# Experimental study of a ventilated facade with PCM during winter period

Alvaro de Gracia[1], Lidia Navarro[1], Albert Castell[1], Álvaro Ruiz-Pardo[2], Servando Alvárez[2], Luisa F. Cabeza[1]

[1]GREA Innovació Concurrent, Universitat de Lleida, Edifici CREA, Pere de Cabrera s/n, 25001, Lleida, Spain. Tel: +34.973.00.35.77. Email: lcabeza@diei.udl.cat

[2]Grupo de Termotécnia, Universidad de Sevilla, Escuela de Ingenieros Camino de los Descubrimientos s/n. 41092, Seville, Spain, Phone: 34-954487471, Email: arp@esi.us.es

## Abstract

The aim of this article is to test experimentally the thermal performance of a ventilated double skin facade (DSF) with phase change material (PCM) in its air channel, during the heating season in the Mediterranean climate. Two identical house-like cubicles located in Puigverd de Lleida (Spain) were monitored during winter 2012, and in one of them, a ventilated facade with PCM was located in the south wall. This ventilated facade can operate under mechanical or natural ventilation mode and its thermal control depends on the weather conditions and the energetic demand of the building. Hence, three different tests were performed: free floating, controlled temperature and demand profile conditions. The experimental results conclude that the use of the ventilated facade with PCM improves significantly the thermal behaviour of the whole building (working as a heat supplier in free floating tests and reducing significantly the electrical consumption of the HVAC systems). However, these improvements might be increased if thermal control is used. Moreover, the measured electrical energy consumption of the heat pumps and fans indicates that the use of mechanical ventilation in this system is not justified; unless a fast heating supply is needed.

**Key-words:** Double skin facades (DSF), phase change materials (PCM), buildings, experimental measurements.

## 1. Introduction

New policies are being promoted all over the world to reduce the energetic demand of the HVAC systems used in the building sector, and hence reduce the $CO_2$ emissions. In the world, the building sector (residential and commercial) is consuming around 40 % of the final energy [1]. In order to reduce this high energy demand, the European directive on the energy performance of buildings [2] dictates that all the EU member states must approve energetic policies to promote the inclusion of very low and even close to zero energy buildings.

The high potential of the building envelopes in the energy demand reduction and consequently in electrical energy savings has been widely proved [3-5]. The main effort in this topic was focused in increasing the thermal resistance of the envelopes by improving the insulation [6,7]. However, a lot of research also evaluated its thermal energy storage capacity. Within this context, many latent heat storage applications in buildings have been studied [8-10], since the use of phase change materials (PCM) in the envelopes smoothes the daily temperature fluctuations and can absorb solar radiation and internal thermal loads [11].

In addition, the use of ventilated double skin facades (DSF) in the building sector has recently become more popular. Those facades, if well designed, can efficiently reduce the overall HVAC energy consumption of buildings by absorbing part of the solar radiation during winter and preventing overheating during warm periods [12]. Those constructive systems are based on a special type of envelope, where a second skin, usually a transparent glazing, is placed in front of a regular building facade. The air space in between (the channel) can be mechanically or naturally ventilated to improve the thermal performance of the building [13]. Ventilated facades can operate under different modes (Trombe wall, internal and/or external ventilation) depending on the air flow path, as shown in Figure 1.

In this study, the use of PCM is combined with the ventilated facade constructive system. Macro-encapsulated PCM panels were installed inside the air chamber of a ventilated facade, and its thermal performance was experimentally studied and compared against a conventional constructive system. Two identical house-like cubicles were monitored, and in one of them, a ventilated facade with PCM was located in the south wall.

The PCM inside the air cavity will not only increase the solar energy absorption capacity during winter but it might be used as a cold storage system during warm periods, as well. This ventilated facade with PCM in the air chamber might reduce both heating and cooling demands of the building. However, this paper fully describes the available experimental set-up, focusing in the potential of using this special building envelope to reduce the heating demand during winter period.

## 2. Experimental set-up

In order to test the improvement in the thermal performance of a building due to the use of a ventilated DSF with PCM in its air cavity, two real cubicles with the same inner dimensions (2.4 x 2.4 x 5.1 m) were monitored in the experimental set-up located in Puigverd de Lleida, Spain. The constructive system used in the walls of both cubicles is based on alveolar bricks (30 x 19 x 29 cm) with an external cement mortar and inner plaster coating. The only difference between the two cubicles is that one of them has a ventilated facade with PCM inside its air chamber in the south wall, while the other cubicle keeps the basic constructive system (Figure 2). Both roofs were made using concrete pre-cast beams, 3 cm of polyurethane and 5 cm of concrete slab. The polyurethane is placed over the concrete and it is protected with a cement mortar roof with an inclination of 3%, a double asphalt membrane and 5 cm of gravel [5].

