [K]
T_{∞}	Internal ambient air temperature [K]
T_{pc}	Phase change temperature [K]
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]
$T_{interior}$	Temperature of internal ambient of the cubicle [K]
TES	Thermal energy storage
TCM	Thermo-chemical materials
$t_{av.out}$	Period of time where outside temperature is below 21 ºC [h]
$t_{i.ch}$	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·s^{-1}]

Greek symbols

ΔT_{ml}	Logarithmic mean temperature difference [K] $\left(= \dfrac{T_{e.air} - T_{\infty}}{\ln \dfrac{T_{i.pcm} - T_{e.air}}{T_{e.air} - T_{\infty}}} \right)$
α_s	thermal diffusivity in the solid phase [m^2·s^{-1}]
θ_m	Superheat parameter $\left(= \dfrac{T_{pc} - T_{\infty}}{T_{i.pcm} - T_{\infty}} \right)$
ρ_{air}	Air density [kg·m^{-3}]
ε_{charge}	Charge efficiency
$\varepsilon_{discharge}$	Discharge efficiency
ε_{col}	Solar air collector efficiency
$\varepsilon_{col.required}$	Solar air collector efficiency required

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1 Introduction

1.1 Energy overview of the building sector

The buildings sector consumes nearly one-third of global final energy consumption (Figure 1), making it responsible for about one-third of total energy-related carbon dioxide (CO_2) emissions [1,2].

Space heating in the European Union (EU) is the largest end-use in terms of final energy consumption, accounting for two-thirds of residential energy use and about 40% of services energy consumption (Figure 2). However, space heating demand registered considerable differences depending on the region. In colder climates, Nordic countries and some Eastern European states 65% of the total final energy demand in building could be attributed to space heating. On the other hand, in Mediterranean countries, space heating demand usually accounts for less than half of the building energy consumption [2].

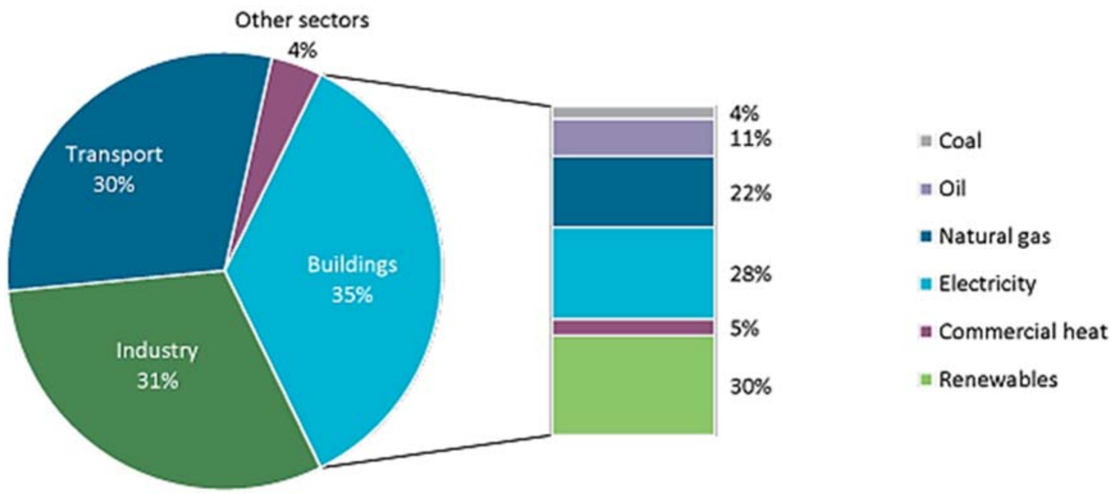

Figure 1. Final energy consumption by sector and buildings energy mix, 2010 [2]

Between 2000 and 2010 space cooling energy consumption increased in both the residential and services sub-sectors by nearly 60%. The higher comfort requirements and the recent rise in the number of air-conditioning systems in European countries are the main causes of this energy increase [3], resulting in a final energy use in buildings between 3% and 6%.

Due to these energy trends, the agreement of 20% reduction of greenhouse gas emission and energy consumption was expressed in the Horizon 2020 programme [4]. In this respect, the International Energy Agency (IEA) published the latest version of the Energy Technology Perspectives 2012 [5]. This document was written to identify how existing and emerging technologies can bring significant reductions in global CO_2 emissions.

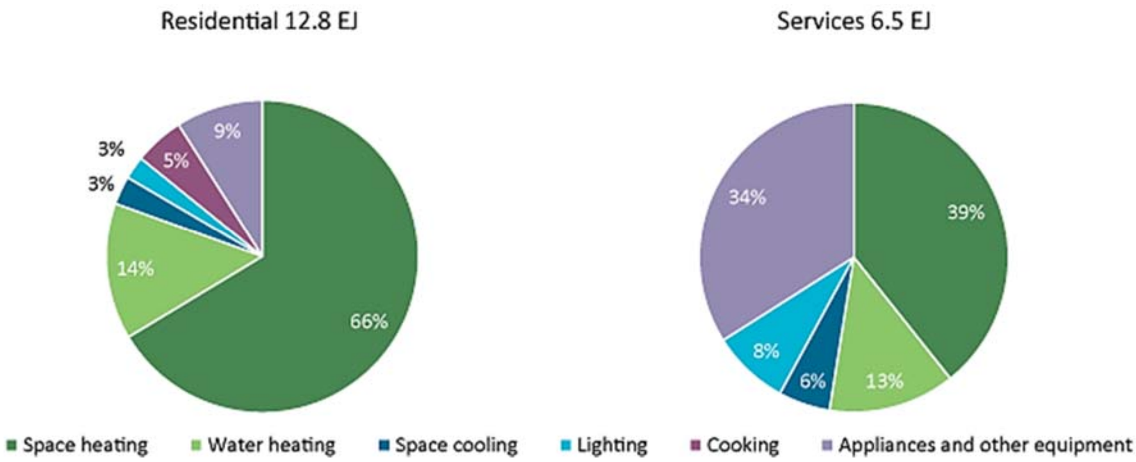

Figure 2. Residential and services sub-sectors energy consumption by end-use for EU in 2010 [2]

More than half of the current building stock in Europe will still be standing in 2050. The fact that most buildings last for decades should be taken into account by energy policy makers. The building stock is very long-lived, therefore, actions on appliances, equipment and systems are key to achieve CO_2 emissions reduction.

Energy demand in commercial and industrial sectors experience daily, weekly or seasonal variations. Thus, these demands can be matched with the energy supply through the help of TES systems. In last decades, researchers have claimed the importance of thermal energy storage (TES) technologies as a significant part to achieve more efficient systems. The developed TES techniques have large potential to make use of the thermal equipment more efficiently and to increase the energy storage capacity [6].

1.2 Thermal energy storage (TES)

Energy can be stored in different ways, but in most sectors energy is produced and transported as heat, hence thermal energy storage has high potential and efforts in its detailed study are warranted. Different thermal storage methods can be found depending on the process that is affecting the material or storage medium.

1.2.1 Sensible heat storage

Sensible heat storage is carried out when changing the temperature of a storage medium, without having a change in its phase in the storage process. The amount of heat that a sensible TES system can store depends on the temperature difference between the initial and final conditions, the mass of the storage medium, and its heat capacity [6], and can be expressed as:

$$Q = m \cdot c_p \cdot \Delta T \qquad \text{Eq. 1}$$

where, m is the mass of the storage material, c_p is the specific heat of the storage material, and ΔT is the temperature difference from initial to final conditions.

1.2.2 Latent heat storage

The latent heat is the energy absorbed or released by a substance when it changes from one phase to another. The latent heat change usually is much higher than the sensible heat change. During the phase changing process (Figure 3) the temperature remains constant at its so-called *phase change temperature* [7].

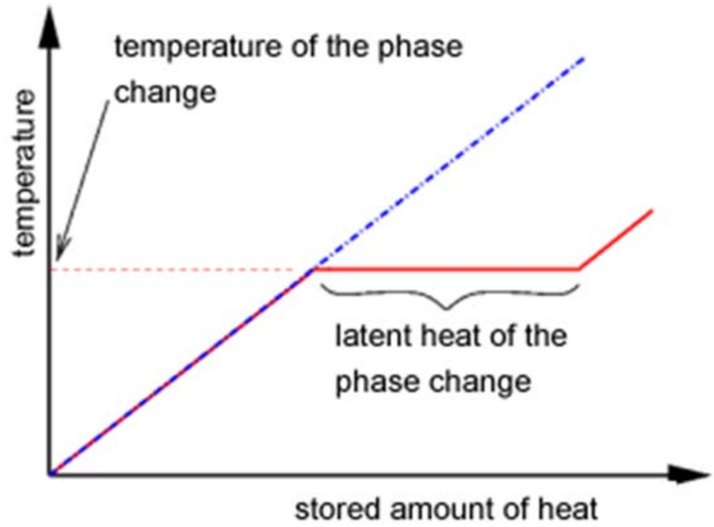

Figure 3. Thermal energy stored vs. temperature during a phase change

Three different phase changes are possible: solid-solid, solid-liquid, and liquid-gas. The solid-liquid phase change, apart from store large amounts of heat, is the most used phase change for TES applications because of the small volume change and consequently the small pressure change [7].

The energy density is drastically increased when phase change materials (PCM) are used. Having a phase change within the temperature range of the storage ($\Delta T=T_2-T_1$), the stored energy in a PCM can be calculated as follows:

$$Q_{latent} = \int_{T_1}^{T_{pcm}} \left(m \cdot C_{p,s} \cdot dT \right) + m \cdot H_{latent} + \int_{T_{pcm}}^{T_2} \left(m \cdot C_{p,l} \cdot dT \right) \qquad \text{Eq. 2}$$

where, Q_{latent} is the sensible and latent energy stored, $C_{p,s}$ and $C_{p,l}$ are the specific heat of the material at solid and liquid state respectively, and H_{latent} is the heat of fusion at the phase change temperature T_{pcm}.

1.2.3 Thermo-chemical energy storage

Thermochemical energy storage is based on reversible physical and chemical processes or reactions (Eq. 3) involving two substances named thermochemical materials (TCM). Endothermic processes absorb energy (heat), which can be stored as long as desired until the reverse (exothermic) process is forced. When the exothermic process takes place, the released heat can be then used for several applications.

$$A + Heat \leftrightarrow B + C \qquad \text{Eq. 3}$$

where, the heat is absorbed to transform the chemical *A* into two new chemicals, *B* and *C*. Hereafter, the two new chemicals must be stored in separate vessels at ambient temperature. Whenever the heat is required, chemical *B* reacts with chemical *C* to form the original chemical *A* and the stored heat is released.

