Influence of the use of PCM drywall and the fenestration in building retrofitting

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Building retrofitting is one of actions promoted by the European Union in order to reduce the energy dependence, the consumption of fossil fuels and the CO₂ emissions. In climates with high thermal variability, thermal mass can increase the hours of thermal comfort and reduce the need for mechanical conditioning systems, helping to reduce the energy consumption in both new and existing buildings. However, it is not always feasible to use traditional materials to increase thermal energy storage in building retrofitting. The use of Phase Change Materials (PCM) can be an alternative to provide high thermal storage capacity to rehabilitated buildings as their applications have relatively low weight and need little or no additional space. Different ways in which PCM can be used in building rehabilitation have been analyzed, and the influence of PCM drywall panels and fenestration was evaluated in different Spanish cities. The results reflect the importance of the Window to Wall ratio and the Shading Factor in the thermal behavior of buildings. Also, they show that, with proper selection of these parameters, the use of PCM drywall can contribute to increase the thermal comfort, reducing the peaks and temperature fluctuations in existing buildings, particularly under overheating conditions.

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1. Introduction

The European Union has been taking steps to reduce energy consumption in buildings, ensuring comfort conditions. Directive 2010/31/CE hardens the energy efficiency requirements for both new and existing buildings [1], moving toward nearly zero energy buildings by 2020. This directive emphasizes that the consumption of fossil energy must be reduced, increasing both the energy efficiency and the use renewable energy. Its goals include reducing CO₂ emissions, securing of energy supplies and minimizing the energy dependency in EU countries. The energy dependence, in Spain, is greater than the EU average, reaching almost 75% [2]. Therefore in this country is more urgent to strengthen energy measures in the building sector.

In Spain, most of the energy consumption in buildings is related to external climate protection and the need for mechanical systems to maintain indoor comfort [2]. This situation is aggravated by the growing demand for air conditioning. Buildings constructed using the 2006 Building Code (CTE) will have better energy performance, but the existing buildings are the main consumers of energy. In Spain, there are currently 2262 million m² of housing and 476 million m² of commercial buildings constructed before the new energy requirements [1]. It is necessary to implement corrective design strategies, and use materials and equipment that help improve the energy performance of the existing building stock.

Improving the envelope is a fundamental action to increase the energy efficiency of existing buildings. The retrofitting building process usually includes increasing the insulation level and the improvement of glazing. The Spanish climatic zones in general have significant daily temperature swings. This variability in daily temperature enables the use of other strategies that could further increase the efficiency of existing buildings. Some of these strategies are related to thermal mass, Window to Wall ratio (WW ratio) and Shading Factor (Fs). Thermal mass has a significant influence on the heat transfer inside building spaces, providing them Thermal Energy Storage capacity. This capacity helps to reduce thermal peaks and smooth thermal variations within buildings, contributing to increased thermal comfort, and reducing the necessity of mechanical conditioning equipment. In heating periods, the heat that penetrates the interior of the buildings is storage and released hours later when there is no solar contribution. In cooling periods, the thermal mass can eliminate or reduce the overheating. The proper selection of the glazing characteristics, its size and its...
shading devices, has also a significant impact in the interior comfort, reducing the need of mechanical equipment for heating or cooling the buildings [3]. The thermal mass and the fenestration are related, the optimal amount of thermal mass required depends on, among other things, the area of glazing [4]. The “Mass to glass ratio” defines the relationship between the areas of thermal mass and the glazing. Proper planning of fenestration and thermal mass could increase the benefits of solar radiation during heating periods and avoid overheating during cooling periods, thus improving thermal conditions and also helping to reduce energy consumption.

Usually, heavy building materials, such as stone, brick or concrete, are used to provide thermal mass in buildings. Thermal Energy Storage capacity of these materials is linked to their weight (mass), the heavier the material the higher the thermal energy stored. However, in building retrofitting, when it is necessary to increase thermal mass, is not always feasible to use heavy materials, due to the excess weight added to the structure, or due the reduction of interior space. An alternative is the Latent Heat Thermal Energy Storage using Phase Change Materials (PCM). These materials are substances of relatively low weight and high heat of fusion, capable of storing and releasing a large amount of heat in latent form. The temperature of these materials is kept almost constant during its phase change. These characteristics make them suitable to be used for thermal conditioning in buildings. PCMs work differently to heavy materials; however, they are also able to improve the interior thermal conditions and help to reduce energy consumption in buildings [5-9].