A metallic structure is used to build the ventilated facade with an air cavity of 15 cm thick, which represents 0.36 m$^2$ of channel area ( $A_{channel}$ ). The inner layer is based on the alveolar brick constructive system while the outer envelope is made by a glass layer.

The ventilated facade has an effective solar absorption area of 6.4 m$^2$ ( $A_{solar}$ ) and it is equipped with three fans (FCL 133 Airtecnics) in the inlet of the air channel to provide mechanical ventilation when needed. Moreover, in order to control the operational mode of the facade, six automatized gates (Figure 3) were installed at the different openings of the channel. Hence, the air can flow through the facade from outdoor or indoor, or operate as a Trombe wall. Those gates are controlled by ST450N linear spindle actuators. A system to control the fans and gates is programmed in a Microchip 18F45J10.

The PCM used in this application was the macro-encapsulated salt hydrate SP-22 from Rubitherm. The selection of this PCM (melting temperature at 22 ºC) allows the ventilated facade to store high quantities of solar energy during winter periods, and to be used as a cold storage system during summer periods using the night free cooling effect. A total of 112 PCM panels are distributed over the facade creating 14 air flow channels as shown in Figure 4. The use of this thin air flow channels maximizes the heat transfer area between the air flow and the PCM.

Both cubicles were fully instrumented and the following data was registered at five minutes intervals to evaluate their thermal performance:

- Internal wall temperatures (east, west, north, south, roof and floor) measured with Pt-100 DIN B.
- Indoor air temperature and humidity (at a height of 1.5 m and 4.5 m) measured with ELEKTRONIK EE21.
- Electrical consumption of the HVAC systems using an electrical network analyser (MK-30-LCD).

Moreover, in order to analyse the behaviour of the ventilated facade with PCM, the following data was also measured:

- Air temperature of the cavity at different heights and locations (10 Pt-100 with an irradiative cover).
- Air velocity of the cavity at different heights and locations (4 hot wire sensors KIMO CTV 210).
- Pressure drop across the air cavity (KIMO CP 200).
- Outer and inner skin surface temperature (glass and alveolar brick, respectively) at different heights and locations (6 Pt-100 each).
- External surface temperature at different heights and locations (6 Pt-100).
- Heat flux transferred to indoor (2 HUKSEFLUX HFP01).

- Heat flux transferred to the front and back surface of a PCM panel (2 HUKSEFLUX HFP01).
- Temperature of the PCM at three different heights (3 Thermocouples Type T, 0.5 mm thick inserted in the PCM panels).
- Front and back surface temperature of the PCM panels (2 Thermocouples Type T).

In addition, the weather data was also registered every 5 minutes. Two Middleton Solar pyranometers SK08 were used to capture the horizontal and vertical global solar radiation, the outer air temperature and humidity were measured using an ELEKTRONIK EE21 with a metallic shield to be protected against radiation, and finally the wind speed and direction was provided by a DNA 024 anemometer.

The experimental set-up offers the possibility to perform two kinds of indoor conditions: free floating temperature and fixed controlled temperature. Both cubicles are provided by two heat pumps (Fujitsu Inverter ASHA07LCC), located at different heights (3 and 5 m).

## 3. Methodology

In this paper, the thermal performance of the ventilated facade is experimentally tested under different weather conditions (severe and mild Mediterranean winter), thermal control (free floating and controlled temperature conditions) and ventilation mode (mechanically and naturally ventilated facade). The different tests under severe winter (SW) conditions were performed from the 9$^{th}$ to the 22$^{nd}$ of February 2012, which were clear sunny days (global solar radiation peaks of 1200 W/m$^2$) with an outer temperature oscillating from around 12 ºC to -4 ºC. On the other hand, the mild winter (MW) conditions experiments were tested from the 1$^{st}$ to the 29$^{th}$ of March 2012, with similar solar radiation than in the previous experiments (global solar radiation peaks of 1100 W/m$^2$) but with outer temperatures varying from 24 ºC to 4 ºC.

