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

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Abstract

Solar energy has been widely introduced in the building market to provide electricity, heating and domestic hot water for a sustainable development. However, the low-density and the mismatch between energy supply and demand make appropriate its combination with thermal energy storage (TES) systems. The integration of these technologies (solar thermal and TES) in the building design is a key aspect to reduce energy consumption. Latent heat storage using phase change materials (PCM) presents an advantage in comparison to conventional sensible heat storage systems due to the required volume. In this context, an innovative system that integrates PCM inside the structural horizontal building component is presented in this paper. The slab consisted of a prefabricated concrete element with 14 channels filled with macro-encapsulated PCM which is used as a storage unit and a heating supply. In order to melt the PCM the system is coupled to a solar air collector. The prototype is tested in an experimental facility located in Puigverd de Lleida (Spain) where its thermal performance is evaluated under real weather conditions. This study demonstrates the high potential of the concrete slab on reducing the energy consumption compared to a conventional heating system.

Keywords: thermal energy storage (TES), phase change materials (PCM), Active system, energy savings, heating system

1. Introduction

The European building sector is responsible of the 40% of primary energy consumption and 24% of greenhouse emissions [1]. The improvement in the building materials and design and the implementation of renewable energies in the building sector have been identified as plausible solutions to reduce this high consumption and environmental impact.

Within this context, the building sector has adopted the implementation of solar energy to achieve more sustainable performances providing electricity, heating and domestic hot water [2]. The use of solar thermal for heating purposes in winter has a great potential to reduce the consumption of fossil fuels. However, the low-density and intermittency of this technology makes appropriate its combination with thermal energy storage (TES) systems [3]. Moreover, the implementation of TES systems in solar thermal facilities allows the user of the building to control the heating supply and hence maximize the economic and environmental benefits.

In addition, energy storage is not only playing an important role in energy conservation but also on improving the performance of energy systems, especially intermittent energy sources such as solar. Within this context many studies have worked on thermal stratification [4], and the location of the coil [5], among others, as some of the aspects taken into account in solar water tanks due to their strong influence on the overall solar system performance.

The integration of these technologies (solar thermal and TES) in the building design is required to promote them as an attractive alternative to the conventional systems [6]. A key aspect of this integration inside the building is the required volume to host the storage system. Here, latent heat storage using phase change materials (PCM) presents a clear advantage in comparison to conventional sensible heat storage systems [7]. Several researchers have integrated PCM inside the building design, using the floors [8], suspended ceilings [9], external facades [10] and the ventilation system [11] in order to limit as much as possible the space occupied by the storage.

In this respect, this paper presents an innovative system to integrate PCM and use the storage for heating and cooling purposes. The structural building component used as horizontal separation between floors is provided with 14 channels in which tube-shaped macro-encapsulated PCM is included. This latent heat storage is used to store solar energy during winter and as a cold storage system during summer using low temperatures at night. A similar operating principle both for heating and cooling was tested by de Gracia et al. [12,13], but incorporating the PCM in the cavity of a ventilated double skin facade, showing important net energy savings, especially during winter. The incorporation of the PCM inside the slab instead of installing it in an external component such as the ventilated facade, presents important improvements. Heat losses or gains to the outer environment are completely avoided and also the ratio between the area where the PCM can be included and the area to heat or cool is higher compared to the facade.

In this paper, the thermal performance of the active slab with PCM is experimentally tested under Mediterranean continental weather conditions for heating purposes. In addition, the energy performance of the active slab system is compared to a conventional heating system in order to quantify the potential of the new system.

2. Methodology

2.1 Experimental set-up

The experimental campaign makes use of two monitored cubicles with internal dimensions of 2.4x2.4x5.8 m and based on an alveolar brick constructive system. The only difference between these two cubicles is that one of them uses a conventional slab for separation between floors (reference cubicle), while the other one uses a prefabricated concrete slab with phase change materials inside its hollows (active slab cubicle) and is provided by a solar air collector as shown in Figure 1. The two cubicles are located in the experimental set-up of Puigverd de Lleida (Spain), under Mediterranean continental weather conditions, corresponding to Csa (Warm Temperate, summer dry, hot summer) according to the Köppen-Geiger climate classification [14].

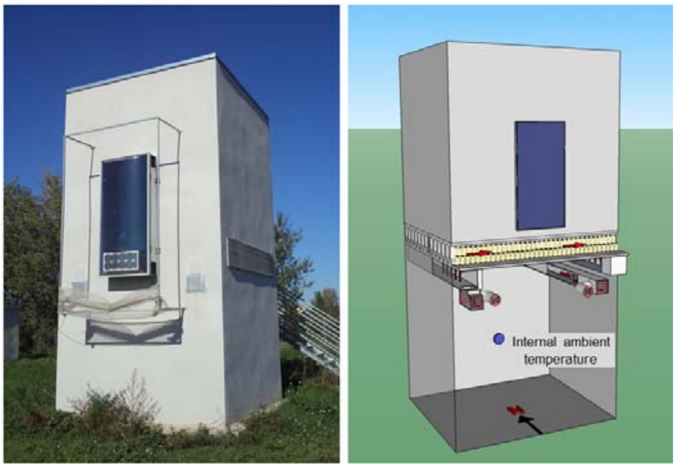

Figure 1. Active slab cubicle in the experimental installation of Puigverd de Lleida (left) and 3D scheme (right).

The active slab is based on a 30 cm thick prefabricated concrete component, with 14 air channels wherein the PCM is located. Six gates (Madel CTM-AN 250x200 mm) and a fan (Sodeca CMP-512-2M) are installed in the air duct installation below the slab and make possible to circulate an air flow from and to the slab channels from different sources, such as, indoor environment, outdoors and solar collector. The versatility provided by the gates at the air duct installation allows the system to operate under different modes, as shown in Figure 2.

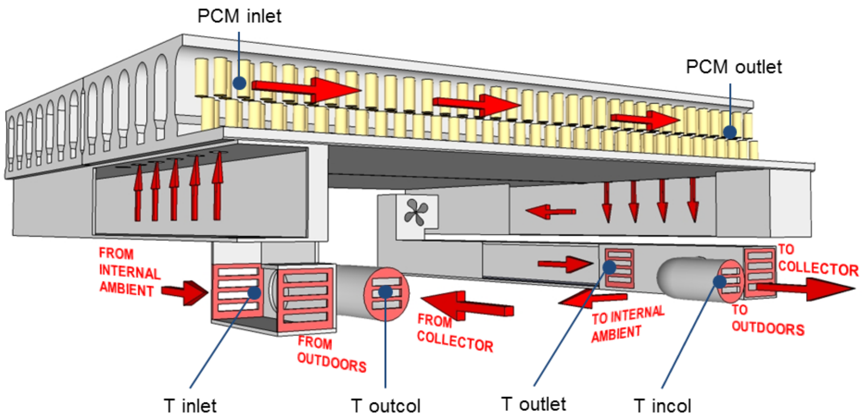

Figure 2. 3D scheme of the active slab system.