Since the storage is based on the molecular bonds formation, the thermochemical energy storage is suitable for long-term storage or seasonal storage, keeping stored the heat from summer to provide heat during winter time. However, this technology has some limitations such as material development, reactor configuration and costs that should be addressed to be competitive with the other technologies.

1.3 TES applications in buildings

The potential of TES implementation in buildings is widely known as a technology to reuse waste energy, as a peak load shifting strategy or to overcome the mismatch between supply and demand among others [8]. Especially in the renewable energy implementation, TES offers the capacity to store thermal energy in off-peak load conditions to match the on-peak demand periods [9].

TES in buildings can be applied in passive systems acting as a delay of the peak heating or cooling demand, or working in active systems reducing directly the energy consumed by the HVAC systems or DHW facilities [10]. Moreover, the use of latent heat storage materials is of large interest because of the narrow temperature range where the PCM can store heat or cold with high storage density [7]. Therefore, PCM applications in buildings are expected to have large potential and many studies of PCM materials characterization and compatibility with building materials [11] have been carried out to provide wide information to building engineers and final users.

1.3.1 Passive TES systems

Most ancient thermal storage systems applied in buildings are the use of high inertia materials such as stone, rammed earth or adobe bricks. However, this method requires large wall thickness (more than 30 cm) which is not accepted in building sector nowadays. Thereby, PCM could be an alternative to these heavy walls by their inclusion in building envelope, having high storage density in much lower volume and increasing the thermal energy storage capacity in a specific thermal range. A state of the art of passive TES applications in buildings is presented in this thesis (chapter 4), focusing on the PCM incorporation.

Also the combination of the high thermal mass facade with solar energy, such as the Trombe wall system, has been widely studied as a potential passive heating system. And later on, by the incorporation of mechanical devices, these technologies increased their potential to reduce the energy consumed by the heating equipment.

1.3.2 Active TES systems

From an energy perspective, buildings are complex systems in which the interaction of technologies has almost always an influence on energy demand. It is well known that TES coupled with heating and cooling equipment will help to improve efficiency, to increase the implementation of renewables and to offer increased system flexibility [2]. But also, the implementation of TES in ventilations systems [12] and DHW facilities [13] are potential applications. The TES applications that have been incorporated in buildings as active systems are reviewed in this thesis (chapter 6).

1.4 GREA background on PCM in buildings

The GREA research group from the University of Lleida has wide experience on the implementation of latent heat storage materials in buildings acting as passive systems. They have tested phase change materials embedded in the building envelope as passive cooling systems in their experimental set-up located in Puigverd de Lleida (Spain).

In 2002, within the framework of a European Project (MOPCON), two house-like cubicles based on prefabricated concrete panels system were built in the mentioned facility [14]. One of them was enhanced with micro-encapsulated PCM inside the concrete mixture with a phase change temperature of 26 ºC. The latent heat of the PCM was used as a passive cooling protection from the high temperature peaks during summer season. The results obtained during this experimentation demonstrated that the concrete with PCM cubicle had lower amplitude in the internal ambient temperature oscillation and the maximum temperature peak was delayed two hours.

However, the main problem found when mixing micro-encapsulated PCM with the concrete is the effect on the mechanical properties [15]. Many studies investigated on the topic concluding that 5% by weight of concrete is the maximum practical content of micro-encapsulated PCM to be used in a concrete mix application [16,17]. This fact leads to a low presence of PCM in the concrete mixture and therefore a low influence on the thermal performance of this application.

Based on this finding, the macro-encapsulation of PCM was tested in Puigverd de Lleida facility, since it allows incorporating higher amount of PCM with no materials compatibility problems. In 2007, four cubicles were built to test the effect of PCM in brick construction systems [18]. Two of them were based on the traditional brick system, two layers of brick with an air chamber in between and 5 cm of insulation (Figure 4.up); the only difference between them is the inclusion of macro-encapsulated PCM (RT-27) in one of the cubicles. The PCM was encapsulated in aluminium panels and placed in Southern and Western walls, and the roof. The other two cubicles were built with alveolar brick system (Figure 4.down) and one of them was enhanced with PCM panels (SP-25).

In this way, a direct comparison was done on the temperature evolution and energy consumption of the cooling equipment. The results obtained from the experiments demonstrated that the PCM cubicles could reduce up to 15% their energy consumption compared to the cubicles without PCM during the cooling period.

The potential and contribution of the PCM as a passive cooling system in buildings was demonstrated by achieving significant energy savings and thermal comfort at building prototype scale. However, depending on the weather conditions some problems were observed when solidifying the PCM at night limiting the potential of the passive system in specific conditions.

Figure 4. Brick traditional system cubicles (up) and alveolar brick system cubicles (down)

With this background, an active TES application for buildings was decided to be tested in the experimental facility of Puigverd de Lleida (Spain). The use of PCM with an active solidification and melting could overcome the problems found in the passive applications. Therefore, in 2010, two double height cubicles were built to test a ventilated facade with PCM in the air chamber. In one cubicle the new concept was tested, while the other one acted as a reference (Figure 5). The double skin facade (DSF) was designed to work as a storage unit and a cooling and heating supply.

During winter, the facade works as a solar collector during daytime, melting the macro-encapsulated PCM. Then, the heat is stored in the facade until a heating supply is needed in the internal ambient. Results from winter campaign reflected the potential of the DSF by reducing the energy consumed by the HVAC system up to 19% and 26% compared to the reference cubicle, when programmed to maintain a set point of 21ºC and 19ºC, respectively [19].

Figure 5. Double skin facade with PCM (left) and double height reference cubicle (right)

On the other hand, summer operating mode solidifies the PCM through outside low temperatures at night. The PCM remains in solid state and once the cooling loads increase during daytime the cold is injected into the internal ambient of the cubicle. The results show that SP-22 as PCM limits strongly the possibility of using the system as cold storage because of its hysteresis (melting ~22ºC and solidification ~18ºC). Also the electrical savings achieved in the HVAC do not compensate the consumption of the fans. However, the system has high potential in providing night free cooling, and also in overheating prevention during peak load hours [20].

In this respect, some issues in the DSF concept could be improved, and a slab system based in the same concept was designed. The expected upgraded properties were the fact that with this new system the storage unit will be located inside the building; hence the heat losses or gains should benefit the internal ambient conditions.

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2 Objectives

The main objective of this PhD thesis is to study different PCM applications in buildings to reduce the energy consumed due to the heating and cooling equipment. Apart from a study of a PCM passive application in buildings, the analysis of a new active TES system consisting of a concrete slab with PCM macro-encapsulated inside its hollows is one of the highlights of this thesis. This innovative active TES system is studied to assess its potential in reducing heating and cooling energetic consumption. To accomplish the aforementioned objective, several specific objectives were specified:

- To review the passive thermal energy storage technologies used and applied in buildings.
- To continue with the analysis of a PCM passive system implemented in an experimental facility and tested under real weather conditions.
- To review the active thermal energy storage technologies used and applied in buildings, especially those which are integrated into the building structure or components.
- To analyse and evaluate theoretically the new TES active technology presented as active slab for reducing the energy consumption of the heating and cooling equipment.
- To test experimentally the active slab in summer conditions and to evaluate the potential on cooling demand reduction.
- To study experimentally the active slab coupled to a solar air collector as a heat storage unit and heating supply during winter season.

3 PhD thesis structure

The PhD thesis is based on six papers; all of them have been already published in SCI journals (Figure 6).

This PhD thesis is included in the thermal energy storage framework, specifically in buildings applications. A review of passive applications of TES in buildings is done in paper 1. Passive TES systems studied last years to reduce heating or cooling loads in buildings are reviewed. Also, a special focus on the latent heat storage materials is done as well as their incorporation methods and locations where the PCM was incorporated.

Related to passive TES systems, a continuing study of phase change materials (PCM) incorporation in building envelopes as a passive cooling system is done in paper 2. The effect of thermal loads coming from occupancy or equipment inside the building is studied in an experimental cubicle with PCM in the envelope. The most interesting aspect is the comparison between the PCM performance with and without thermal loads.

After seeing the limitations and the capacity of energy demand reduction of the passive TES systems, a step forward was done by the active TES systems review in paper 3. Some active or partially active systems are presented in the review with the particularity of being integrated in the building structure or in building components. The importance of this building integration is critical for users, and building designers acceptance.

Then, in paper 4, the proof of concept of a new technology that includes PCM inside the hollows of a concrete slab is presented as an active slab. The slab component acts as a storage unit and a heating and cooling supply, and the PCM provides high thermal storage capacity at a comfort temperature range.

The active slab is tested under real conditions in an experimental facility. A complete test campaign is performed under summer conditions and is presented in paper 5. The potential as cooling supplier is studied under different scenarios and compared to conventional cooling equipment.

Moreover, during winter season, the active slab is coupled to a solar air collector to store heat inside the concrete slab and then provide heating supply to the experimental cubicle. Paper 6 presents experiments to test the potential of the active slab for heating purposes and the energy consumption reduction arose from this new technology.