This study was based on the need to determine the potential of improving thermal performance in existing buildings, in Spain, by the use of Latent Heat Thermal Energy Storage (LHTES). At the same time, the influence of the correct selection of the size of the glazing (WW ratio) and Shading Factor (fs) was analyzed. It was decided to use PCM drywall after studying the potential applications of Phase Change Materials in building retrofitting. This material is suitable for building rehabilitation due it has relatively low weight, requires little or no extra space, and it can replace or be placed on the existing finishing material. The influence of this application of PCM drywall panels in the operative temperature was evaluated in five cities with the most representative climates on the Spanish mainland. The evaluation was done comparing the influence of the use, or not, of PCM drywall with different WW ratios and fs.

2. Phase change materials: possibilities on the building retrofitting

In recent years, there has been great interest in PCMs, and its potential applications for space heating or cooling [7], proposing the use of these materials as an alternative to traditional solutions of thermal mass. In climates with large daily temperature swings, the correct use of PCM in building retrofitting can help to increase the interior thermal comfort. The PCM help to reduce the peak temperature, smooth the daily temperature fluctuations, maintain the temperature of the interior surfaces in the range of thermal comfort, and reduce the negative effects of air temperature stratification [8].

The viability of using Phase Change Materials in the rehabilitation of buildings depends on the local climate, and in the possibility of guaranteeing that the thermal energy can be charged and discharged in daily cycles. Therefore, to achieve the desired results, it is necessary to select the switch temperature correctly, taking into account the local climate, the orientation of the room and the size of glazing, and implement appropriate strategies of ventilation and sun screening. The use of PCM in building retrofits may be reasonable in:

a. Lightweight construction buildings.

b. Heavyweight construction, when interior insulations need to be added.

c. Heavyweight construction, in which their mass cannot be used as a thermal storage medium.

d. Buildings where is aimed to improve the energy efficiency of the HVAC or the renewable Energy Systems with the use of Thermal Energy Storage.

Adding thermal energy storage capacity to existing lightweight buildings could significantly improve their thermal behavior. Most heavyweight buildings have sufficient thermal mass. However, in some cases the building mass is not usable for stabilizing their interior temperature. Increase the insulation level on the exterior is probably the best solution to improve the existing building envelopes in Spain. This solution prevents heat loss in winter and reduces unwanted heat gain in the hot season; and also minimizes thermal bridges and enables the use of thermal mass in heavyweight buildings. However, sometimes, either because of limitations of the regulations, or because the building facades are protected by cultural or historical interest, it is not possible to add insulation on the exterior of the buildings. In such cases, the required additional insulation must be applied to the interior, precluding the utilization of the buildings’ mass. The use of PCM could return thermal energy storage capacity to these buildings. Similarly, the use of PCM could help improve the thermal performance of heavyweight buildings, in which their mass elements are separated from inhabited areas by materials with low thermal conductivity.

Phase Change Materials can be used in building retrofitting in both passive and active applications. The PCM can be used as a component, integrated into construction materials or in thermal storage units [9]. PCM components are applications in which a PCM layer or element is added to the construction section. In most of the cases, the PCM components are placed behind the interior finishing materials. Integrated PCM solutions are those in which the PCM is mixed with, impregnated or incorporated, into a construction material such as drywall panels. In Integrated PCM solutions, no additional layers are needed as they replace conventional construction materials. The PCM components and the PCM integrated into construction materials may be used in active and passive systems. Finally, the PCM storage units are linked to HVAC or other mechanical systems. Storage units are part of an active system, and they are usually thermally separated from the building interior by insulation. The functioning of the storage units and other active PCM systems is not dependent on meteorological changes as their thermal energy is transferred through the circulation of a fluid, usually water or air. This functional independence provides them with flexibility in terms of where the PCM application should be located. However, the location of passive PCM applications is related to how they will work, the way in which the energy will be charged and discharged, and its primary purpose, cooling, heating or both [10]. Zhang et al. suggest that the best location for passive PCM applications is within the living spaces, in walls and partitions [11]. In addition to vertical surfaces, place the PCM at ceilings offer three significant advantages: large areas for heat transfer, the heat exchange surface is not reduced by the placement of furniture, paintings, curtains or carpets, and in the case of macro-encapsulated PCM there is less risk of material leakage by drilling or punctures. However, being horizontal surfaces with down-draught heat flow, the thermal resistance is greater than the vertical or other horizontal surfaces, like floors [12].