As it was shown in Figure 1, a solar air collector is implemented in the south wall of the cubicle with the active slab. The collector has a surface of 1.3 m^2 and a power rating of 1330 Wp (AIRSOL-20), moreover it incorporates a fan connected to a photovoltaic panel. With the use of the previously defined gates, the solar energy can be used directly to heat the indoor environment or to melt the PCM located inside the slab hollows.

It is well known that an appropriate control system is required to manage active systems in the building sector not only to maximize its thermal benefits and hence justify the high cost investment, but to avoid undesired performance, such as overheating, as well. The control system used in this research makes use of five temperature sensors located in the slab and decides the charging, discharging, and storage periods based on weather conditions and energy requirements of the heating demand.

Moreover, both cubicles are equipped with two heat pumps (Fujitsu inverter ASHA07LCC), one for each floor, in order to control the indoor conditions. The electrical energy required by each heat pump to meet the demand is measured and registered using an electrical network analyser (Circutor MK-30-LCD). A list and description of the sensors used in this prototype is provided in Table 1.

Table 1. Sensors description used in the experimental facility.

	Type of sensor	**Accuracy**
Weather conditions		
External temperature and humidity	ELEKTRONIK EE21	± 2%
Solar irradiance, horizontal and vertical	Middleton Solar pyranometers SK08	± 2 $W{\cdot}m^{-2}$
Wind speed and direction	DNA 024 anemometer	-
Cubicles internal conditions		
Internal surface temperature of walls, roof and floor	Pt-100 DIN B	± 0.3 ºC
Inside temperature and humidity	ELEKTRONIK EE21	± 2%
Active slab system		

PCM temperatures inside the aluminium tubes	Pt-100 1/5 DIN B	± 0.3 ºC
Air temperature and velocity at the inlet and outlet of the slab	KIMO CTV210	± 0.03 m/s ± 0.25 ºC

As it was previously stated, the PCM is located inside the hollows of the active slab. 1456 aluminium tubes of 12 mm diameter and 100 mm of height are placed in each hollow, making a total of 52 kg of PCM. The selected PCM for this application is paraffin (RT-21) with melting temperature between 21-22 ºC from Rubitherm [15]. This PCM was selected due to its high enthalpy of fusion (134 kJ/kg), stability, lack of corrosion problems and melting range, which is appropriate for heating and cooling purposes since it can provide thermal comfort conditions for both periods (18ºC for heating and 25ºC for cooling according to ASHRAE [16]). The PCM tubes are distributed in cross flow along the hollow using a wooden frame as shown in Figure 3.

Figure 3. Macro-encapsulated PCM in aluminium tubes and incorporated inside the concrete slab hollows.

2.2 Operating principle

The operating principle of the active slab in winter is based on the storage of the solar energy captured by the solar air collector through the melting process of the PCM, and its release once it is required by the demand with the solidification of the PCM, covering totally or partially the heating demand. Figure 4 shows a sketch of the operating principle of this system under winter conditions.

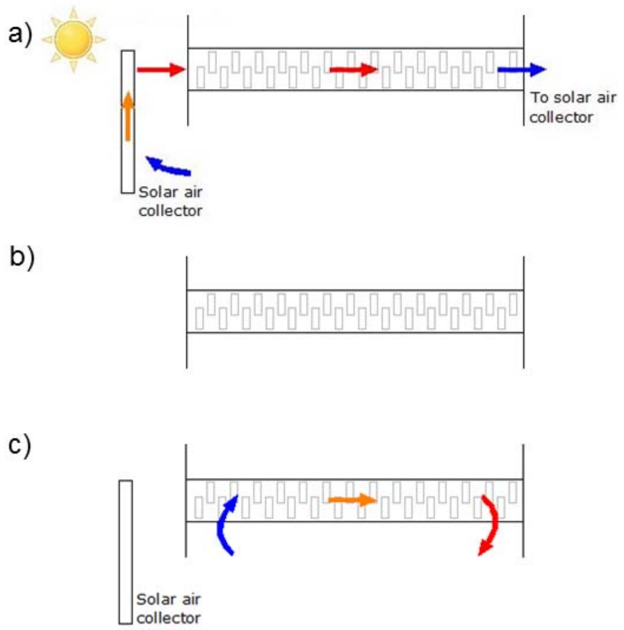

Figure 4. Operating modes from the active slab in winter period: a) charging process, b) storage, c) discharging process.

2.3 Description of experiments

This paper presents a complete experimental campaign during winter. Within this period three different tests have been performed. In all of them the set point of the heat pumps of the active slab cubicle and reference cubicle were set to 18ºC and the control system was applied to avoid undesired effects such as charging without solar radiation or discharging without enough stored energy in the slab. Moreover, in both experiments the charging process was enclosed between 09:00 and 16:00, while the discharging process was limited within 16:00 and 09:00.

a. <u>*Heat Storage* test (HS): </u>In this experiment the charging and discharging processes of the PCM are completely separated and no heating supply is provided to the indoor environment during the charging process. Hence, the operational principle is sequential between charging, storage, and discharging.

b. <u>*Day Discharge* test (DD):</u> In this experiment the charging and discharging process are not consecutive; the system can perform the discharging mode at any time during the whole day as long as a heating demand is needed in the internal ambient. The system can operate only in one mode at the same time (charging or discharging), and the control system gives priority to cover the heating demand (discharging). Thereby, a heating supply can be provided during daytime when the indoor temperature is below set point and PCM temperature at the same time.

c. <u>*Day Discharge and Set point* test (DD + SP):</u> In this experiment the same criteria as the previous one (DD) are applied but with the addition of a new parameter to optimize the heating supply. The control system added a set point temperature to the active slab system (19 ºC) which is above the set point temperature of the heat pump. Therefore, the active slab will have priority if a heating supply is needed.

3. Results and discussion

3.1 *Heat Storage* test

During the *Heat Storage* experiments the authors observed three different behaviours in the active slab depending on the thermal response of the PCM. As it was stated in previous studies [17] the weather conditions are determinant to melt the PCM. In some tests a complete melting was not achieved, however interesting results were found and analysed.

- <u>No PCM melting</u>

The first experiment was performed from December 14th to 17th. During this period the minimum temperatures were around 0 ºC and maximum temperatures did not exceed 11 ºC. Daily solar vertical irradiation values were not higher than 7 MJ/m^2, due to the mostly cloudy conditions.

These days are an example of the active slab performance under cloudy conditions. During the first and last day the charging mode run some hours, the third day the charge lasted few hours and the second day there was no charging period. As it was programmed, the control system decided the charging mode operation, in this case, depending on the available solar radiation. Temperatures of the PCM located at inlet and outlet part of the active slab are presented in Figure 5. PCM was clearly not melted any day during the experiment which means that there was no heat stored and hence, no heat discharging period.