The sequence of operation of all the experiments is similar and is shown in Figure 4. The ventilated facade acts as a solar collector during the solar absorption period (Figure

5a). Once the PCM is melted and the solar energy is needed by the heating demand, the heat discharge period starts. During this period the openings drive the air flowing from indoor to the facade cavity, where it is heated up by the PCM panels and sent it back into the cubicle (Figure 5b). This discharge period is performed until no more thermal energy is needed or can be provided by the facade; hereafter the system closes all the openings, acting as a Trombe wall, to minimize the heat losses to the environment (Figure 5c). The different weather conditions and energetic demand scenarios define the timing of this mode of operation as well as the ventilation mode.

As it was previously said, the thermal control of the ventilated facade depends on the weather conditions and the energetic demand of the building, for that purpose three different experiments were performed:

- Free floating (FF): During these experiments no HVAC system is used, hence the thermal response of the building is evaluated by its indoor air temperature. This experiment is presented in the mechanically ventilated mode for severe and mild winter weather conditions. During the experiments under severe winter conditions, the system discharges the absorbed solar heat from 12:00 to 18:00 h, while during the mild winter test, the discharge period is programmed from 18:00 to 23:00 h.
- Controlled Temperature (CT): The indoor temperature of each cubicle is fixed by using the heat pumps. The electrical energy consumed by each heat pump is measured and compared. This experiment was performed in the mechanically and naturally ventilated mode for severe and mild winter weather conditions. Moreover, different temperatures set points were analysed. Similarly as in the FF experiment, the heat discharge schedule varies depending on the weather conditions (from 12:00 to 18:00 h during severe winter conditions and from 12:00 to 23:00 h in the mild period).
- Demand Profile (DP): In the mild season, the HVAC systems were controlled by a timer, so they operate altogether with the facade from 18:00 to 23:00 h, simulating the demand profile of a conventional house. This experiment is presented with the facade operating as a Trombe wall, and in the mechanically and naturally ventilated mode.

In order to analyse the thermal performance of the system two parameters are introduced. The heat injection efficiency ($\eta_{sol}$) is calculated as the ratio between the amount of heat that the system is able to pump to the inner environment ($Q_{fac}$), by the amount of solar heat absorbed by the facade ($Q_{sol}$), as shown in Equation 1.

$$\eta_{sol} = \frac{Q_{fac}}{Q_{sol}} \qquad \text{(Eq.1)}$$

where,

$$Q_{sol} = \int \dot{Q}_{glob\_rad} \cdot A_{solar} \cdot dt \qquad \text{(Eq.2)}$$

$$Q_{fac} = A_{channel} \cdot \rho_{air} \cdot Cp_{air} \cdot \int v_{air} \cdot (T_{outlet} - T_{inlet}) \cdot dt \qquad \text{(Eq.3)}$$

The second parameter is the load reduction efficiency ($\eta_{load}$), which is used in the controlled temperature and demand profile experiments and is defined as the ratio between the thermal energy saved in the heat pump ($Q_{load\_reduction}$), by the amount of heat injected by the facade ($Q_{fac}$). The electrical energy savings measured from the heat pumps installed in the reference and ventilated facade cubicles are multiplied by the COP (4.55 kW/kW) of these heat pumps in order to calculate the $Q_{load\_reduction}$.

$$\eta_{load} = \frac{Q_{load\_reduction}}{Q_{fac}} \qquad \text{(Eq.4)}$$

## 4. Results

4.1 Free floating (FF)

4.1.1 FF under severe winter (FF SW)

The free floating experiments were tested under severe and mild winter conditions. The severe winter experiment was performed from the 9$^{th}$ to the 12$^{th}$ of February 2012. During these four days, the measured outdoor temperature oscillated from 8 to -4ºC, and the global radiation on vertical surface was 99.6 MJ/m2, giving a total radiation incident on the facade of 159.37 MJ / day (Eq.2). A fraction of the absorbed heat is pumped to the interior of the cubicle from 12:00 to 18:00 using the fans at a fixed air flow rate of 2600 $m^3$/h. The heat injected from the facade to the inner environment was 57.2 MJ/day (Eq.3), hence the system has an efficiency of pumping the absorbed solar heat of 36 % (Eq.1). The amount of solar heat which was not pumped to the interior regards to heat losses to the environment and the reflection of solar radiation occurring in the outer skin. Moreover, it is important to highlight that the temperature of the overall thermal mass of the facade at the end of the discharge is much higher (around 20ºC) than the temperature at the beginning of the solar absorption period (around 0ºC). Hence, part of the solar heat is also used to cover this difference.