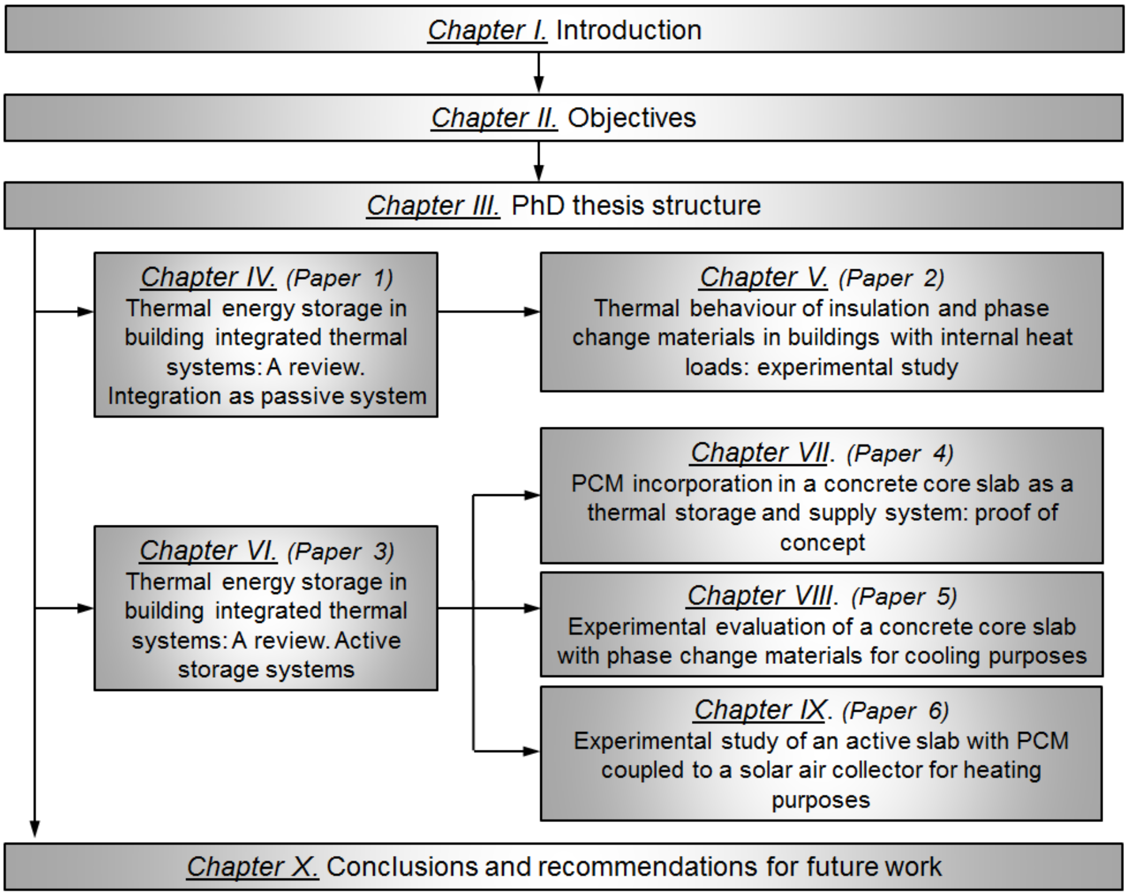

Figure 6. PhD structure scheme

4 Thermal energy storage in building integrated thermal systems: A review. Integration as passive system

4.1 Introduction

Energy trends in the building sector have dramatically increased the last decades. HVAC systems take part as a significant energy consumer accounting for 60% and 40% of the final energy use in residential and commercial buildings, respectively [1]. Therefore, the reduction of the energy demand and energy consumption of these systems is now identified as a priority need.

Nowadays, thermal energy uses in building sector play an important role, being around 60% in the residential and 50% in the commercial buildings [2]. This fact reported the importance of the TES (thermal energy storage) in buildings especially in renewable energy systems. A lot of work has been done on TES technology for energy reduction in building applications. However, the volume occupied and the space required in the building by these systems is still an important handicap. Therefore, the integration of thermal energy storage systems is of much interest to achieve a better acceptance of the technology.

This paper is focused on the passive thermal energy storage systems that are applied in buildings and at the same time become part of the building core (usually walls, ceiling or floor). A review of the studies published with these characteristics and a classification through their storage method and the location of the TES system was done in this paper.

4.2 Contribution to the state of the art

The aim of this paper was to review the studies where thermal energy storage passive systems were integrated in building components such as walls, ceilings or floors. Moreover, a classification was done taking into account the thermal energy storage method (sensible or latent) and the location where the passive storage system is placed.

The sensible TES passive applications in buildings are known as the traditional method used in houses to protect them from outdoor weather conditions. This paper presents studies of different high thermal mass materials, from the most traditional ones (stone or earth) to the contemporary ones (concrete or alveolar brick). Also the enhancement of these high thermal inertia systems was reviewed with solar walls applications.

Concerning the latent heat storage passive systems, this paper provides an overview of all the phase change materials (PCM) incorporation methods to construction materials. Pros and cons of each method are highlighted as well as the effect of the PCM incorporation into the properties of the construction materials.

On the other hand, studies of PCM applications as passive systems are reviewed and classified depending on the method used to incorporate the PCM, (inside the material or as a new layer in a construction system), and where the material is embedded. A summary table with performance and characteristics of systems integrating PCM as a new layer in the building envelope is provided in this paper.

Finally, although the different reviewed studies reflect quite disperse and not comparable results, this paper contributes to highlight the most relevant aspects and aims to be a guideline on TES incorporation into buildings as passive system. Also an overview is provided of the different methods, locations, and possible passive systems to provide energy savings through the integration of thermal energy storage systems in buildings, especially through latent heat storage materials.

4.3 Contribution of the candidate

This paper was done under the COST Action BISTS TU1205 framework. The candidate was proposed to lead a review on building integrated solar thermal systems (BISTS) which was directly related to her research topic.

The candidate defined the structure of the paper and proposed a list of references to review, which were later extended by the co-authors. In addition, the candidate led the sensible heat storage and passive applications in buildings of latent heat storage systems chapters.

The final writing was done by the candidate as well as the conclusions and the summarized performance and characteristics of the addition of PCM as new layer in Table 4.

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4.5 Journal paper

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Review

Thermal energy storage in building integrated thermal systems: A review. Part 2. Integration as passive system

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L. Navarro, A. de Gracia, D. Niall, A. Castell, M. Browne, S. J. McCormack, P. Griffiths, L.F. Cabeza. Thermal energy storage in building integrated thermal systems: a review. Part 2. Integration as passive system. Renewable Energy 2016;85:1334-56.

http://dx.doi.org/10.1016/j.renene.2015.06.064

5 Thermal behaviour of insulation and phase change materials in buildings with internal heat loads: experimental study

5.1 Introduction

It is well known that there is a high potential of energy savings when improving the building envelope. Thermal insulation, if well implemented, has been considered the most cost effective solution to protect the building from the external weather conditions. Whether in new or refurbished buildings thermal insulation can provide reasonable energy consumption with satisfactory thermal comfort conditions and low operational costs [1].

Many researches have published about thermal insulation guidelines or recommendations [2], optimum thicknesses and economic analysis [3], location of the insulation layer in facades [4], and its effect on energy consumption [5]. Although most of the building regulations were just taking into account the insulation thickness and thermal resistance to evaluate the thermal performance of building envelopes, thermal inertia was recently included. This fact is because in several research studies it was demonstrated that providing thermal inertia to the building envelope is also crucial in terms of energy demand reduction [6].

However, the main parameters that are taken into account in research studies when proposing new systems are the comfort requirements and the weather conditions, without considering the internal loads. Lighting, occupancy, and equipment are influencing in the heating and cooling demand and a different effect should be reflected depending on the building envelope properties.

Some studies stated that thermal insulation is more effective with high demand on external load protection than in buildings where internal loads are dominant

[7]. Others talked about the influence of thermal mass location in the envelope of a building with high internal heat loads [8]. But there is still a need for a detailed study of the influence of internal heat loads in the overall thermal performance of a building.

Taking as a reference previous studies [9] performed in the experimental facility of Puigverd de Lleida, the objective of this study was to analyse experimentally the influence of internal heat loads when insulation and phase change materials (PCM) are placed in the external walls of the buildings.

5.2 Contribution to the state of the art

This paper provides an experimental study in the facility of Puigverd de Lleida (Spain) during summer period. The testing presented in the paper shows the performance of three house-like cubicles with traditional brick system and the same dimensions. The difference between them is that one of them has no insulation (REF), another has 5 cm of Polyurethane (PU), and the last one has 5 cm of PU and macro-encapsulated phase change materials (PCM), with a melting temperature around 27 ºC (RT-27), on the internal face of the insulation.

Two types of experiments were performed: the free floating, without any cooling device, and the controlled temperature, where a set point temperature in the heat pump was fixed. In both type of experiments the internal loads were simulated using an infrared radiator with a timer that programmed an office profile scenario (9-14h and 16-19h).

The paper shows in the free floating experiments that the PCM cubicle had low dissipation of the internal loads. The internal heat gains as well as the heat coming from outside were absorbed and stored by the PCM. This fact led to higher internal ambient temperature in this cubicle compared to the Reference and PU ones.

The same happened during the controlled temperature experiments, where different set point temperatures were tested from 20 ºC to 29 ºC. In all of them the PCM cubicle consumed more energy from the heat pump than the PU one, because of the higher internal ambient temperature mentioned before. Moreover, results of experiments with set point temperatures of 20 ºC and 24 ºC were compared with previous studies [9] done in the same experimental set up but without internal heat loads. The PCM cubicle registered an improvement of 15% compared to the PU one in the test without internal loads, as it can be seen in Table 1. On the contrary, when internal loads were included in the experiments, the PCM did not provide any benefit comparing to the PU cubicle. In this last case, the PCM cubicle consumed 17% more energy than the PU one.

These results demonstrate that the inclusion of PCM into buildings envelope is not recommended for reducing summer peak temperatures in buildings with high internal loads unless a proper ventilation strategy can be programmed.

5.3 Contribution of the candidate

The experiments presented in this paper were planned by the research group as a further study on the passive PCM applications in buildings. When the candidate began the PhD, in order to start getting familiar to the PCM integration in buildings and its effect, the experiments presented in this paper were performed.

The data treatment, graphics, and analysis of the tests were also a task of the candidate as well as the writing of the scientific article.

Table 1. Comparison between experiments for cooling with and without internal heat loads

			Energy consumption (kWh)	Energy savings (%)[a]	Improvement PCM (%)[b]
SP 24 ºC	Internal loads	REF	9.2	0	-
		PU	5.58	39.30	0
		PCM	6.53	29.00	-16.98
	Without internal loads	REF	9.38	0	-
		PU	4.58	51.12	0
		PCM	3.91	58.33	14.75
SP 20 ºC	Internal loads	REF	22.19	0	-
		PU	17.61	23.63	0
		PCM	18.09	18.49	-2.70
	Without internal loads	REF	20.53	0	-
		PU	8.34	59.39	0
		PCM	8.03	60.89	3.71

[a] Compared to REF cubicle

[b] Compared to PU cubicle

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5.5 Journal paper

Energy Efficiency (2015) 8:895–904
DOI 10.1007/s12053-015-9330-x

ORIGINAL ARTICLE

Thermal behaviour of insulation and phase change materials in buildings with internal heat loads: experimental study

Lidia Navarro • Alvaro de Gracia • Albert Castell •
Luisa F. Cabeza

The pages 52 to 61 contain the article:

L. Navarro, A. de Gracia, A. Castell, L.F. Cabeza. Thermal behaviour of insulation and phase change materials in buildings with internal heat loads: experimental study. Energy Efficiency 2015;8:895-904.

http://link.springer.com/article/10.1007/s12053-015-9330-x

6 Thermal energy storage in building integrated thermal systems: A review. Active storage systems

6.1 Introduction

Since the targets of Horizon 2020 [1] were established, European Union's members had to adapt their building regulations to achieve energy efficiency improvements, to promote renewable energies and to reduce greenhouse gas emissions. Within this context, low energy and net zero energy buildings are becoming the tendency to follow in the building sector. The use of solar energy and other renewable energies in these buildings create the necessity of having also thermal energy storage systems, which improve the efficiency of these renewable technologies.