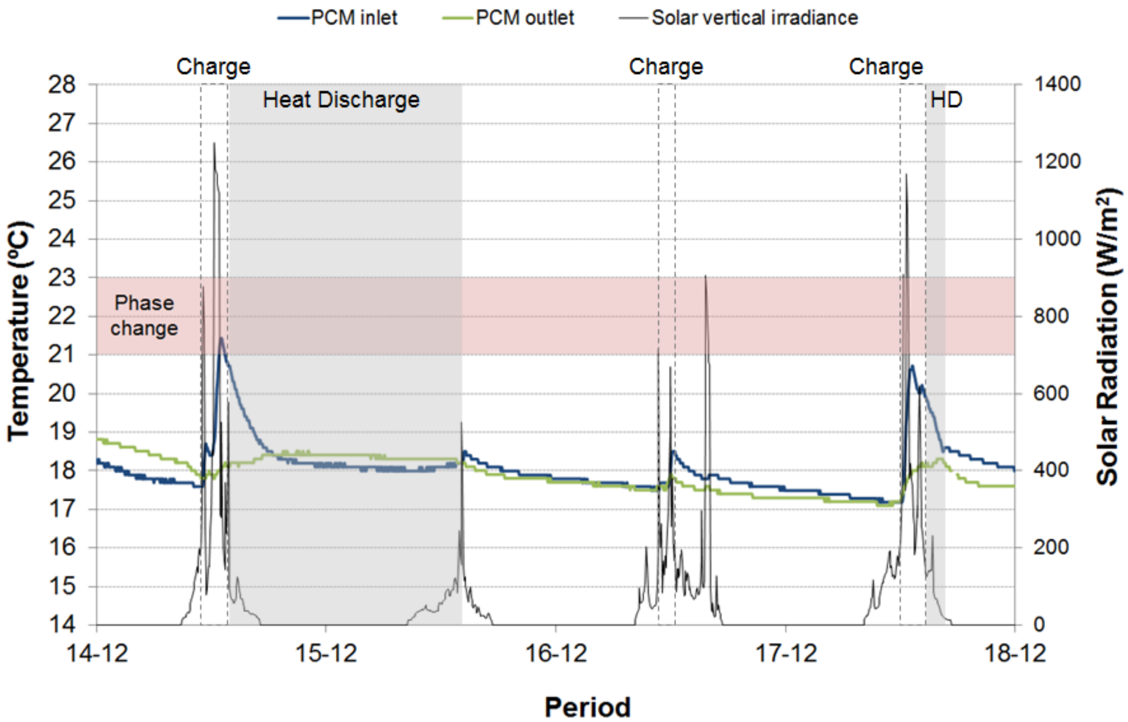

Figure 5. PCM temperatures and concrete surface temperature of the *Heat Storage* experiment with No PCM melting.

- <u>Partial PCM melting</u>

Later on, the same type of experiment was performed during February 14th to 17th. Outside temperatures were similar than the test previously presented with maximum temperatures between 14 ºC and 17 ºC and minimum values oscillating between -2 ºC and 2 ºC. However, the solar radiation during these days was higher, but still not constant because of partly sunny conditions. Solar vertical irradiation fluctuated between 5 MJ/m^2 and 28 MJ/m^2 depending on the day as it can be seen in Figure 6.

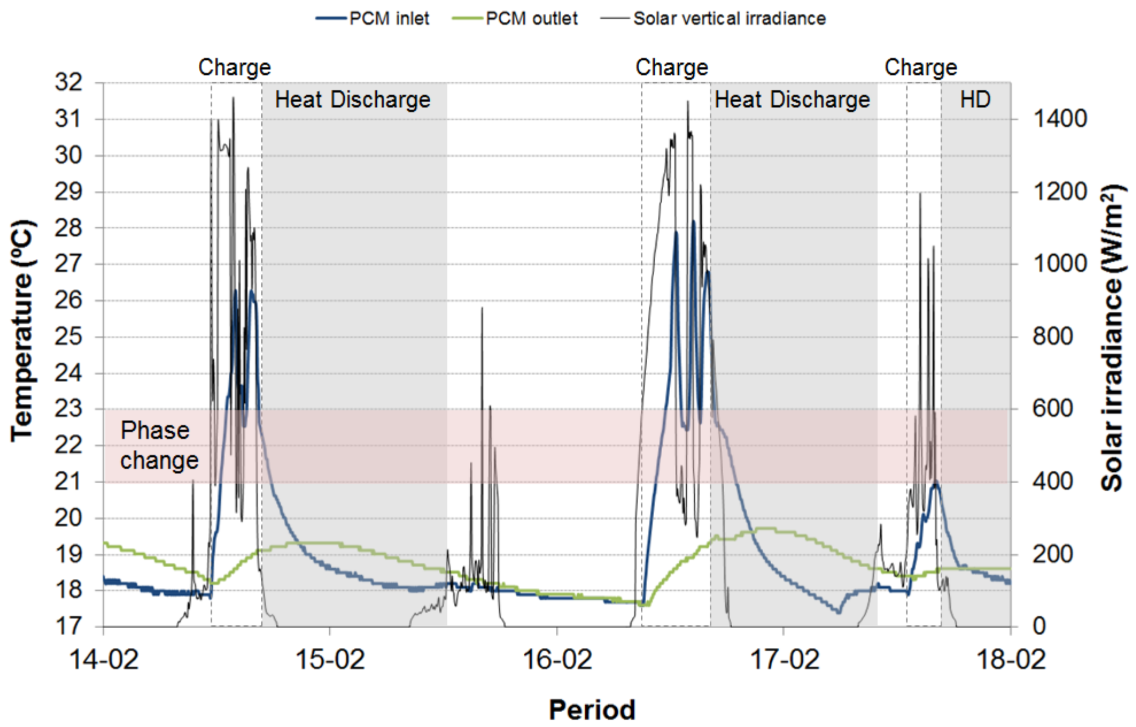

Figure 6. PCM temperatures and solar vertical irradiance of the *Heat Storage* experiment with partial PCM melting.

Temperatures of the PCM located at inlet and outlet part of the active slab are presented in Figure 6. First of all, a difference between the two PCM sensors is observed. While, during some days, PCM inlet was moving inside the phase change range, the PCM at the outlet part was in solid state during the four tested days. This effect is observed during all the experiments presented with higher or lower differences between the PCM inlet and outlet temperatures. A detailed study should be done to optimize the PCM quantity in the active slab taking into account the solar collector area.

Moreover, the sunny and cloudy days could be easily detected by observing the PCM inlet temperature. As it was seen in Figure 6, 15th and 17th had lower solar radiation than the rest of the days, hence the PCM these days was not melted. In addition, during February 15th of the active slab was in storage mode during the whole day, with no charging neither discharging period due to the control strategy.

Figure 7 analyses in detail a cloudy day test, presenting the temperature evolution of February 16th. First, the solar radiation evolution during the charging period is reflected in the temperature response at the inlet of the slab (T_{inlet}). Two significant temperature drops are observed in the air inlet of the slab (due to cloudy periods) which at the same time affects directly to the PCM temperature (PCM_{inlet}) at the inlet of the slab. On the other hand, during the night heat was discharged through the solidification of the PCM_{inlet} as can be clearly seen in Figure 7. The PCM effect kept the air supply (T_{outlet}) around 19.5 ºC during almost all the discharging process.