The indoor temperatures of both cubicles are presented in Figure 6. The indoor temperature of the reference cubicle (REF) drops daily due to the tendency of the outdoor temperature, while the use of the ventilated facade with PCM (FAC) makes the temperature increase every day from 9 ºC to 18 ºC. The discharge period of the system is also shown in Figure 6.

The thermal profiles of the PCM and the air flow at the inlet and outlet of the channel are presented in Figure 7 altogether with the indoor and outdoor environmental temperatures of the ventilated facade cubicle during the $12^{th}$ of February 2012. This figure shows that the system does not use the whole available latent heat, stored in the PCM, since after the discharge (18.00 h) the PCM in the upper part of the facade is just starting its solidification process. Hence, the discharge might have been prolonged in order to take advantage of the stored latent heat. Thus indicates the necessity of using a thermal control system which can be programmed depending on the energy demand, production and storage, and not only using the time as controlling parameter.

The PCM and air flow temperature drops to values close to 0 ºC during night time. However, the temperatures of the whole ventilated facade increase fast with the solar radiation due to the greenhouse effect, achieving its maximum just before the discharge. A vertical thermal gradient was measured in the airflow during the solar absorption period (12 ºC) indicating an important air stratification in the air channel.

It is important to highlight that the system is still absorbing solar radiation during the discharge period, when working under these operational mode. This is why the PCM and air flow temperatures increase until 15:00 even though part of the solar heat is being used and injected to the interior of the cubicle.

Figure 7 also shows that the inlet temperature of the channel is not equal to the indoor temperature, which coincides with the measurements and simulations performed by Saelens et al. [14]. This research stated that in order to estimate the inlet temperature entering in a ventilated facade, the heating and cooling due to contact with the bounding surfaces must be taken into account, as well as the heating due to solar radiation.

4.1.2 FF under mild winter (FF MW)

The free floating experiment under mild winter weather conditions was tested the 16th and 17th of March 2012. The solar radiation incident to the facade during these two days was 163.2 MJ/day (Eq.2). The system discharges this solar heat from 18:00 to 23:00, injecting to the indoor environment 31.6 MJ/day, which produces a $\eta_{sol}$ =19.4 %. It can be seen that the efficiency of pumping the absorbed solar heat has been reduced in comparison to the previous experiment (FF under severe conditions). This occurs because in the experiment described in Figure 6 the heat is being discharged at the same time as it is being absorbed. On the other hand, in the experiment presented in Figure 8 the absorbed solar energy is stored for later uses and hence exposed during more time to the heat losses to the environment. The measurements under these climatic conditions proved that the ventilated facade improves strongly the thermal performance of the cubicle, making the use of HVAC system almost not necessary, since the indoor temperature is nearly all the time inside the thermal comfort range.

During this experiment, since the discharge was programmed after the whole solar energy was absorbed, the PCM at the upper part of the facade achieved 55 ºC (Figure 9). Looking at the PCM curve, both melting and solidification process can be easily identified, showing an important hysteresis between the phase change temperatures during heating (23 ºC) and cooling (20 ºC). Furthermore, it can be also seen that the latent heat is only partially used and the discharge process might have been prolonged.

Finally, special attention on the PCM temperature peak must be taken into account in order to avoid melting of the nucleants included in the PCM, which will lead to stronger subcooling effects and the malfunction of the system.

### 4.2 Controlled temperature (CT)

#### 4.2.1 CT 21 ºC Mechanically Ventilated under severe winter (CT MV SW 21)

As previously said, during the controlled temperature experiments, two heat pumps were used in each cubicle and their electrical energy consumption was registered. The first CT experiment was tested from the $15^{th}$ to the $17^{th}$ of February 2012 with the heat pumps working the whole day at a set point of 21ºC and the fans pumping air from 12:00 to 18:00 h. The solar heat incident to the facade during this period was 169.6 MJ/day (Eq.2) and the heat injected from the facade to the indoor environment was 60.56 MJ/day, giving an efficiency $\eta_{sol}$ of 35.7 %. Note that this efficiency is similar to the value in the free floating experiment under the same climatic conditions and time schedule of discharge (36 %).