Building integration can be defined by the idea of a functional or construction incorporation of the technology in the building structure [2]. Therefore, as it was mentioned in chapter 4, the integration of these systems in the building is one of the aspects that researchers are taking into account to achieve a competitive technology for a future inclusion into the building sector. This involves especially the TES systems that work actively because the equipment that composes them usually needs significant amount of space and sometimes a special room to install them.

The aim of this paper is to identify TES systems integrated in the building as an active system and to classify them depending on the location where the storage is placed.

6.2 Contribution to the state of the art

The building integration of TES active system has not been widely considered but the review presents some of the studies done so far that include the integration characteristic.

A classification of the different TES technologies was done based on the location where the systems are integrated. Authors created Figure 7 to show the different building components that can hold the TES active systems.

First, building core activation technologies were defined as those systems that use building structure components (walls, ceiling or floors) as storage unit and for heating or cooling purposes. These components are usually high thermal mass materials such as bricks or concrete and some of them can be enhanced by the addition of phase change materials (PCM). Building core activation systems are demonstrated to be an interesting technology of TES integration for new construction. Moreover, ceiling and floor activation are usually exposed and hence are considered more appropriate than walls that can be covered by furniture and decoration. This fact becomes important in public or office buildings, where these systems can provide potential energy savings.

On the other hand, suspended ceilings are also used as active TES systems for heating or cooling. However, these systems have lower thermal storage capacity compared to the building core activation systems, since gypsum or metal panels are used in most cases. For this reason, the inclusion of PCM gives higher storage capacity to these panels and makes them interesting for building energetic refurbishment.

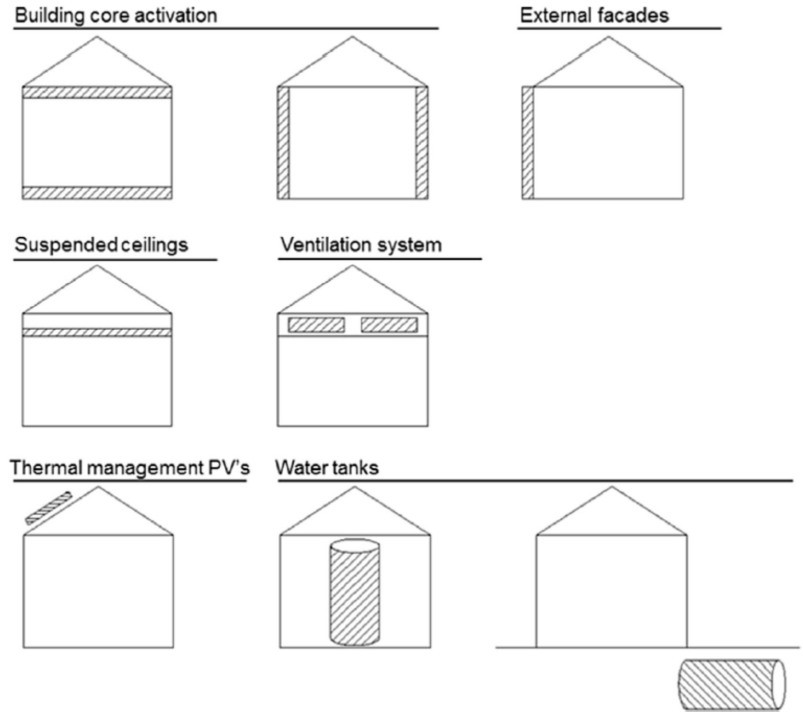

Figure 7. Thermal energy storage integration in buildings

External facades or ventilated facades, as well as the ventilation systems (air ducts or air handling units) which are usually found in large and office buildings were identified to have high potential for the integration of TES systems. In the case of ventilated facades, the combination of solar energy and TES was tested through sensible and latent heat methods, providing benefits during heating periods and dealing with overheating effect during hot periods. On the other hand, some commercial technologies that included the storage unit in the air handling unit were reviewed.

Other active applications of TES in buildings were found on thermal management of building integrated photovoltaic (BIPV) by combining them with PCM, and with the Trombe wall concept with mechanical ventilation.

Also, the paper presents some seasonal thermal water tanks coupled to solar systems for domestic hot water and heating applications. The main issue to highlight is their architectural integration; some of them were located in the stairwells of single houses and apartments building, and others as underground storage system in a single family house. The main drawback of these systems is the important required volume that require, so their integration had limited potential.

Finally in this paper, the candidate provides a summary table where the main properties that enclose the systems reviewed are presented. The location and climatic conditions where the study was performed, the application of the system and its description, and the building type are some of the aspects treated in the table.

6.3 Contribution of the candidate

This paper was done under the COST Action BISTS TU1205 framework. The candidate was proposed to lead a review on building integrated solar thermal systems (BISTS) which was directly related to her research topic.

The candidate defined the structure of the paper and proposed a list of references to review, which were later extended by the co-authors. In addition, the candidate led the building integration definition, building core activation, suspended ceilings, ventilation systems, TES into solar collectors, and TES for thermal management of building integrated photovoltaic chapters.

The final writing was done by the candidate as well as the conclusions and the summarized performance and characteristics of the active TES systems.

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6.5 Journal paper

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Review

Thermal energy storage in building integrated thermal systems: A review. Part 1. active storage systems

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http://dx.doi.org/10.1016/j.renene.2015.11.040

7 PCM incorporation in a concrete core slab as a thermal storage and supply system: proof of concept

7.1 Introduction

Nowadays, energy policies [1] and building regulations are determining new limits on the energy consumption in buildings. Therefore, low energy or zero energy buildings are becoming the target to achieve by the building stock. These new policies give importance to the research and development of technologies focused on reducing the energy demand and the greenhouse gas emissions [2], by promoting the use of renewable energies [3]. However, the mismatch between supply and consumption that characterize most renewable energies should be solved by a proper thermal energy storage system [4].

Relative to the aspects mentioned in chapter 6, the building integration of new technologies developed is a key aspect to achieve better acceptance by architects and engineers in order to be incorporated in the building designs. In this context, an innovative integrated active system is presented as a heating and cooling technology. A prefabricated concrete slab used as a thermal storage and energy supply system is presented in this paper. The concrete core slab is used as the storage unit by the incorporation of PCM inside its hollows. A proof of concept study is presented in this paper, having as a main objective to demonstrate that the PCM selection and the whole technology design has significant potential for both heating and cooling seasons.

7.2 Contribution to the state of the art

The innovative system, so-called active slab, presented in this paper consists of a prefabricated concrete component formed by 14 channels where the PCM is located (Figure 8). An air duct installation is implemented with 6 gates and a fan to allow the air flow into the channels of the concrete slab. The PCM (RT-21) is macro-encapsulated in aluminium tubs and fixed in wood structures following criteria of heat transfer enhancement between the air and the PCM in cross-flow.

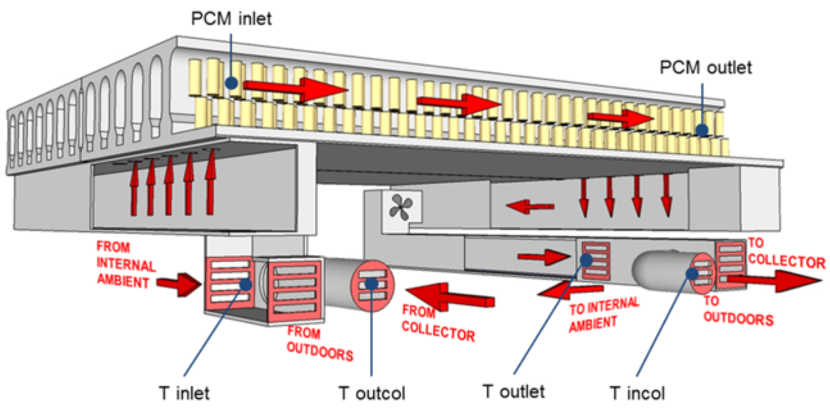

Figure 8. Scheme of the active slab prototype

As it was mentioned before, the system is designed to provide heating and cooling. The operational principle during summer season consists of the solidification of the PCM at night taking benefit of the low external temperatures. Once the PCM is solidified, the cold is stored inside the slab ready to cover the cooling loads that the internal ambient requires during the day. When cooling is required, the inner air is pumped into the hollows of the slab and a cooling supply is provided by the active slab. On the other hand, in winter period, a solar air collector located in the south facade is used to melt the PCM during the daytime. Then, the heating supply can be provided by pumping the internal ambient air through the slab and exchanging the heat stored in the PCM in liquid state.

The system potential, both in winter and summer modes was defined by some design parameters, being one of the most important the phase change temperature of the PCM. Therefore, the suitability of the phase change temperature of the PCM used against the climatic conditions of the experimental set-up where the prototype was tested (Puigverd de Lleida, Spain) were studied. For the summer conditions, the power achieved from night external temperatures below 21 ºC to solidify the PCM (Power available) was compared to the power needed by the PCM to be solidified (Power required). This comparison was represented in Figure 9 where in 68% of the summer days analysed from June to September, the power required was completely covered.