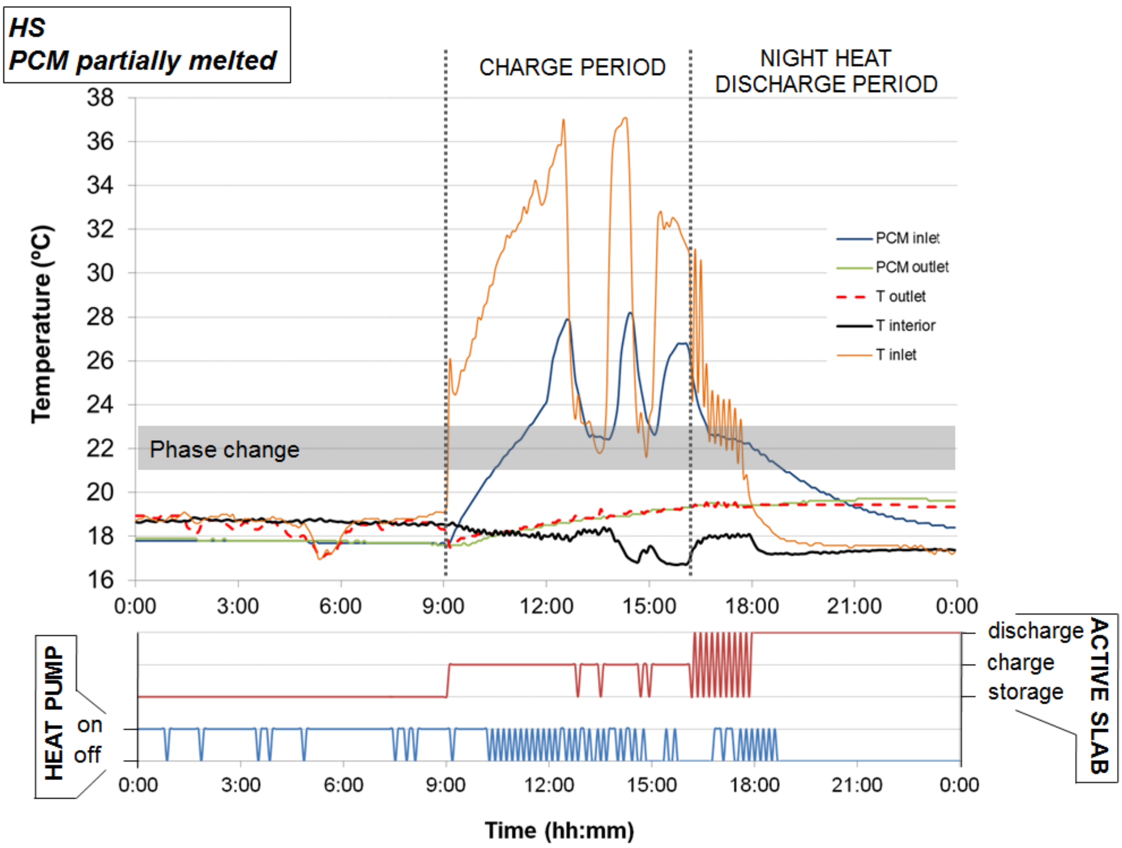

Figure 7. Daily temperature evolution of the active slab cubicle during February 16th.

- <u>Complete PCM melting</u>

Later on, the same *Heat Storage* program was tested from March 5th to 8th with milder weather conditions. During these days maximum temperatures were around 12 ºC and minimum temperatures fluctuated between 0 ºC and 3 ºC. Sunny conditions were registered during the four days with an oscillation of the solar global vertical irradiation on the south facade between 25 MJ/m^2 and 34 MJ/m^2.

During this experiment, the PCM located at the inlet part of the slab did the complete cycle of melting and solidification all days (Figure 8) and achieved maximum temperatures of 28 ºC and 29 ºC. On the other hand, PCM outlet temperature was higher than in previous experiments, between 19 ºC and 21 ºC, but still did not achieve the phase change process, remaining solid during the four days.

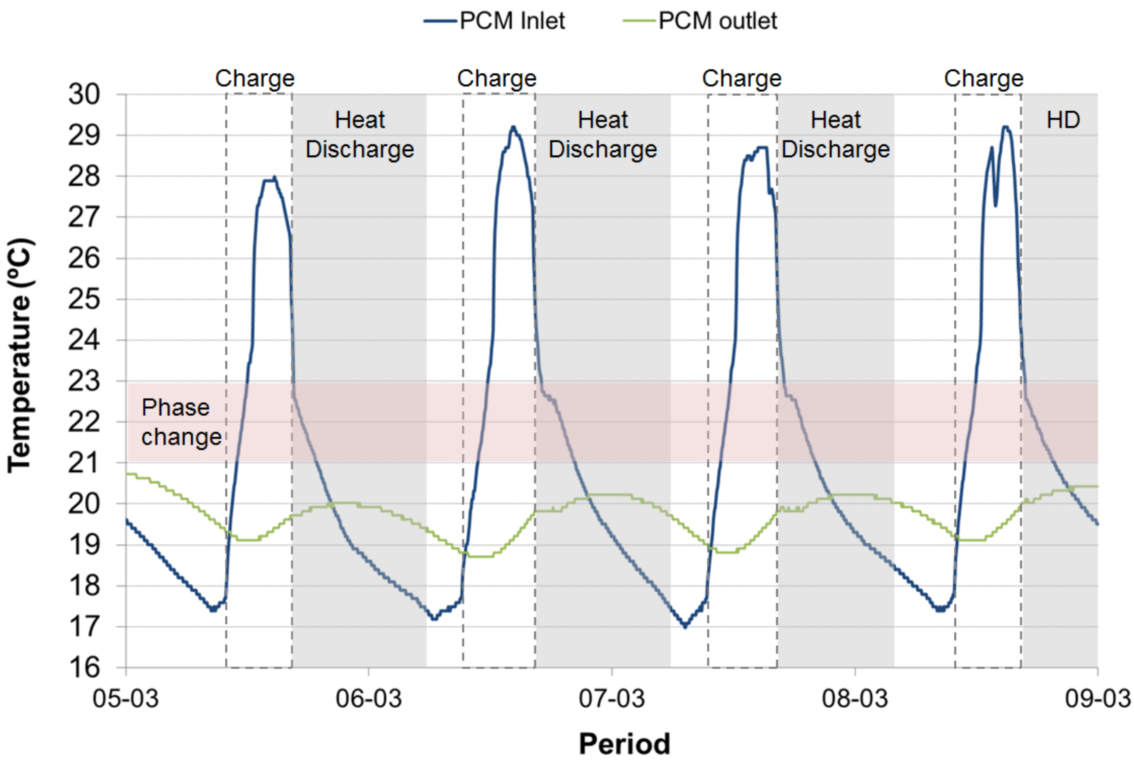

Figure 8. PCM temperatures of the *Heat Storage* experiment with complete PCM melting.

The daily temperature evolution of the active slab during the third day of this experiment is presented in Figure 9. Temperature at inlet part of the slab (T_{inlet}) showed the profile of a clear sunny day during the charging period, since the air is coming from the solar air collector. During this process, T_{inlet} rose up during daytime, achieving the maximum temperature of 37 ºC around 1 pm. Therefore, due to the injection of hot air into the slab, the PCM inlet temperature increased until 28 ºC turning into liquid state. However, in the PCM outlet temperature a slight effect could be observed, rising from 19 ºC to 20 ºC.