This study is centered on passive PCM applications, specifically those that can be used in the interior of rehabilitated buildings. Passive PCM applications are easy to implement, no additional energy is required for their use, and thermal energy is stored or released automatically when the temperature rises or falls beyond the
Fig. 1. Building retrofit with the use of PCM: applications in walls, partitions and ceiling.

Fig. 2. PCM at buildings’ interior: walls and partitions (similar PCM applications can be used also at ceiling).
applications. The operating temperature range of Latent Heat Systems can be quite narrow, and the transition zone of the PCM must be entirely within this range [22]. Therefore, the switch temperature is one of the most relevant criteria for PCM selection [10]. The switch temperature must be selected taking account the climate and the main purpose of the application, help in heating or cooling periods [16]. The PCM with a switch temperature that performs well in heating periods has a marginal effect in cooling periods and vice versa [6]. As shown in Table 2, most of the applications designed for heating periods have switch temperatures between 17 °C and 21 °C, and most designed for cooling periods have switch temperatures between 25 °C and 28 °C.

Shiore et al., Athienitis et al. and Scalat et al. worked with PCM soaked drywall for heating periods, using switch temperatures between 16 °C and 21 °C, finding a reduction of the interior swing temperature between 1.7 °C and 4.0 °C [13–15]. Scalat et al. also, tested their 17–21 °C PCM drywall in summer conditions and found a low reduction of overheating due to the low switch temperature. Voelker et al. carried out their research on PCM gypsum plaster with a switch temperature between 25 and 28 °C [23]. They found that it was possible reduce the cell temperature by up to 4 °C. They also found that the effectiveness of the PCM may be significantly reduced after several consecutive hot days. Schossig at al. carried out an experiment with 15 mm gypsum plaster with 20% PCM in the interior of the test cell, and found a temperature reduction of up to 4 °C and a significant reduction in the number of hours with temperatures above 28 °C. Kuznik et al. studied the efficacy of a composite material, a mix of a copolymer and microencapsulated paraffin with a switch temperature of 21.7 °C [8,19]. They found that the air temperature fluctuated between 18.9 °C and 36.9 °C in the reference room and 19.8 °C and 32.8 °C in the PCM room, achieving a temperature swing reduction of 4.7 °C. Konuklu et al. packaged microencapsulated PCM with two different switch temperatures (26 °C and 23 °C) in aluminum foil, and placed these packages in the interior of the test cell. In summer conditions, they found a temperature reduction of 2.5 °C and a cooling load reduction of 7%. In winter, an increase of 2.2 °C in temperature and a heating load reduction of 17% were achieved [24].

3. Influence of the use of PCM drywall and the fenestration in the building retrofit: methodology

3.1. Starting premises

The study was based on three premises:

1. In Spain, the thermal Energy Storage can help increase thermal comfort in rehabilitated buildings.
2. Thermal comfort can be significantly improved by selecting an appropriate fenestration size (WW ratio) and an adequate Shadow Factor (fs), whether using PCM or not.
3. The high capacity of Thermal Energy Storage of PCM drywall panels could smooth out indoor temperature fluctuations, reducing the thermal peaks and helping to get more hours with temperatures within the thermal comfort range.

3.2. Study variables

From the starting premises of the study, it was selected the following variables: Climatic Zones (Cities), Window to Wall ratio (WW ratio), Shading Factor (fs) and the possibility of using PCM drywall panels or not.