Figure 10 shows that the heat pumps in the reference cubicle were working all the time, while in the FAC cubicle the heat pumps did not need to heat up the indoor air during the discharge period. Thus, produces a significant difference in the electrical energy consumption of the HVAC system of the REF cubicle (40.58 MJ/day) and the FAC cubicle (30.76 MJ/day). In addition, in the mechanically ventilated experiments it is important to take into account the electrical energy consumption of the fans (120 W). The fans consumed 2.59 MJ/day, hence the use of the ventilated facade operating under the described conditions achieved a net electrical energy reduction of the HVAC system of 7.77 MJ/day (19.14 % in comparison to the reference). This energy savings would have been higher if the system had used the stored latent heat in the discharge period. However, it could not be used since the set point of the HVAC system was set to 21 ºC and the solidification process of the PCM SP-22 was at 20 ºC.

Furthermore, the 9.82 MJ/day of electrical energy savings registered from the heat pumps corresponds to 44.681 MJ/day of thermal energy savings, since the COP of the heat pumps is 4.55 kW/kW. Hence, the system operating under these conditions presents a load reduction efficiency $\eta_{load}$ of 73.7% (Eq.4). It is important to highlight that not all the heat injected by the facade can be directly used to reduce the heating load of the cubicle, since the FAC cubicle presented an important stratification of the air inside (the hot air is pumped to inside from the upper part of the facade), and overheating of the indoor environment above the set point temperature, which increases the heat losses to the outer environment in comparison to the REF cubicle.

4.2.2 CT 19 ºC Mechanically Ventilated under severe winter (CT MV SW 19)

As it was discussed, in the previous experiment the PCM did not release its latent heat during the discharge period, since its phase change temperature during the solidification process was below the HVAC set point (19 ºC and 21 ºC, respectively). Therefore, the previous experiment was repeated with a set point of 19 ºC during the 18$^{th}$ and 19$^{th}$ of February 2012. However, the latent heat could not been injected to the indoor environment during this experiment since, once the discharge period was finished, the PCM was still above the phase change range.

Nevertheless, the experiment was useful to determine how the set point of the HVAC system influences the efficiency of the ventilated facade.The solar heat incident to the facade during this period was 163.9 MJ/day (Eq.1) and the heat injected from the facade to the indoor environment was 52.73 MJ/day ($\eta_{sol}$ of 32.2 %). Moreover, the ventilated facade presents a load reduction efficiency ($\eta_{load}$ ) of 92.3 %, which involves an electrical energy reduction of 34 % in the FAC cubicle compared to the REF one.

4.2.3 CT 21 ºC Naturally Ventilated under severe winter (CT NV SW 21)

From the 21$^{st}$ to the 23$^{rd}$ of February 2012 the system was programmed to discharge the absorbed solar radiation from 12:00 to 18:00 without the use of fans. The registered thermal profiles during this experiment are presented in Figure 11, showing how the indoor environmental temperature did not vary abruptly once the naturally ventilated discharge started. The system operating under this mode reduced the electrical energy consumption of the HVAC in 7.79 MJ/day (18.7 % in comparison to the reference cubicle), which is similar to the electrical energy savings achieved in the analogue experiment with the facade using the fans (CT MV SW 21). However, it is important to highlight that the HVAC system was operating due to insufficient temperature at the beginning of the discharge, while it did not operate during the whole discharge in the mechanically ventilated test. Thus, the use of fans is unnecessary in this system, unless the energetic demand of the indoor environment needs a fast response.

The heat injection efficiency $\eta_{sol}$ was 35.2 %, close to the one in mechanically ventilated test. This high value might not be expected because of the difference in the air velocities, 1.9 m/s in the MV tests and less than 0.7 m/s when NV, as it can be seen in Figure 11. However, it is justified by the high thermal gradient between the inlet and outlet of the channel, being more than 12 ºC when naturally ventilated, while this value was less than 4 ºC in the mechanically ventilated operational mode.

The latent heat stored in the PCM could not be used during the heat discharge of this experiment, since the temperature at which the heat pumps are set (21 ºC), is higher than the phase change temperature (20ºC).

4.2.4 CT 19 ºC Mechanically Ventilated under mild winter (CT MV MW 19)

The mild winter conditions allow the system to discharge the absorbed solar heat from 12:00 to 23:00. Thus, altogether with the low set point of the heat pumps (19 ºC) enables the use of part of the stored latent heat in the PCM during its solidification process, as seen in Figure 12. In the experiment performed from the 1$^{st}$ to the 3$^{rd}$ of March 2012, the HVAC system of the FAC cubicle not only did not need to provide heat during the discharge period, but during several hours after the discharge has finished, as well. Hence, the discharge period might have been prolonged and/or started earlier, which highlights again the necessity of using a programmable thermal control system.