Moreover, during the discharging period the solidification of the PCM inlet, which takes place between 23 ºC and 22 ºC, can be clearly seen. Therefore, the outlet air temperature (T_{outlet}) was kept at 20 ºC providing heat to the internal ambient and maintaining the interior temperature ($T_{interior}$) at 18 ºC. In addition, during this day the active slab cubicle just needed the heat pump support to maintain the indoor set point temperature during daytime, and not during the evening and night. Also, related to the heat pump work and the active slab, at the beginning of the discharge process both systems were operating alternatively. The control system should be addressed in scenarios like the one mentioned by adding higher complexity to the decisions.

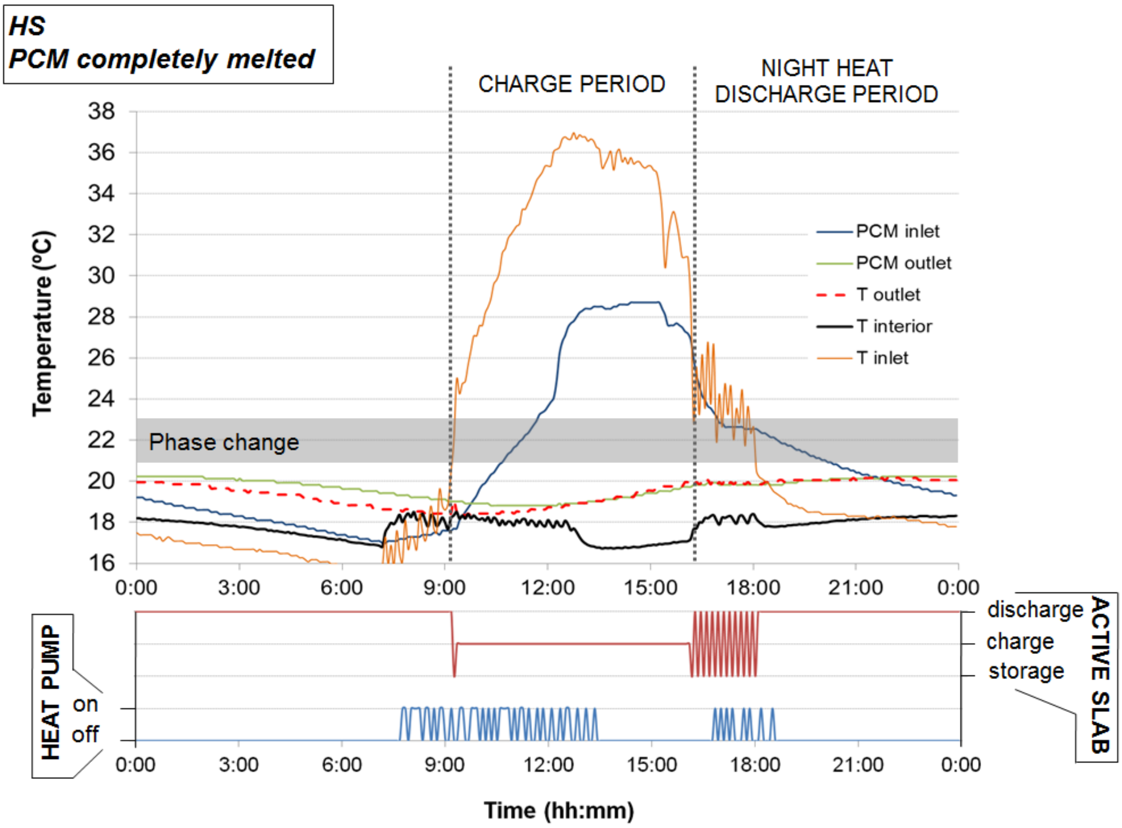

Figure 9. Daily temperature evolution of the active slab cubicle during March 7th.

3.2 *Day Discharge* test

As well as in the *Heat Storage* experiments, in the *Day Discharge* tests the different responses on the PCM were identified in the experiments presented below. As it was previously explained in section 2.3, during *Day Discharge* experiments the charging process is interrupted if the PCM temperature is higher than the indoor temperature of the cubicle (DD) or if the internal ambient temperature is below the set point temperature (DD+SP).

First of all the *Day Discharge* experiment was tested during February 19th and 20th. Weather conditions were considered severe since minimum temperature values were around -5 ºC and maximum temperatures about 15 ºC. However, these days were clearly sunny with a daily vertical solar irradiation of almost 31 MJ/m^2.

Temperature evolution of the active slab cubicle during these days is presented in Figure 10. Regarding the sunny conditions previously mentioned, temperature of the air at inlet of the slab (T_{inlet}), which is coming from the solar air collector, rose up during daytime achieving a maximum of 34 ºC. Hence, conditions were favourable to achieve a successful charge. However, as PCM inlet temperature shows in Figure 10, the melting process was achieved with more difficulty because of the day discharges. During the day discharging process the control system of the active slab was combining the charging and discharging modes depending on the temperature evolution. That is the reason why the PCM inlet temperature looks unstable during this period. On the other hand, PCM outlet temperature remained out of the phase change range temperatures during both days.