3.2.1. Climate zones

Spain has diverse climate conditions throughout its territory. Five cities were chosen to corroborate the starting premises; these cities represent the different climate zones in continental Spain. This selection was made using the classification established by the Spanish Building Code (CTE) in the document HE. This document establishes twelve climate zones based on the climatic severities of winter (SCI) and summer (SCV). The climatic severities were defined taking account the Degree Days and the Solar Radiation in each city. The Code identifies four climatic severities of summer represented by numbers from 1 to 4, and five severities of winter represented by the letters A, B, C, D and E [25]. Table 3 shows the five cities selected, their climate zone, and other information relevant to the study, like the global radiation [26].

3.2.2. Window to Wall ratio and Shading Factor

In each of the cities, five different Window to Wall ratios (WW ratio) were evaluated: 10%, 20%, 30%, 40% and 60%. Similarly, five Shading Factors (fs) were evaluated: 0.1, 0.3, 0.5, 0.7 and 0.9. The fs value equal to one means that there is no shading in the glazing, and the fs value equal to zero means that the glazing is entirely shade. The experimental rooms were identified using the following nomenclature: the first two letters identify the city (see Table 3), followed by two numbers with a “w” to specify the WW ratio and two numbers with an “s” to specify the fs. For example, MA20w50s, refers to a room located in Madrid with a WW ratio equal to 20% and a fs equal to 50%.

3.3. Preliminary study: influence of thermal mass in the studied climatic zones

Initially, a preliminary study was conducted to get a first approximation of the influence of the use of thermal mass in the rehabilitation of buildings in the five selected cities. The calculations were made with Climate Consultant 5.0 [27], using the comfort model defined in the ASHRAE Handbook of Fundamentals 2005 [28]. This model establishes two zones of comfort in terms of clothing, heavy in the colder months and lightweight for the warmer months. The results provide a preliminary idea about the potential numbers of hours that could be added to the comfort periods by the implementation of different design strategies. Since the main objective of this preliminary work was to determine the influence of thermal mass, only three strategies were analyzed:
Table 2

<table>
<thead>
<tr>
<th>Location (season)</th>
<th>Switch Temp. (°C)</th>
<th>PCM areal/floor area (m²)</th>
<th>Component format</th>
<th>PCM (%)</th>
<th>Thickness (mm)</th>
<th>PCM wt% (wt%)</th>
<th>Thermal peak reduction (high/low)</th>
<th>Temp. swing reduction (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shenyang (winter)</td>
<td>1.7</td>
<td>1.4</td>
<td>C/0.3</td>
<td>NO</td>
<td>NO</td>
<td>NO</td>
<td>40</td>
<td>1.4</td>
</tr>
<tr>
<td>Montreal (winter)</td>
<td>4.0</td>
<td>3.36</td>
<td>C/0.1</td>
<td>NO</td>
<td>NO</td>
<td>NO</td>
<td>40</td>
<td>0.9</td>
</tr>
<tr>
<td>Lab (summer)</td>
<td>3.5</td>
<td>5.66</td>
<td>C/0.9</td>
<td>NO</td>
<td>NO</td>
<td>NO</td>
<td>40</td>
<td>1.9</td>
</tr>
<tr>
<td>Weimar (summer)</td>
<td>3.0</td>
<td>1.4</td>
<td>C/0.6</td>
<td>NO</td>
<td>NO</td>
<td>NO</td>
<td>40</td>
<td>1.2</td>
</tr>
<tr>
<td>Freiburg (summer)</td>
<td>5.0</td>
<td>4.25</td>
<td>C/0.4</td>
<td>NO</td>
<td>NO</td>
<td>NO</td>
<td>40</td>
<td>2.0</td>
</tr>
<tr>
<td>Lab (winter)</td>
<td>2.5</td>
<td>3.38</td>
<td>C/0.1</td>
<td>NO</td>
<td>NO</td>
<td>NO</td>
<td>40</td>
<td>0.9</td>
</tr>
<tr>
<td>Lab (spring/fall)</td>
<td>2.7</td>
<td>3.38</td>
<td>C/0.1</td>
<td>NO</td>
<td>NO</td>
<td>NO</td>
<td>40</td>
<td>0.9</td>
</tr>
<tr>
<td>Athens (summer)</td>
<td>4.3</td>
<td>3.38</td>
<td>C/0.1</td>
<td>NO</td>
<td>NO</td>
<td>NO</td>
<td>40</td>
<td>0.9</td>
</tr>
<tr>
<td>Adana (winter)</td>
<td>4.0</td>
<td>3.38</td>
<td>C/0.1</td>
<td>NO</td>
<td>NO</td>
<td>NO</td>
<td>40</td>
<td>0.9</td>
</tr>
</tbody>
</table>