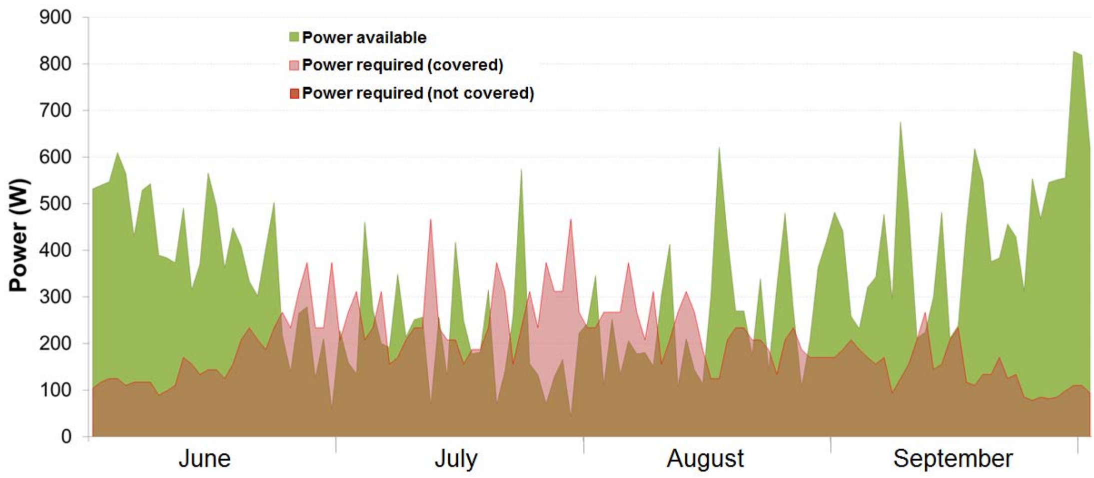

Figure 9. Power available and required to charge the PCM during summer season

On the other hand, in the winter season the solar radiation was taken into account to study the potential of energy availability to melt the PCM. Therefore, in Figure 10 the solar air collector efficiency needed to melt the PCM was calculated and represented, as well as the daily vertical solar irradiance. Figure 10 shows that a solar air collector efficiency of 30% was enough to cover the energy required during 85% of the winter days.

Furthermore, the active slab was installed in a house-like cubicle of the experimental set-up located in Puigverd de Lleida, Spain. In this paper, few experiments were programmed to evaluate the thermal storage capacity and storage efficiency of the active slab. Complete charge and discharge processes were set through a time schedule program for both winter and summer modes.

In the winter tests, the PCM was observed to provide a fast heating supply, while the concrete component contributed to extend the heating supply by its slow discharge of the energy stored. Furthermore, low discharge efficiencies were observed during the summer tests, which are mainly attributed to the energy losses during the storage period. However, since the storage unit is located inside the house-like cubicle, energy losses became direct energy gains (heating or cooling).

The potential of the innovative system to store and provide heating and cooling supply is demonstrated in this paper. The experiments performed were designed to assess the active slab potential; the implementation of a control system could optimize the performance of the active slab. Finally, the main conclusion drew from this paper is the promising potential that the active slab demonstrated for winter and summer modes. So, the results obtained warranted further research through a complete experimental campaign to test different scenarios and weather conditions.

7.3 Contribution of the candidate

The candidate worked in the definition and calculation of the parameters described in the paper, as well as the theoretical analysis of the slab components.

The candidate was involved in the whole process of the active slab prototype construction in a house-like cubicle in the facility of Puigverd de Lleida (Spain).

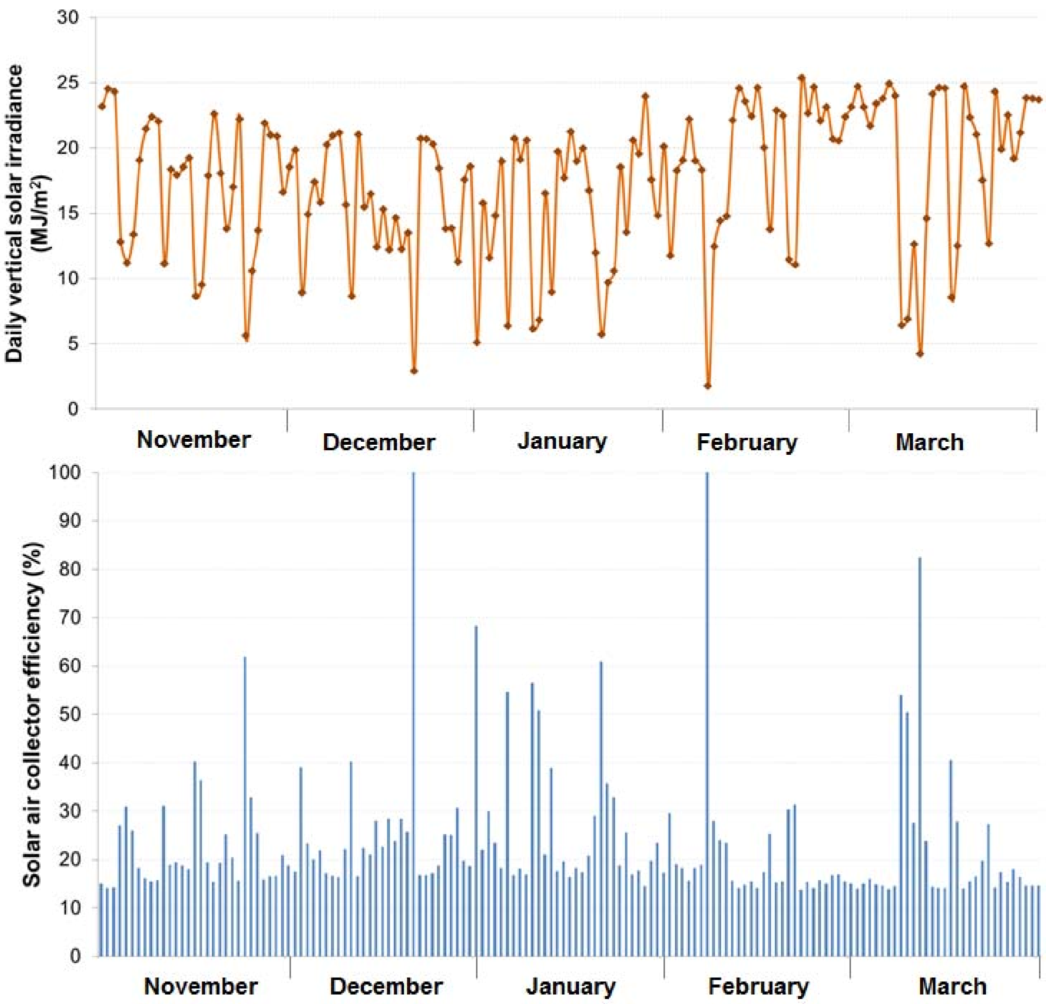

Figure 10. Daily vertical solar energy received (up) and solar air collector efficiency required to charge the PCM (down).

The sensors installation, the data registration connection and the monitoring of the active slab was also carried out by the candidate. The planning and conduction of experiments was also developed by the candidate.

Finally, the data analysis, graphics and writing was also done by the candidate.

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7.5 Journal paper

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PCM incorporation in a concrete core slab as a thermal storage and supply system: Proof of concept

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http://dx.doi.org/10.1016/j.enbuild.2015.06.028

8 Experimental evaluation of a concrete core slab with phase change materials for cooling purposes

8.1 Introduction

In the recent years a rise in the number of installed air-conditioning systems has been observed, resulting in peak load problems, increasing the electricity cost and affecting the energy balance of the electricity grid [1]. Hence, it is critical to reduce the energy consumption of the building, especially during peak load periods. Space cooling energy consumption in buildings increased by nearly 60% between 2000 and 2010 and accounted for roughly 4% of total global buildings energy use in 2010 [2]. Therefore, the energy reduction strategies for cooling purposes are of much interest for the building sector.

In chapter 7, the active slab technology is presented as a storage unit integrated in the building structure. Following the results obtained in the proof of concept paper (chapter 7), an experimental summer campaign is presented in this paper to evaluate the potential of the system as a cooling supply unit under different scenarios. Moreover, two house-like cubicles of 2 storey were used to study the energy performance of the new technology, one of them acting as a reference and the other one being used to test the active slab. Both cubicles are equipped with a heat pump that will act as a conventional cooling system in the case of the reference cubicle, and as a support cooling system in the case of the active slab cubicle. Thereby, the energy consumed by the heat pumps can be compared between both cubicles.

8.2 Contribution to the state of the art

During summer, the active slab is used as a storage unit and a cooling supply component. The operating principle of this technology is based on the night free cooling concept. At night-time the active slab uses the low external temperatures to solidify the PCM (Figure 11.a). In addition, the possibility of using the night free cooling mode during this period can reduce the internal ambient temperature (Figure 11.b). The storage mode can be used after the PCM solidification (Figure 11.c) and once there is a cooling demand inside the cubicle the internal ambient air is pumped into the slab to be cooled down (Figure 11.d).

The versatility of this technology offers the possibility of testing different operating modes, distinguishing time schedule and temperature dependence programs. In this last one, different strategies such as night free cooling (FC), fan savings (FS) and passive discharges (PD) were combined with the cold storage (CS) sequence. Thereby, three different programs (CS+FC, CS+FC+FS, PD) were tested under mild and severe summer conditions.

In time schedule tests was demonstrated that a control system is needed to manage this type of active systems in order to avoid unfavourable effects such as overheating in the internal ambient. On the other hand, in the control temperature experiments the active slab was not able to cover the whole cooling load, but significant energy savings were registered compared to the reference cubicle. Figure 12 shows the energy consumption of the active slab and the reference cubicle under different weather conditions and different control strategies. The energy reduction achieved in the active slab cubicle was between 30% and 55% under mild conditions and between15% and 20% under severe conditions.

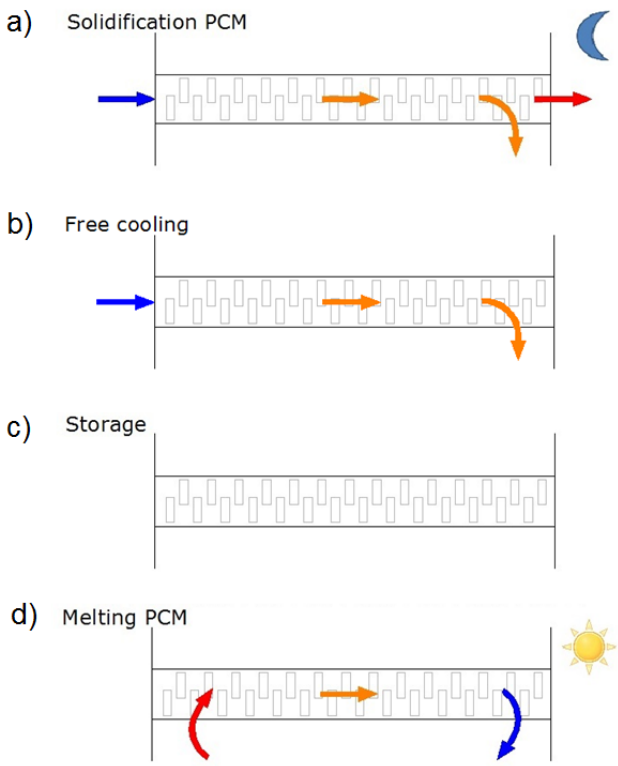

Figure 11. Schematic operating modes from the active slab in summer period

During this experimental campaign the free cooling potential of the active slab was observed to provide some energy benefits by cooling down the internal ambient during night time. Moreover, the passive discharge strategy was tested under severe summer conditions, when the outside temperatures during night-time were not favourable to solidify the PCM. As it is shown in Figure 12 passive discharge tests (PD) were still successful, achieving 20% and 25% of energy reduction in the active slab cubicle.