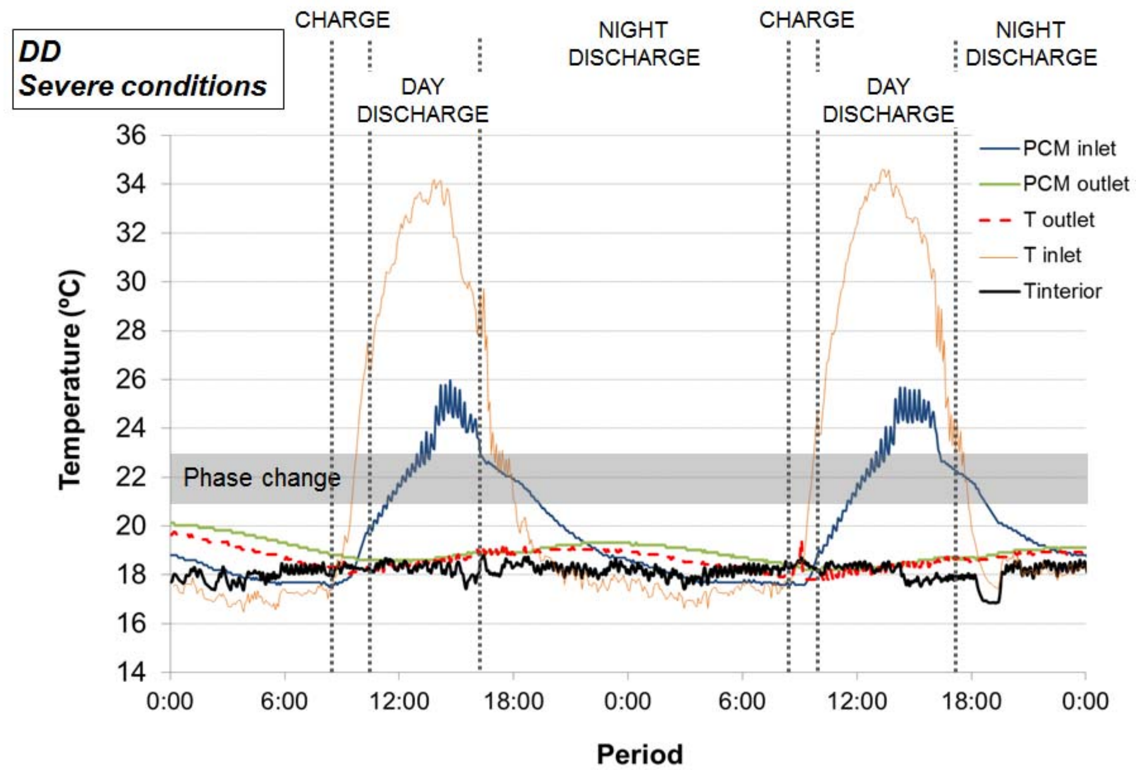

Figure 10. Temperature evolution of the active slab cubicle during February 19th and 20th.

Regarding the air temperature at the outlet of the slab, temperatures during both days were between 18 ºC and 19 ºC. Whether in the day or night discharge, this air temperature (T_{outlet}), which should provide heating to the internal ambient of the cubicle, was not enough to maintain a set point temperature of 18 ºC during all day, so the heat pump was switched on during 15 h each day.

The same type of experiment (DD) was performed during March 16th and 17th. This time weather conditions were milder than in the previous one with minimum and maximum temperature of 2 ºC and 12 ºC, respectively. Also, sunny conditions were registered with solar vertical irradiation values of 29 MJ/m^2 per day.

Looking at the temperatures evolution, the thermal performance of the active slab during DD experiment under mild winter conditions (Figure 11) does not reflect significant differences to the experiments presented before, where the same experiment was tested under severe conditions (Figure 10). Air temperature at the inlet of the slab (T_{inlet}) followed the same pattern during daytime, rising up at the same time as the solar radiation increased its intensity. The PCM inlet temperature also shows that the melting was achieved but with unstable conditions due to the day discharges.

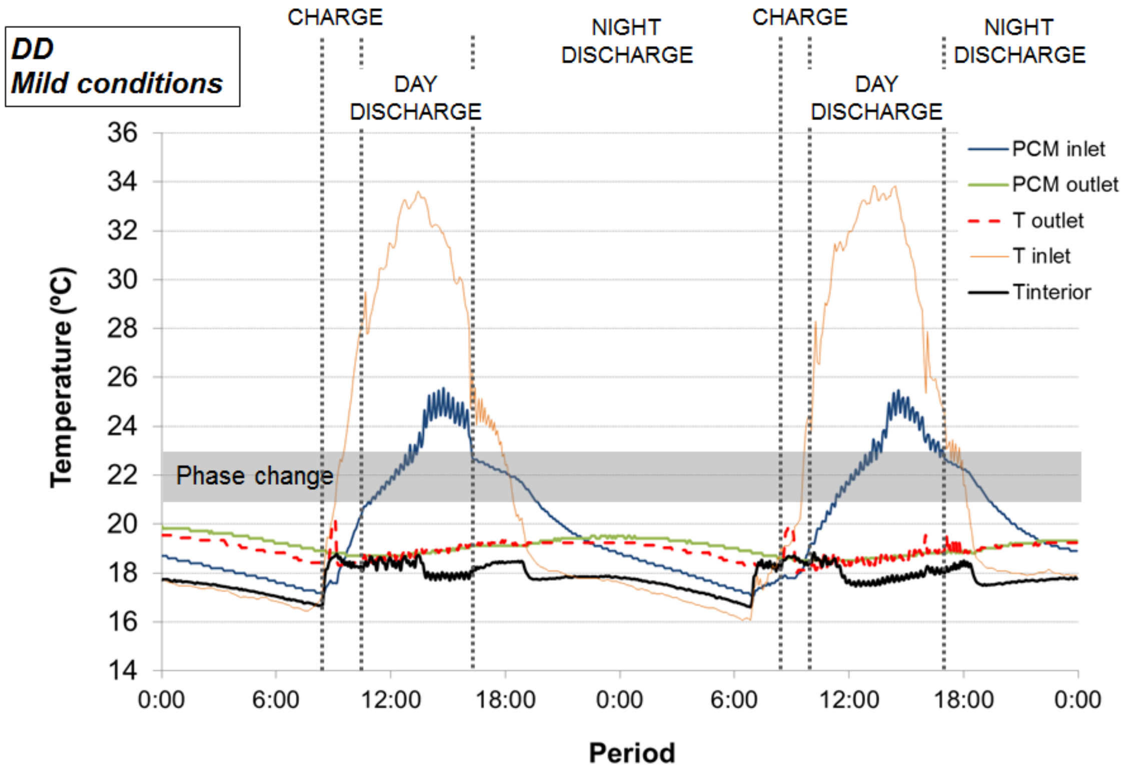

Figure 11. Temperature evolution of the active slab cubicle during 16th and 17th March.

Furthermore, the temperature (T_{outlet}) of the air supplied during the night discharge was between 19 ºC and 20 ºC. This fact together with the mild weather conditions of these days resulted in not using the heat pump at night, and just 6 h of heat pump use was registered. The energy consumption benefits provided from this are commented and analysed in following sections.

Finally, the *Day Discharge* with set point experiment (DD+SP) was tested to optimize the use of heat discharges during daytime and hence, maximize the energy benefits through the use of the active slab. Figure 12 presents the temperature evolution of the active slab during February 28th and March 1st under mild winter conditions. Minimum temperatures registered were between 3 ºC and 6 ºC, while maximum values fluctuated between 12 ºC and 15 ºC. Mostly sunny conditions were observed with daily solar vertical irradiation values of 24 MJ/m^2 and 20 MJ/m^2.

Similar results to the DD test under mild conditions (Figure 11) were observed in the DD+SP experiment. However, the variability of the solar radiation was observed in the temperature at inlet part of the slab (T_{inlet}), and as a result the PCM at the inlet does not completely melt during daytime. Moreover, the temperature of the air supply (T_{outlet}) was between 18.5 ºC and 19 ºC, contributing to a low use of the heat pump to achieve the set point temperature in the cubicle.