3.4. Main study: influence of PCM drywall and fenestration in the climate zones studied

3.4.1. Introduction

Once the potential benefits of using thermal mass (sensible heat storage) in the cities studied were verified, a study to determine the influence of the use of PCM (latent heat storage) and the fenestrations in building retrofitting was carried out. The starting premises corroboration was made using a comparative method aided by thermal simulations. The air temperature is not a sufficient indicator to determine the thermal comfort. It is necessary to take into account other factors as the influence of radiant energy of the surrounding surfaces. Since the PCM add thermal energy storage capacity to the rooms, it is expected that the temperature of the room’s surfaces were a significant factor in the thermal comfort. Therefore in the analysis of this work the operative temperature was used. The operative temperature is a weighted value that representing both dry bulb air temperature and the mean radiant temperature of the rooms [29].

3.4.2. PCM application

The use of microencapsulated PCM drywall panels was decided. Drywall panels are one of the most common interior finishing materials and the microencapsulated PCM have the advantages of easy application, proper heat transfer and no need for protection against encapsulation destruction [16]. Spain’s climatic conditions, with many hours of temperatures exceeding 26 °C, have considerable potential to reduce overheating. As shown in Table 2, the PCM gypsum applications with switch temperature between 25 °C and 28 °C have performed effectively in cooling periods. In the market, there are microencapsulated PCM with switch temperatures of 21 °C, 23 °C and 26 °C, and PCM drywall with a switch temperature of 23 °C and 26 °C. The latter was the switch temperature selected in the present study. Regarding the thickness of the panels, as shown in Table 2, in works with PCM drywall panels, a thickness of 10 and 13 mm was used, and in those with PCM gypsum plaster, a thickness of 15–30 mm was used. 15 mm panels were chosen as the best results were achieved using these as shown in Table 2. It is possible to find PCM drywall with that thickness. The maximum weight ratio of microencapsulated PCM that can be incorporated in drywall panels is 30% [19]. Taking into account the climate in Spain, the need to reduce overheating, the findings of the literature and the availability of PCM products in the market, 15 mm 26 °C drywall panels with 30% of microencapsulated PCM were selected. These panels have 3 kg of PCM per m², and their thermal properties are: Thermal Conductivity 0.18 W/mK (PCM in solid state), Latent Heat DH: 330 kJ/m and Specific Heat 1.20 kJ/kgK.

3.4.3. Test rooms

Two similar study rooms were used: ones identified as “Reference Rooms” finished with standard drywall panels and the others identified as “Experimental Rooms” finished with PCM drywall panels. The floor area of the study rooms was 18 m² (3 m × 3 m × 6 height, width and depth), and their length was oriented to the east–west axis. The boundary conditions used in the study were the same as those used in the validation process of the simulation software as explained in Section 3.4.5; the side facing south was the only one in contact with the outside, the other sides, interior walls, floor and ceiling, were considered to have an adiabatic relationship with the interior of the building. The rooms had a window in the south wall. These windows had insulated double-glazing mounted in a thermal break aluminum frame. The
windows’ Thermal Transmittance (U-value) were 1.2 W/m²K and their Solar Heat Gain (G-value) coefficient was 0.62. As shown in Table 2, the researchers who studied PCM drywall and PCM gypsum plaster used a PCM area/Floor area ratio between 2.56 and 5.30. The Experimental Rooms of this study have a PCM area/Floor area ratio of 3.00, a total of 54 m² of PCM drywall panels covering the ceiling and the interior faces of the north, east and west walls.

### 3.4.4. Simulations

The simulations were performed in pairs, analyzing both rooms with and without PCM drywall, and evaluating 25 different cases in each city resulting from the combination of WW ratio and fs. A total of 125 double simulations were carried out. The purpose of these simulations was to determine the influence of the PCM drywall panels and the fenestrations in the thermal behavior of the test rooms, quantifying the following four indicators:

1. Total number of hours within the range of thermal comfort (21°C and 26°C).
2. Number of hours within the range of thermal comfort that potentially can be added.
3. Reduction of daily thermal peaks.
4. Reduction of daily thermal swings.