Despite all the energy benefits provided by the active slab, the weak point of this technology was the electrical energy consumed by the fan that provides the air circulation through the slab. This issue makes difficult to balance the energy benefits during the experiments presented in this paper, so the optimization of the fan operation is critical.

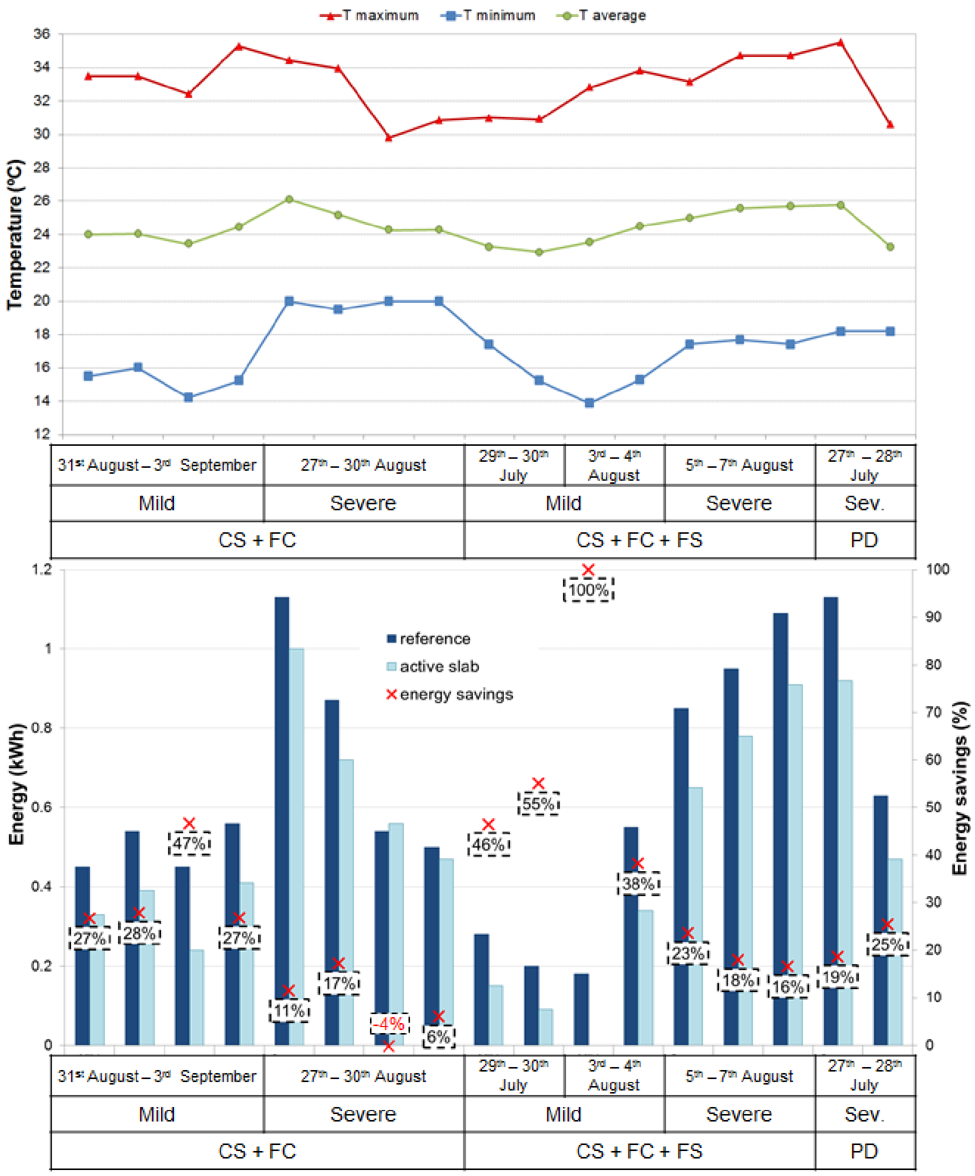

Figure 12. Weather conditions (up), daily electrical energy consumption of the heat pump of active slab and reference cubicles (down), during experiments under mild and severe summer conditions

8.3 Contribution of the candidate

The candidate was involved in the experimentation process placed in the facility of Puigverd de Lleida (Spain), from set-up and control strategies design to experiments conducting and data treatment.

The analysis and evaluation of the data obtained during the test, as well as the parameters defined to quantify the performance of the active slab were also part of the candidate work.

Finally, the data analysis, graphics and writing was also done by the candidate.

8.4 References

1. Directive 2010/31/EU of the European parliament and of the council of 19 May 2010 on the energy performance of buildings. Available from: http://www.epbd-ca.eu
2. Transition to sustainable buildings. Strategies and Opportunities to 2050. International Energy Agency (IEA). Available from: http://www.iea.org/etp/buildings (February 2016).

8.5 Journal paper

Energy and Buildings 116 (2016) 411–419

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ELSEVIER

Experimental evaluation of a concrete core slab with phase change materials for cooling purposes

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The pages 119 to 127 contain the article:

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http://dx.doi.org/10.1016/j.enbuild.2016.01.026

9 Experimental study of an active slab with PCM coupled to a solar air collector for heating purposes

9.1 Introduction

Improvements in the building materials, design and the implementation of renewable energies in the building sector have been identified as potential solution to reduce the high energy consumption and CO_2 emissions [1]. Within this context, solar energy has been widely introduced in building sector to provide electricity, heating and domestic hot water [2]. However, the implementation of thermal energy storage (TES) systems is critical to overcome the main drawback of the renewable energies, the gap between the supply and demand [3]. Therefore, the combination of both solar energy and TES systems, as well as their integration in the building design is shown as an attractive alternative to conventional systems.

In this respect, this paper presents an active slab system which stores solar energy inside a building component with phase change materials (PCM) for heating purposes. A prototype was installed in the experimental set-up of Puigverd de Lleida (Spain), where tests under Mediterranean continental weather were carried out. The thermal performance of the active slab during winter period is presented in this paper. As it was mentioned in chapter 8, both cubicles are equipped with a heat pump, which in this case worked as a heating conventional system in the reference cubicle and as a heating support in the active slab cubicle. Hence, the energy consumption of the heat pumps installed in both cubicles are compared to quantify the potential of the new system versus a conventional heating system.

9.2 Contribution to the state of the art

A solar air collector is installed in the south facade of the active slab house-like cubicle for the winter mode. So the operating principle starts with the melting of the PCM during daytime through the hot air from the solar air collector pumped into the concrete slab (Figure 13.a). The heat charged during daytime can be stored inside the building component (Figure 13.b) until a heating supply is needed. Then the internal ambient air passes through the slab where is heated by the heat exchange with the PCM (Figure 13.c).

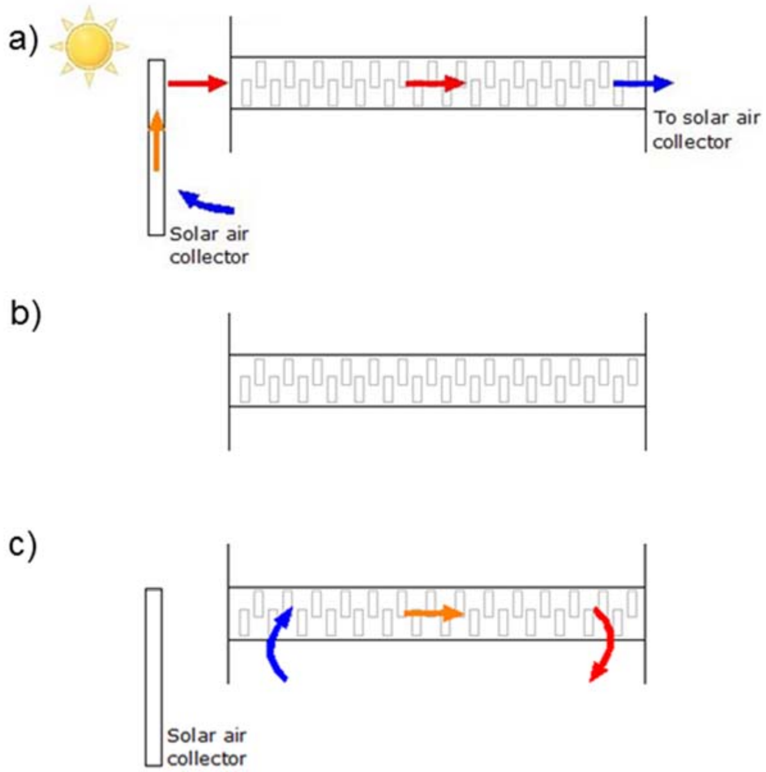

Figure 13. Operating modes from the active slab in winter period: a) charge process, b) storage, c) discharge process

In the experimental winter campaign presented in this paper two main control strategies were tested depending on when the discharge sequence (Figure 13.c) is performed. Heat Storage (HS) represented tests where the heating supply was performed during evening (from 16.00 h), while Day Discharge (DD) is relative to experiments where the discharge process was done during daytime.

Different PCM behaviour was observed in the experiments presented in this paper. Achieving a complete melting and solidification process or not was dependant on the weather conditions, especially on the daily solar irradiance.

This fact was reflected in the energy consumption analysis of HS tests, as shown in Figure 14. The results demonstrate that even if the PCM is not completely melted in some experiments, a reduction between 10% and 20% of the energy consumption is achieved in the active slab cubicle. On the other hand, when the PCM is completely melted the net energy savings achieved (taking into account the fan energy consumption) are between 50% and 60%.

Moreover, DD tests were expected to provide higher benefits than HS sequence by reducing the cooling energy demand during daytime. However, around 25% of energy savings were achieved in the active slab cubicle under severe conditions, while tests performed under mild conditions registered about 40% of energy reduction.

Finally, the importance of the control system on the performance of the active slab was observed during this experimental campaign. Therefore, operating strategies should be improved to optimize and maximize the performance of the technology.