The facade injected 62.85 MJ/day, being the 40 % of the incident solar radiation. Although the heat injection is useful and makes the use of HVAC unnecessary during the whole discharge, this is more significant during the first 6 hours, when the thermal gradient between the inlet and outlet channel achieves 4 ºC. Moreover, this injected heat increases the indoor temperature up to 28 ºC, producing overheating and underlining the critical necessity of a thermal control system.

The use of the ventilated facade under this operational mode reduces a 57 % the electrical energy consumption of the HVAC in comparison to the REF cubicle. However, it must be taken into account that from the 8.443 MJ/day saved by the system, the fans consumed 4.75 MJ/day. It is important to highlight the energy consumption difference in the REF depending on the weather conditions. It consumed 14.673 MJ/day and 31.3 MJ/day during mild and severe winter conditions, respectively.

### 4.3 Demand Profile (DP)

#### 4.3.1 DP 19 ºC Naturally Ventilated under mild winter (DP NV MW 19)

During the demand profile experiments, the HVAC system was only connected from 18:00 to 23.00, simulating a real domestic thermal demand. In the FAC cubicle, the ventilated facade discharged the stored heat during this demand period. The system operating in naturally ventilated mode reduced the electrical energy consumption of the HVAC from 2.565 MJ/day (REF) to 0.353 MJ/day (FAC), being the use of an active heating system under mild winter conditions almost unnecessary. Furthermore, as shown in Figure 13, the PCM releases part of its stored latent heat, and the indoor temperature of the FAC cubicle is inside the thermal comfort range almost during the whole demand period.

The thermal profile of the PCM close to the inlet of the channel shows clearly the melting and solidification process occurring from 10:30 to 12:00 h and from 20:30 to 1:00 h, respectively. The solidification process of the PCM shows a clear hysteresis in the phase change temperature when compared against the melting (fusion at 23 ºC and solidification at 20 ºC). Moreover, this process is clearly affected by subcooling. Even though the phase change temperature during the solidification is at 20 ºC, the PCM temperature falls down to 18 ºC without starting the solidification process, hereafter, once the crystallization starts, the PCM returns to 20 ºC where phase change occurs.

4.3.2 DP 19 ºC Mechanically Ventilated under mild winter (DP MV MW 19)

The ventilated facade operating with mechanical ventilation under mild winter conditions reduces the electrical energy consumption of the HVAC from 4.625 MJ/day (REF) to 1.976 MJ/day (FAC). However, this 2.65 MJ/day of electrical energy savings does not balance the energy consumed by the fans during the experiment (4.75 MJ/day), which supports the idea that the fans must be only used when a fast thermal heating is demanded in the cubicle.

4.3.3 DP 18 ºC Trombe Wall under mild winter (DP TW MW 18)

As previously discussed, after the heat discharge period, the ventilated facade can operate as a Trombe Wall, and hence reduce the heat losses through the southern facade as well as acting as a solar collector. In the experiment performed from the 27$^{th}$ to the 29$^{th}$ of March 2012 (mild winter conditions), the HVAC system was programmed to operate from 18:00 to 23:00 h with a set point at 18 ºC. The Trombe wall, by limiting the heat losses, decreases the electrical energy consumption from 1.82 MJ/day (REF) to 0.44 MJ/day (FAC), which implies a reduction of more than 75 %, without any ventilation system under these climatic conditions and thermal demand.

## 5. Discussion

A summary of the main results extracted from the Controlled Temperature (CT) and Demand Profile (DP) experiments is presented in Table 1. The heat injection efficiency ($\eta_{sol}$) is very sensitive to the operational schedule, being around 35 % when the system discharges the absorbed solar radiation from 12:00 to 18:00 h (severe winter experiments), 40 % when this discharge period is extended until 23:00 h. This heat injection efficiency is reduced significantly for the demand profile experiments, since the use of the solar energy (from 18:00 to 23:00) does not match with its production. During these experiments, a significant difference was measured between the mechanically ventilated (19 %) and the naturally ventilated (10.9 %) operational mode, which is justified since the use of fans supplies the stored heat faster, limiting the heat losses.