### 3.4.5. Simulation software

The final report of the IEA ECES Annex 20, sustainable cooling with thermal energy storage, includes the results of a comparative study on the design and analysis tools that can be used to simulate thermal energy storage systems, including the ones suitable for the use of PCM in buildings [30]. From those, PCMexpress was selected to carry out the thermal simulations in this work. PCMexpress is a simplified planning and simulation tool designed to get a quick approximation of the thermal behavior of buildings using PCM. This software was developed within the framework program “Active thermal storage systems in buildings using phase change materials”. It was conceived for support in the initial design phase, facilitating a reliable decision-making process [30]. The mathematical models and calculation engine of the software were developed at the Fraunhofer Institute for Solar Energy (ISE) working in collaboration with industrial partners [30,31]. The decision to use PCMexpress was based on the following:

- It was designed to simulate the thermal and energy performance of buildings with PCM.
- Makes it possible to use the variables of this study and evaluate the four selected indicators (see Sections 3.1 and 3.4.4).
- Calculates the operative temperature of the rooms. (This parameter was used for the analysis of the present study.)
- Performs fast double simulations, shows the behavior of the buildings with and without PCM.
- PCM simulation based on a simplified Enthalpy Method. (The Enthalpy Method is used by ESP-r and EnergyPlus).
- Results were validated using the ESP-r results as a reference [31].

PCMexpress has a comprehensive database of material (with emphasis on PCM materials), construction systems and European weather files. Materials and construction system can be created and added to the software libraries. In PCMexpress, generic HVAC solutions can be defined using predefined systems. The software is structured to work with Room Combinations, and it can simulate up to ten Room Combinations, each one of them may be made up of three zones [30].

PCMexpress has a component-oriented calculation core and uses the Node-Edges model. In this model, the layers of the wall constructions, the air and the partitions were represented as heat capacity and temperature-prone nodes. The edges represent the flow of energy (heat transfer) between the nodes. Energy sources and sinks, such as the radiation through the window and onto the outer wall, heating and cooling surfaces, air exchange and internal heat loads act as “external sources” of the corresponding node. The energy flows are tracked, and the overall energy balance is monitored in the external edges. The PCM effect is calculated using a simplified enthalpy method. The thermal behavior of the PCM applications is defined using enthalpy–temperature characteristic curves. The curves of the materials included in the software were defined according the German Institute for quality Assurance and Certification (RAL) [30].

The results are presented in reports and explanatory graphics, always making a comparison of the two systems, one with and other without PCM. By default, three types of results are obtained: the rooms operative temperature in relation to the Outdoor Running mean temperature according to EN 15251, the frequency distribution of the room temperatures and the daily progress charts with the highest PCM effects [30,31]. Also, changing the default settings, the software generates a text file with the calculated data of each room on an hourly basis. The file includes, among other information, the air temperature, the temperature of the surfaces and the operative temperature. There are other software capabilities that have not been used in this study such as the possibility of simulating active surfaces with water circulation, or carrying out economic analysis, comparative amortization studies based on the guide VDI 2067, developed by the Association of German Engineers [31]. Researchers at the Fraunhofer Institute conducted a validation study, comparing the PCMexpress results with those obtained with ESP-r software. The model selected for the validation process was chosen from the DIN 4108-2:2003-07, and consisted of rooms of 3.9 m × 5.2 m × 3.0 m, with only one exterior wall with a window, and with their interior walls, ceilings and floors related adiabatically with the interior of the building. The results of this study indicate that the validation was successful, despite the simplifications of the program in relation to the glazing, and they found a satisfactory correlation between the results of ESP-r and PCMexpress [31].