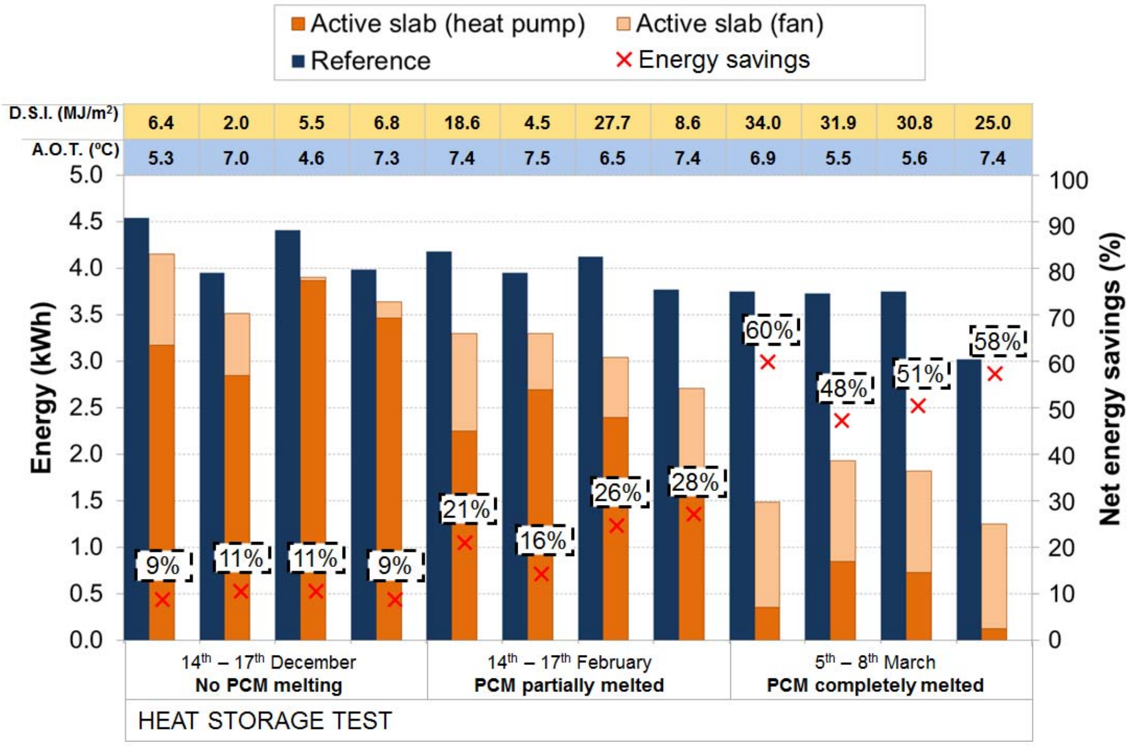

Figure 14. Electrical energy consumption of the heat pumps of the reference and active slab cubicle during Heat storage (HS) experiments. D.S.I (Daily Solar Irradiance), A.O.T. (Average Outside Temperature).

9.3 Contribution of the candidate

The candidate was involved in the experimentation process placed in the facility of Puigverd de Lleida (Spain), from set-up and control strategies design to experiments conduction and data treatment.

The analysis and evaluation of the data obtained during the test, as well as the parameters defined to quantify the performance of the active slab was also part of the candidate work.

Finally, the data analysis, graphics and writing was also done by the candidate.

9.4 References

1. Eurostat, Final energy consumption by sector, 2014. Available at: http://epp. eurostat.ec.europa.eu/portal/page/portal/statistics/search_database (December 2015)
2. G. Tsalikis, G. Martinopoulos. Solar energy systems potential for nearly zero energy residential buildings. Solar Energy 2015;115:743-56.
3. Z. Zhou, Z. Zhang, J. Zuo, K. Huang, L. Zhang. Phase change materials for solar thermal energy storage in residential buildings in cold climate. Renewable and Sustainable Energy Reviews 2015;48:692-703.

9.5 Journal paper

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Experimental study of an active slab with PCM coupled to a solar air collector for heating purposes

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The pages 135 to 144 contain the article:

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http://dx.doi.org/10.1016/j.enbuild.2016.06.069

10 Conclusions and recommendations for future work

10.1 Conclusions of the thesis

This PhD thesis has contributed to the thermal energy storage field applied in buildings for energy savings. An overview on the TES applications in buildings has been done from passive to active systems implementation. Special attention was given to the phase change materials use because of their high potential on energy storage. Also, an important part of this thesis is focused on the analysis of the thermal performance of an innovative slab with phase change materials. This active TES system has two main benefits: its integration into the building structure, and the potential to reduce heating and cooling loads of a building.

The main achievements of this PhD are the following:

- The literature reviewed on TES applications in buildings showed the necessity of their integration in the building components, especially the active systems, to achieve better acceptance in the building sector.
- The inclusion of PCM in the building envelope as a passive cooling system is not recommended in buildings with high internal heat loads unless proper natural ventilation for PCM and internal ambient discharge can be programmed.
- Concerning the active slab performance:
    - The potential of the free cooling and the passive discharge strategies should be taken into account to provide higher benefits to the system, since the cold storage capacity is quite sensitive to the outer conditions.
    - The high potential of the system coupled to a solar air collector as a heat storage unit and heating supply is highlighted through the energy savings achieved in the experimental study.

The main outputs from the review of passive TES system integrated in the building envelope, structure or components are:

- Many studies were found in the literature of PCM applications in buildings as a passive system that can be classified in two main types: mixed with building materials (concrete, plaster), or as a new layer in the construction system.
- Several methods of PCM incorporation inside the material are reviewed concluding that direct incorporation, immersion, and vacuum impregnation methods could have leakage problems and possible incompatibility with some building materials, mainly with concrete.
- Moreover, material properties are demonstrated to be affected, such as mechanical strength and durability among other, regardless the method used to add PCM in the material. Hence, these aspects should be taken into account when designing the PCM application.
- Macro-encapsulated PCM is used as a new layer in the construction system. These studies are growing in interest, as their encapsulation eliminate leakage problems, incompatibility with construction materials, and do not affect materials properties.
- The incorporation of phase change materials into the building envelope is demonstrated to improve the stability of the internal temperatures by the thermal inertia effect.

In this respect, a TES passive system was tested in the experimental set-up of Puigverd de Lleida (Spain) in 2009. The thermal performance of the macro-encapsulated PCM embedded in the brick construction system was demonstrated to reduce the energy consumption of the cooling equipment during summer season. Later on, a set of experiments were performed again in the house-like brick cubicles to evaluate the influence when adding internal heat loads. Therefore, three cubicles (without insulation, with polyurethane, with polyurethane and PCM) were compared under summer conditions to determine the effect of internal loads in the performance of thermal insulation and thermal inertia (using PCM).

The main conclusions obtained from the experimentation are:

- During free floating test, the PCM cubicle showed low dissipation capacity of the heat loads. The heat from the internal loads was stored in the PCM and maintained the indoor temperature at higher values than the other cubicles (without insulation and with polyurethane (PU)).
- For this reason, in the controlled temperature experiments the PCM cubicle consumed more energy from the heat pump to cool down the internal ambient than the other cubicles (without insulation and with PU).
- A comparison between the results obtained with and without internal heat loads demonstrated the high influence of the internal gains in both polyurethane insulation and PCM systems.

Moving to thermal energy storage systems for active applications in buildings, the existing literature of technologies that integrate the storage volume inside the structure or building components is reviewed concluding:

- The integration in buildings is considered relevant to overcome the problems of space availability for installations and therefore to achieve the acceptance of the building sector (architects, building engineers, builders, etc).
- An effort should be done to design an integrated active TES system taking into account climatic conditions, aesthetical and functional requirements.
- Building core activation is demonstrated to be a powerful solution that involves the building structure (slab, facades) as the thermal storage unit.

On the other hand, suspended ceiling products could be adequate for energetic refurbishment in old buildings, but usually with less thermal storage capacity than the previous ones.

- Office and commercial buildings have high potential to incorporate an active TES system in ventilated or double skin facades for their large surfaces. Also, large buildings have potential of the TES integration in the ventilation system (air ducts or air handling units).
- The architectural integration of seasonal thermal water tanks has been applied in central Europe countries making them a feature of stairwells in single or apartment buildings. However, their potential is limited since the integration of these huge water tanks requires lot of space.

A new technology of active TES system was designed and built with the purpose of covering completely or partially the heating and cooling demand of the building. The concept was based on including PCM inside a prefabricated concrete slab and installed in a house-like cubicle of the experimental facility.

- The suitability of the concept in the Mediterranean continental climate was studied to ensure that the available energy is able to charge the PCM.
- The theoretical performance of the system discharge suggested that the PCM will provide a fast heating supply, while concrete will slowly discharge its energy contributing to extend the heating supply period.
- The technology was installed in a house-like cubicle in the experimental facility of Puigverd de Lleida and the performance of the concept was tested under real conditions showing a significant potential of energy consumption reduction.

Moreover, from the experimental campaigns performed in the facility of Puigverd de Lleida, where the active slab was tested under summer and winter conditions, the following conclusions are drawn:

- Significant energy savings in the HVAC system were achieved by the active slab during cooling season, between 30% and 55% under mild conditions, and between 15% and 20% under severe conditions. However, the high energy consumption of the active slab fan is not balanced by the energy savings previously mentioned.
- Free cooling mode showed potential to cool down the internal ambient, which could be really useful for construction systems with high thermal inertia. Also, passive discharge mode should be taken into account as an interesting alternative for specific scenarios such as days with low cold storage charges among others.
- In winter season, the active slab registered 55% of net energy savings with the heat storage mode (afternoon heat discharge) under sunny conditions, and 20% under cloudy conditions. On the other hand, the day discharge mode was expected to reduce the daytime energy consumed by the heat pump, but the results did not show significant changes from heat storage experiments.
- In both summer and winter tests the system performance showed high dependence on the weather conditions (outside night temperature, solar radiation, etc).
- The experimental campaign of this technology highlights the importance of the control system in the whole performance of the active slab. The strategies designed play and important role and emphasise the need of optimization to achieve better performance of the active slab.

10.2 Recommendations for future work

The research presented from the new technology of active slab with PCM demonstrates the potential on energy demand reduction. However, during the experimentation some aspects were found out to need improvement and further analysis.

Measurements showed the PCM was not working homogeneously along the slab. In some parts of the concrete component, the PCM did not achieve the whole phase change cycle, which involves a loss of the storage capacity of the whole system. Therefore, a detailed study should be performed to overcome this aspect. In relation to this, the air distribution inside the slab hollows, especially during the winter charge when hot air is coming from the solar collector, should be also studied to optimize the charge process. A new design of the air ducts that couple the solar air collector to the slab could be carried out. The implementation of two air inlet gates at different locations of the slab could overcome the differences of the PCM performance.