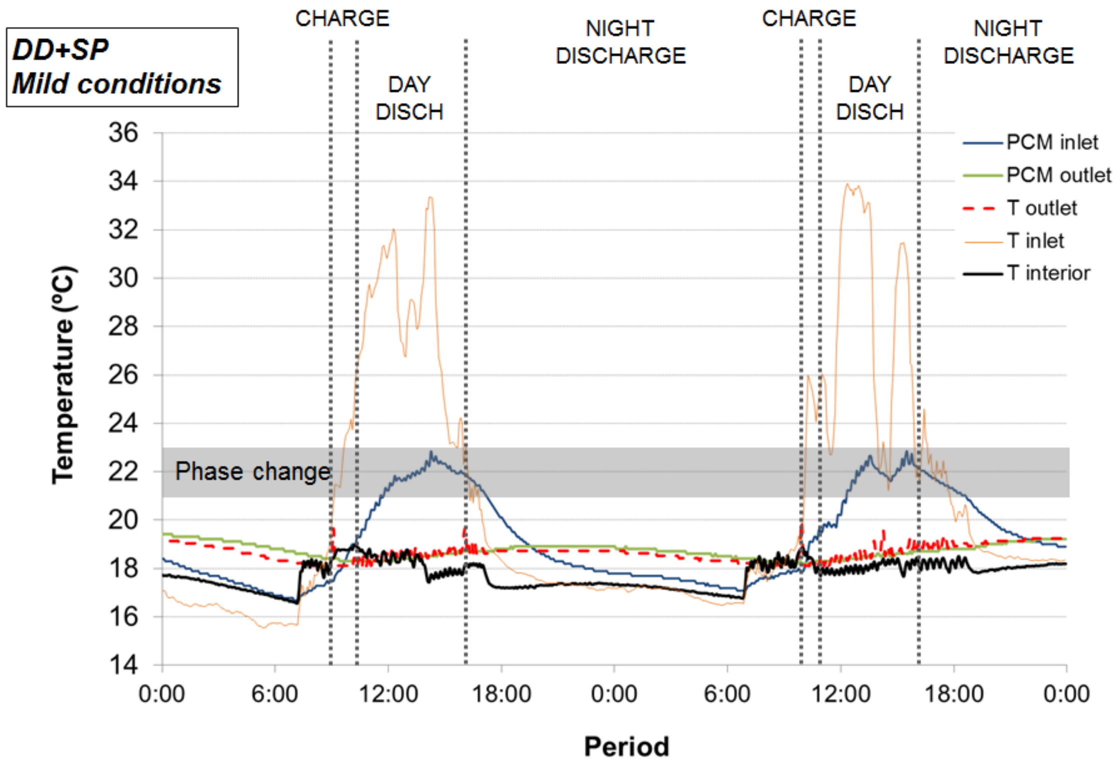

Figure 12. Temperature evolution of the active slab cubicle during February 28th and March 1st.

In general, the DD tests give priority to cover the heating demand during daytime. This fact implies that the PCM may not melt during day charging period, even though the weather conditions are favourable.

3.3 Electrical energy consumption comparison

3.3.1 *Heat Storage* test

The electrical energy consumption registered in the heat pump of the active slab and reference cubicle is compared in Figure 13. The three experiments of *Heat Storage* mode presented before in section 3.1 are distinguished by the PCM response. First, the heating demand from these experiments is reflected on the energy consumption of the reference cubicle, which oscillated between 4.5 kWh/day and 3 kWh/day depending on the outside temperature and especially on the daily solar irradiation.

Regarding the energy consumed by the active slab cubicle, some differences could be observed in the three experiments presented. The test performed during December, where the PCM was not melted due to the mostly cloudy conditions, energy consumption from the heat pump fluctuated between 2.8 kWh/day and 3.8 kWh/day. On the other hand, the electrical energy consumed by the active slab fan during December 16th and 17th demonstrates the fact that the system was almost stopped because of the no melting of the PCM. Thus, the energy savings achieved in the active slab during this test were between 9 % and 11 % compared to the reference cubicle.

Moreover, having similar heating demand to December experiments, in the tests performed in February the energy consumed by the heat pump of the active slab was reduced down to 1.7 – 2.7 kWh/day. However, the energy consumed by the fan due to the active slab operation was increased, being between 0.6 kWh/day and 1 kWh/day. Even though, energy savings achieved were between 16 % and 28 %.

Finally, in the experiments performed during March the heat pump of the active slab cubicle consumed less than 1 kWh/day. On the other hand, the reference cubicle consumed between 2.8 kWh/day and 3.8 kWh/day, which demonstrates that there was still heating demand during these days. Even though 1 kWh/day is added, as the energy consumed by the fan, to the energy consumed by the active slab, the achieved energy savings were between 48 % and 60 %.

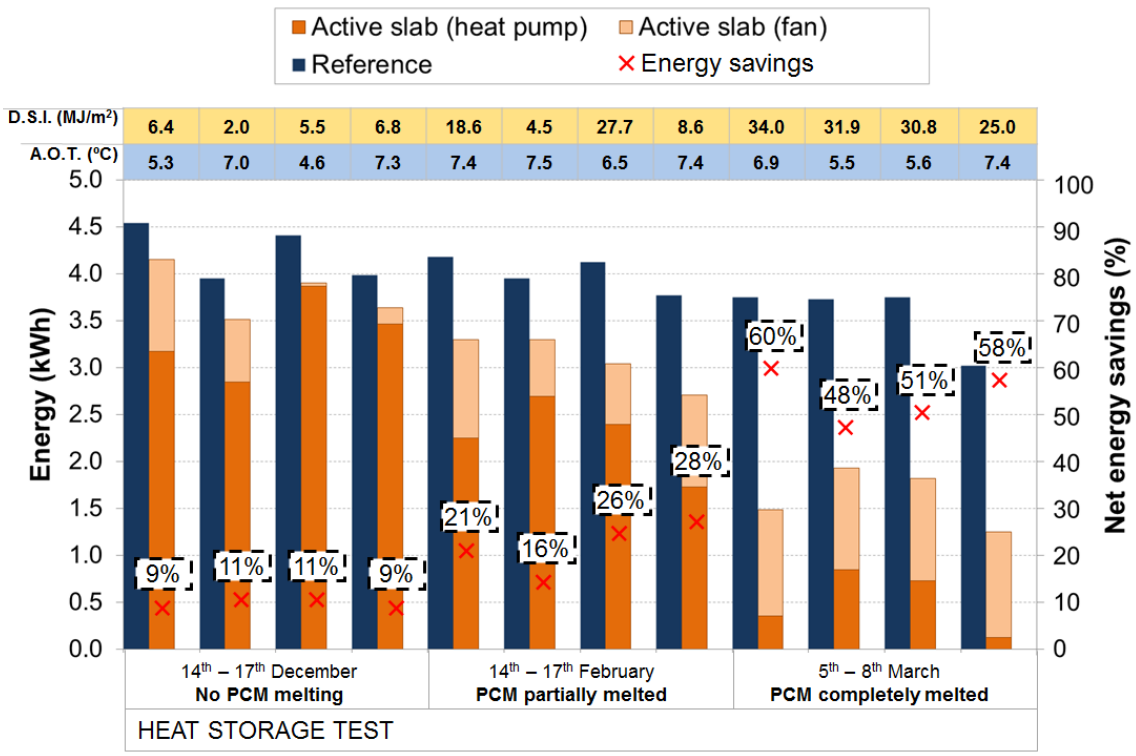

Figure 13. Electrical energy consumption of the heat pumps of the reference and active slab cubicle during *Heat Storage* experiments. D.S.I (Daily Solar Irradiance), A.O.T. (Average Outside Temperature).