Some of the software limitations are: it only analyses rectangular spaces, it uses few parameters to define the glazing elements and HVAC systems, and like the most building simulation software, only gives one value for the interior temperature, thus possible air temperature stratification can not be registered. Furthermore, for the simplified Enthalpy simulation process, it only uses the heating

### Table 3

<table>
<thead>
<tr>
<th>City (ID)</th>
<th>Barcelona (BA)</th>
<th>Bilbao (BI)</th>
<th>Madrid (MA)</th>
<th>Seville (SE)</th>
<th>Soria (SO)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Climate</td>
<td>Humid Mediterranean</td>
<td>Atlantic (humid maritime)</td>
<td>Continental</td>
<td>Warm Mediterranean</td>
<td>Mountain</td>
</tr>
<tr>
<td>Latitude (°)</td>
<td>41.23 N</td>
<td>43.15 N</td>
<td>40.24 N</td>
<td>37.23 N</td>
<td>41.46 N</td>
</tr>
<tr>
<td>Altitude (m)</td>
<td>12.00</td>
<td>19.00</td>
<td>667.00</td>
<td>10.00</td>
<td>1063.00</td>
</tr>
<tr>
<td>CET classification</td>
<td>C2</td>
<td>C1</td>
<td>D3</td>
<td>B4</td>
<td>E1</td>
</tr>
<tr>
<td>Winter climatic severity (degree days)</td>
<td>0.60 &lt; SCI ≤ 0.95</td>
<td>0.60 &lt; SCI ≤ 0.95</td>
<td>0.95 &lt; SCI ≤ 1.30</td>
<td>0.30 &lt; SCI ≤ 0.60</td>
<td>SCI &gt; 1.30</td>
</tr>
<tr>
<td>Summer climatic severity (degree days)</td>
<td>0.60 &lt; SCV ≤ 0.90</td>
<td>SCV ≤ 0.60</td>
<td>0.90 &lt; SCV ≤ 1.25</td>
<td>SCV &gt; 1.25</td>
<td>SCV ≤ 0.60</td>
</tr>
<tr>
<td>Global Radiation (kWh/m² day)</td>
<td>4.56</td>
<td>3.54</td>
<td>4.88</td>
<td>5.23</td>
<td>4.48</td>
</tr>
</tbody>
</table>


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portion of the PCM enthalpy curve, so possible supercooling effect is not considered [30,31]. This study was not affected by this simplification due the microencapsulated paraffin is a stable substance, and the supercooling is unusual in this material [23].

4. Results

4.1. Preliminary study results: influence of the use of thermal mass in Spain

Results of this preliminary study are shown in Fig. 3; the bars indicate the number of hours that could potentially be added to the thermal comfort range as a result of the correct use of thermal mass strategies. The cities with the largest potential to increase in hours of comfort in both cold and hot periods are Seville, Madrid and Barcelona (see Fig. 4). The results also show that summer night ventilation is useful in Seville and Madrid. In Soria, many hours of comfort in the heating periods could be added, and in Bilbao the lowest potential for increasing the number of hours within the thermal comfort range was found.

4.2. Main study results: influence of PCM drywall and fenestration in the climate zones studied

The improvement of thermal conditions in buildings rehabilitated using PCM drywall, varies day-to-day depending on the changing weather conditions of each city studied. Also, there are notable differences in the results of the cases due to the values of the WW ratio and the glazing Shading Factor. For a better understanding of the influence of the use of PCM drywall and the fenestration, the results were organized by cities taking into account the indicators defined in Section 3.4 – Simulations.

4.2.1. Barcelona (BA): additional hours in comfort and percentage of annual hours in comfort

It was found that cases BA40w50s and BA20w90s showed the highest improvement in indoor thermal conditions due to the incorporation of PCM drywall. Comparing those cases with their respective reference rooms, an increment up to 1568 h per year in the number of hours within the thermal comfort range was found, representing an improvement of 30.8% (Fig. 5a). However, in case BA50w10s with PCM drywall, the highest number of hours per year within the range of thermal comfort was found, 88.5% (see Fig. 5b). In Barcelona, the influence of the PCM drywall used had lower influence in rooms with small glazing area (WW ratio = 10) and in rooms with low value Shading Factor (fs = 10). In rooms where WW ratio = 10, when the Shadow Factor increases, both the additional hours within thermal comfort range and the annual percentage of hours in comfort increase. In cases with WW ratio above 20%, the greatest reduction of hours above 26°C is achieved when the fs value is between 0.30 and 0.50.