Moreover, the heat injected to the facade does not directly reduce the electrical energy consumption of the HVAC system, since higher heat losses due to overheating above the set point and air stratification occur in the FAC cubicle. The facade presents the higher load reduction efficiency ($\eta_{load}$) when operating with the fans from 12:00 to 18:00 h and with the set point at 19 ºC.

As shown in Table 1, the use of the facade under the mechanically ventilated mode is unnecessary; unless a fast heating supply is needed. This is justified by looking at the net energy savings that the system can achieve when operating under severe winter conditions at 21 ºC (7.77 MJ/day and 7.79 MJ/day for MV and NV, respectively). Furthermore, the use of fans implies an extra energetic cost to the system when used under mild winter conditions, since the energy savings measured in the HVAC do not compensate the electrical energy spent in the fans (2.65 MJ/day and 4.75 MJ/day, respectively).

It is important to highlight the difference of energetic requirements depending on the weather conditions. This difference strongly influences the percentage of energy savings and must be taken into account when comparing operational modes.

## 6. Conclusions

The thermal behaviour of a ventilated facade with macro-encapsulated PCM in its air cavity is experimentally evaluated and presented in this paper. The experimental set-up consists of two identical house-like cubicles (2.4 x 2.4 x 5.1 m indoor dimensions). The only difference between the two cubicles is that in one of them a ventilated facade with macro-encapsulated PCM (SP 22) inside its air chamber is constructed in the south wall. The ventilated facade acts as a solar collector during the solar absorption period, until the solar energy is demanded and can be discharged to the indoor environment.

Three different sets of experiments were presented in order to test the thermal performance of the system operating under severe and mild winter conditions: free floating, controlled temperature, and demand profile experiments.
The thermal performance of the whole cubicle is improved by the use of this ventilated facade under free floating conditions. While the indoor temperature of the reference cubicle drops daily due to the oscillation of the outer temperature, the use of the ventilated facade with PCM increases the temperature every day from 9 ºC to 18 ºC under severe winter conditions. Moreover, the free floating experiments demonstrated that the use of HVAC system is almost not necessary during the mild winter period.

The use of the ventilated facade reduces significantly the electrical energy consumptions of the installed HVAC systems. These savings depend strongly on the mode of operation and the weather conditions. The authors want to highlight the energy savings registered during the experiments under severe winter, being 19 % and 26 % depending on the HVAC set point (21 ºC and 19 ºC, respectively). It is expected that those values would have been even higher if a thermal control system would have been programmed depending on the energy demand, production and storage.

The measured electrical energy consumption of the heat pumps and fans demonstrated that the use of mechanical ventilation in this system is unnecessary unless a fast heating supply is needed. Furthermore, the experimental results showed that the use of mechanical ventilation during low heating demands periods can produce higher electrical consumption of the overall system, since the energy saved by the HVAC systems does not compensate the electrical energy consumed by the fans.

Moreover, the use of SP-22 as PCM provides almost no thermal benefits in this system, since its phase change temperature during the solidification process is very low (20ºC) to be used in this facade, and only in some operational modes, a part of the stored latent heat is injected to the indoor environment. Hence it must be highlighted that if the system would have used the whole latent heat stored in the PCM, it would have provided even higher thermal benefits.

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## Nomenclature

| | |
|---|---|
| $A_{channel}$ | Cross sectional area of the ventilated facade cavity [m2] |
| $A_{solar}$ | Effective solar absorption area [m2] |
| $Cp_{air}$ | Air heat capacity, [J kg-1 K-1] |
| $Q_{fac}$ | Total injected heat supplied from the facade [J] |
| $Q_{load\_reduction}$ | Thermal load difference between the REF and the FAC cubicle [J] |
| $Q_{sol}$ | Total solar radiation incident in the DSF [J] |
| $\dot{Q}_{glob\_rad}$ | Incident vertical global solar radiation [W m-2] |
| $T_{inlet}$ | Temperature at the inlet of the DSF channel [K] |
| $T_{outlet}$ | Temperature at the outlet of the DSF channel [K] |
| t | Time [s] |
| $v_{air}$ | Air velocity [m s-1] |

Greek symbols

| | |
|---|---|
| $\rho_{air}$ | Air density [kg m-3] |
| $\eta_{load}$ | Load reduction efficiency |
| $\eta_{sol}$ | Heat injection efficiency |