The critical aspect that did not allow the active slab to provide net energy savings during summer is the fan energy consumption. The dimensioning of the fan should be checked to ensure the most adequate sizing and also a search on more efficient typologies of fans could provide higher benefits to the whole technology. Moreover, the incorporation of the variable frequency drive of the fan as a parameter in the control system could be an interesting solution to solve this aspect.

Related to the control system, the implementation of weather forecast, energy demand profiles of the building, and electricity cost profiles in the control algorithm could provide an optimized management of the charge, discharge and storage strategies.

A simulation of the active slab technology would be of much interest as a tool to study how the design parameters (PCM temperature, PCM quantity, climatic conditions …) are influencing the performance of the whole system and which are the most significant ones. Therefore, critical factors could be determined to improve the design of the technology. In addition, the extrapolation of the active slab in other locations could give the potential of the technology under different weather conditions.

11 Other research activities

11.1 Other publications

Other scientific research about thermal energy storage was carried out during the execution of this thesis. The resulting publications are listed below:

- Menoufi K., Castell A., **Navarro L**., Pérez G., Boer D., Cabeza L.F. Evaluation of the environmental impact of experimental cubicles using Life Cycle Assessment: A highlight on the manufacturing phase Applied Energy 2012;92:534-44.
- De Gracia A., **Navarro L.**, Castell A., Ruiz-Pardo A., Alvárez S., Cabeza L.F. Experimental study of a ventilated facade with PCM during winter period. Energy and Buildings 2012;58:324–32.
- De Gracia A., Castell A., **Navarro L.**, Oró E., Cabeza L.F. Numerical modelling of ventilated facades: A review. Renewable and Sustainable Energy Reviews 2013;22:539-9.
- De Gracia A., **Navarro L.**, Castell A., Ruiz-Pardo A., Álvarez S., Cabeza L.F. Thermal analysis of a ventilated facade with PCM for cooling applications Energy and Buildings 2013;65:508-15.
- De Gracia, A., **Navarro, L.**, Castell, A., Cabeza, L.F. Numerical study on the thermal performance of a ventilated facade with PCM. Applied Thermal Engineering 2013;61(2):372-80.
- De Gracia A., **Navarro L.**, Castell A., Boer D., Cabeza L.F. Life cycle assessment of a ventilated facade with PCM in its air chamber. Solar Energy 2014;104:115-23.
- Barreneche C., **Navarro L.**, De Gracia A., Fernández A.I., Cabeza L.F. In situ thermal and acoustic performance and environmental impact of the introduction of a shape-stabilized PCM layer for building applications. Renewable Energy 2016;85:281-6.

Notice that most of the scientific publications mentioned in the above list were related to Dr. Alvaro de Gracia PhD thesis about a double skin facade with PCM. The candidate has collaborated closely with this topic where a lot of knowledge about PCM active applications in buildings was acquired to be applied later in the development of this thesis.

11.2 Contributions to conferences:

The PhD candidate also contributed to some international conferences:

- Safari V, Barreneche C, Castell A, Basatni A, **Navarro L**, Cabeza LF, Haghighat F. Volatile organic emission from PCM building materials. Innostock 2012 - The 12th International Conference on Energy Storage, Lleida (Spain).
- De Gracia A, **Navarro L**, Castell A, Ruiz-Pardo A, Alvárez S, Cabeza LF. Experimental thermal analysis of a ventilated facade with PCM inside the air channel. Innostock 2012 - The 12th International Conference on Energy, Lleida (Spain).
- **Navarro L**, de Gracia A, Solé C, Castell A, Cabeza LF. Use of phase change materials in buildings with internal loads: experimental results. Innostock 2012 - The 12th International Conference on Energy Storage, Lleida (Spain).
- De Gracia A, **Navarro L**, Castell A, Ruiz-Pardo A, Álvarez S, Cabeza LF. Solar absorption in a ventilated facade with PCM: experimental results. SHC 2012 - International Conference on Solar Heating and Cooling for Buildings and Industry, San Francisco (USA).
- **Navarro L**, de Gracia A, Solé C, Castell A, Cabeza LF. Thermal loads inside buildings with phase change materials: experimental results. SHC 2012 - International Conference on Solar Heating and Cooling for Buildings and Industry, San Francisco (USA).

- Rincón L, Serrano S, **Navarro L**, Castell A, Cabeza LF. Experimental thermal behaviour of an innovative insulation material under real operating conditions. Eurosun 2012, Rijeka (Croatia).
- De Gracia A, **Navarro L**, Castell A, Ruiz-Pardo A, Álvarez S, Cabeza LF. Experimental study on the thermal performance of a ventilated facade with PCM in its air cavity. Eurosun 2012 International Conference of Solar Energy and Buldings, Rijeka (Croatia).
- Solé C, Serrano S, **Navarro L**, Barreneche C, Rincón L, Cabeza LF. Laboratory and pilot plant experiments with rammed earth walls. COINVEDI 2012 - 2nd International Conference on Construction and Building Research, Valencia (Spain).
- Castell A, de Gracia A, **Navarro L**, Ruiz-Pardo A, Álvarez S, Cabeza LF. Experimental study of a ventilated facade with phase change material in the air channel. COINVEDI 2012 - 2nd International Conference on Construction and Building Research, Valencia (Spain).
- De Gracia A, **Navarro L**, Oró E, Castell A, Cabeza LF. Numerical analysis of a ventilated facade with PCM. Annex 23 & Annex 25 Joint Workshop - ECES IA - International Energy Agency, 2012, Auckland (New Zealand).
- De Gracia A, **Navarro L**, Castell A, Cabeza LF. Numerical investigation of a ventilated facade with phase change material. The Fifth International Conference on Applied Energy (ICAE 2013), Pretoria (South Africa).
- De Gracia A, **Navarro L**, Castell A, Boer D, Cabeza LF. Optimización del funcionamiento de una fachada ventilada con material de cambio de fase. 8º Congreso Nacional de Ingeniería Termodinámica, 2013, Burgos (Spain).
- **Navarro L**, de Gracia A, Castell A, Alvarez S, Cabeza LF. Design of a prefabricated concrete slab with PCM inside the hollows. ISES SOLAR WORLD CONGRESS 2013, Cancún (Mexico).

- **Navarro L**, de Gracia A, Castell A, Alvarez S, Cabeza LF. Thermal analysis of a prefabricated concrete slab with PCM. International Sustainable Built Environment Conference - ISBE 2014. Doha (QATAR).
- De Gracia A, **Navarro L**, Castell A, Cabeza LF. Numerical study of using PCM in a versatile ventilated facade. Eurotherm Seminar #99 - Advances in Thermal Energy Storage, 2014, Lleida (Spain).
- **Navarro L**, de Gracia A, Castell A, Alvarez S, Cabeza LF. Experimental study of a prefabricated concrete slab with PCM. Eurotherm Seminar #99 - Advances in Thermal Energy Storage, 2014, Lleida (Spain).
- De Gracia A, **Navarro L**, Castell A, Cabeza LF. Energetic performance of a ventilated double skin facade with PCM. Thermal Energy Storage in buildings. A workshop organised by XARMAE, 2014, Barcelona (Spain).
- De Gracia A, **Navarro L**, Castell A, Cabeza LF. Energetic performance of a VDSF with PCM under different weather conditions. Materials Science and Technology (MS&T), 2014, Pittsburg, Pennsylvania (USA).
- **Navarro L**, de Gracia A, Castell A, Cabeza LF. Thermal energy storage in sustainable buildings: passive and active systems. World SB14, 2014, Barcelona (Spain).
- De Gracia A, **Navarro L**, Castell A, Cabeza LF. Numerical study of a ventilated facade with PCM for cooling applications under different climate conditions. Grand Renewable Energy 2014, Tokio (Japan).
- **Navarro L**, de Gracia A, Castell A, Alvarez S, Cabeza LF. Experimental study of active slab with PCM during summer period. EuroSun 2014 - International Conference of Solar Energy and Buldings, Aix-les-Bains (France).
- Barreneche C, **Navarro L**, de Gracia A, Cabeza LF, Fernánez AI. In situ thermal performance of a shape-stabilized PCM layer for building applications. Thermal Energy Storage in buildings. A workshop organised by XARMAE, 2014, Barcelona (Spain).

- **Navarro L**, de Gracia A, Castell A, Cabeza LF. Prefabricated concrete slab with phase change materials for cooling purposes. GREENSTOCK 2015 - The 13th International Conference on Energy Storage, Beijing (China).
- **Navarro L**, de Gracia A, Cabeza LF. PCMs as a tool for increasing thermal inertia in buildings. 36th AIVC Conference. Effective ventilation in high performance buildings, 2015, Madrid (Spain).

11.3 Scientific foreign-exchange:

The PhD candidate did a 3-month exchange during the realisation of this thesis in the Centre for Sustainable Technologies (CST) of the University of Ulster in Belfast, United Kingdom. The research carried out was about thermal energy storage application for domestic hot water tanks. An experimental study about the inclusion of PCM in a hot water tank was done and the storage capacity of the tank when including PCM was analysed. The phase change material used in this application was paraffin (58 ºC as melting temperature) impregnated in rubber spheres. The influence of the PCM spheres on the discharge process of the water tank was studied in the experimental set-up by testing different quantities of PCM. Results showed inconsistency between the different amounts of PCM added. Also significant leakage problems were observed in the water tank of the experimental facility; hence a laboratory analysis was carried out to observe this effect in the spheres.

11.4 Others:

11.4.1 Book chapters participation:

- Cabeza LF, **Navarro L**, Barreneche C, de Gracia A, Fernández AI. Phase change materials for reducing building cooling needs. Eco-efficient Materials for Mitigating Building Cooling Needs: Design, Properties and Applications. Elsevier Ltd, 2015.

11.4.2 Projects participation:

- MECLIDE, Soluciones estructurales con materiales especiales para la climatización tecnológica de Andalucía, 09/373, 2009-2012
- Mejora de la eficiencia energética en edificios mediante el almacenamiento de energía térmica, ENE2011-28269-C03-02, 2012-2014
- El almacenamiento de energía térmica como herramienta de mejora de la eficiencia energética en la industria (TES in industry), ENE2011-22722, 2012-2014

Currently:

- INPHASE, soluciones innovadoras de fachadas prefabricadas de hormigón con PCMs para edificios de consumo de energía casi nulo, 2015-2018
- Identificación de barreras y oportunidades sostenibles en los materiales y aplicaciones del almacenamiento de energía térmica, ENE2015-64117-C5-1-R, Ministerio de Ciencia e Innovación, 2016-2018