Analysing the HS experiments the potential of the solar energy to cover the heating demand should be highlighted. The heating demand fraction covered by solar energy fluctuated between 20% and 40% under the cloudy and partly cloudy conditions, respectively. In addition, having completely sunny conditions the heating demand fraction covered by solar energy is between 80% and 90%.

3.3.2 *Day Discharge* test

In the *Day Discharge* tests, as it was explained before (section 3.2), two typologies of operation were tested, DD and DD + SP. The energy consumption of the DD experiments is presented in Figure 14, where values between both tests are significantly different due to the weather conditions. First, the experiment performed during February was subjected to sever winter conditions which are reflected on the energy consumed by the reference cubicle heat pump (around 4.7 kWh/day). During these days, the active slab cubicle needed a heating supply from the heat pump about 2.7 kWh/day. This represents between 21 % and 26 % of energy savings compared to the reference one taking into account the fan consumption. On the other hand, in the DD test performed during March, the reference cubicle consumed 3.5 kWh because of milder winter conditions. The heating demand was also reduced in the active slab cubicle that needed around 1 kWh/day of heating supply, achieving between 45% and 47% of energy savings compared to the reference. The energy savings mentioned take into account the energy consumption of the active slab fan that consumed 1 kWh/day.

In addition, DD + SP tests were performed under mild winter conditions and the two days presented in Figure 14 show quite different energy consumption values. Reference cubicle consumed between 2.5 kWh/day and 3.5 kWh/day, while the heat pump of the active slab cubicle consumed 1 kWh/day or less. The DD + SP operation was designed to optimize the performance of the active slab. The test performed during February 28th (DD + SP) can be compared to experiments of March (DD) because of their similar weather conditions (daily solar irradiance and average outside temperature). No significant differences can be observed in the energy consumption values between experiments DD and DD + SP. Therefore, under these conditions the DD + SP program did not provide any benefit to the active slab cubicle in terms of energy reduction.

Finally, the performance of HS and DD sequences during March experiments can be compared since weather conditions were similar (solar irradiance and outside temperature). In HS tests the heat pump of the active slab cubicle should cover the heating demand during daytime while the active slab is charging the PCM. On the other hand, in the DD mode the priority of covering the heating demand against charging the PCM should reduce the energy consumption of the heat pump during daytime. However, the results did not show a significant reduction on the energy consumption of the active slab heat pump in the DD tests compared to the HS ones.

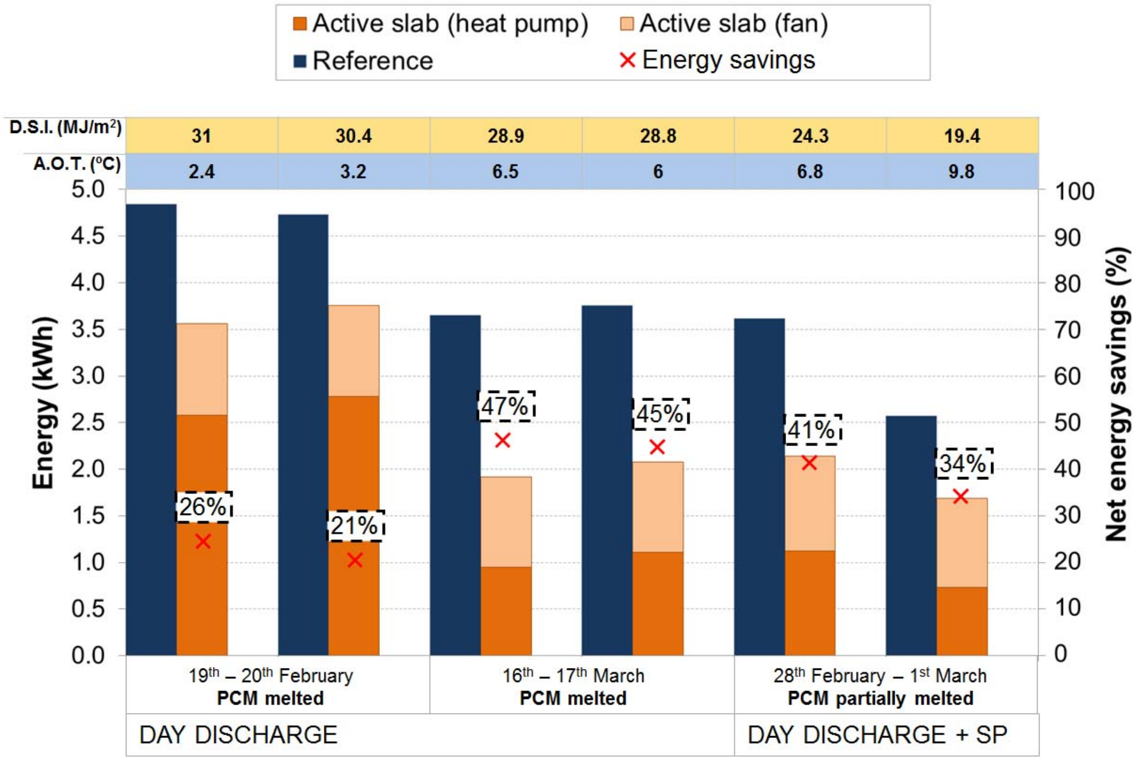

Figure 14. Electrical energy consumption of the heat pumps of the reference and active slab cubicle during *Day Discharge* experiments. D.S.I (Daily Solar Irradiance), A.O.T. (Average Outside Temperature).

4. Conclusions

A prefabricated concrete slab with macro-encapsulated phase change materials inside its hollows is designed to act as a storage unit and a heating supply for buildings. A complete experimental winter campaign is presented in this paper. The active slab performance is studied in the experimental set-up of Puigverd de Lleida (Spain). The innovative system is placed in a house-like cubicle where its performance is analysed and compared to a cubicle with a conventional heating system.

The active slab system is equipped with a control system which decides the operating conditions depending on the temperature of the system and the weather conditions. Three different operating programs were tested, *Heat Storage* (HS), *Day Discharge* (DD) and *Day Discharge and Set Point* (DD+SP) under severe and mild winter conditions.

As a general view, the experimentation shows the dependence on the weather conditions of the active slab performance, especially on the solar radiation. Thus, different PCM behaviour was registered achieving or not a complete melting and solidification depending on the weather conditions. Moreover, the PCM performance is always different between the material located at the inlet and outlet part of the slab. This fact should be studied in detail to optimize the ratio between the quantity of PCM and the solar collector area.

Concerning the energy consumption comparison between the active slab cubicle and the reference one, HS experiments demonstrated that with a partial PCM melting the active slab cubicle can achieve about 20% of energy savings compared to the reference cubicle. In addition, once the PCM can be melted and solidified completely, the energy savings increased up to 55%. It should be taken into account that these values are also dependant on the weather conditions to which the system is subjected.

Higher energy benefits were expected from *Day Discharge* (DD) sequence, since it should have reduced the energy consumption of the heat pump 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.

On the other hand, the control system plays an important role in the performance of the active slab. Hence, the importance on the strategies designed in the control system emphasise the need of optimization and improvement to achieve better performance of the active slab.

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