4.2.2. Bilbao (BI): additional hours in comfort and percentage of annual hours in comfort

In case BI30w70s, the greatest improvement of indoor thermal conditions due to the incorporation of PCM drywall was achieved. Comparing this case with its reference room resulted in 1699 additional hours within thermal comfort range, which means an improvement of 31.1% (Fig. 6a). However, in case BI50w10s with PCM was where the highest number of hours per year within the range of thermal comfort was registered, 88.5% (as shown in Fig. 6b). In Bilbao, rooms with small glazing area (WW ratio = 10) and in rooms with low value Shading Factor (fs = 10) the effect of PCM drywall was low. Less than 300 h of comfort were added during the cooling periods in rooms BI10w10s, BI10w30s and BI20w10s. In rooms where WW ratio = 10, when the value of
fs increases, both the additional hours within thermal comfort range and the annual percentage of hours in comfort increase. In cases with WW ratio above 20%, the greatest reduction of hours above 26 °C is achieved when the fs value is between 0.50 and 0.70.

4.2.3. Madrid (MA): additional hours in comfort and percentage of annual hours in comfort

In this city, case MA20w90s had the highest improvement in indoor thermal conditions by the addition of PCM drywall, comparing this case with the reference one, an annual increment of 1533 h within the range of thermal comfort was found, an improvement of 29.0% (Fig. 7a). It was also found that the highest percentage of hours within the range of thermal comfort was 88.5% in case MA50w10s with PCM (as shown in Fig. 7b). The influence of PCM drywall used was low in cases with small glazing area (WW ratio = 10) and cases with low Shading Factor (fs = 10). In rooms where WW ratio = 10, when increasing the value of the Shadow Factor, both the additional hours within thermal comfort range and the annual percentage of hours in comfort were in turn increased.

4.2.4. Seville (SE): additional hours in comfort and percentage of annual hours in comfort

In case SE10w90s, the greatest improvement of indoor thermal conditions by incorporating PCM drywall was found. In this case, 31.1% of the annual hours were added to the thermal comfort range; 1086 h more than its reference room (Fig. 8b). However, it was in room SE10w30s with PCM in which the highest number of hours per year within the range of thermal comfort was registered, equivalent to 74.9% (as shown in Fig. 8b). Comparing the cases in all cities where WW ratio = 10, Seville cases achieved the highest number of additional hours within the comfort range due the use of PCM drywall.

4.2.5. Soria (SO): additional hours in comfort and percentage of annual hours in comfort

In this city, the rooms SO50w50s and SO40w70s showed the highest improvement in indoor thermal conditions by the addition of PCM drywall. Comparing these cases with their reference rooms, an increment of 1559 h per year within the range of thermal comfort was found, an increment of 26.5% (Fig. 9a). However, it was in case SO40w30s with PCM drywall in which the highest number
Fig. 7. Madrid: annual results of the influence of the usage of PCM drywall and the annual percentage of hours within the thermal comfort range.

Fig. 8. Seville: annual results of the influence of the usage of PCM drywall and the annual percentage of hours within the thermal comfort range.

Fig. 9. Soria: annual results of the influence of the usage of PCM drywall and the annual percentage of hours within the thermal comfort range.
of annual hours within the range of thermal comfort was found, 90.8% (as shown in Fig. 9b). In cases with small glazing area (WW ratio = 10) as well as in cases with low value Shading Factor (fs = 10), the effect of the PCM drywall were less significant than in cases with high WW ratio and fs values. In many of cases with WW ratio = 10, the additional annual hours in the thermal comfort range did not reach 300 h, in case SO10w10s, it did not even reach 100 additional hours. In this city where WW ratio = 30, when the Shadow Factor increases, the additional hours within thermal comfort range are in turn increased.

4.2.6. Thermal peak and daily temperature swing reductions

Thermal Energy Storage in buildings helps to reduce the indoor thermal peaks of both the high and the low temperatures, smoothing the daily thermal swings. These effects were analyzed using the cases in which the greatest increase in the number of hours with the thermal comfort was achieved: BA20w90s, BI30w70s, MA20w90s, SE10w90s and SO50w50s. As shown in Fig. 10, the cases in cities with the coolest temperatures, Soria and Bilbao show a similar pattern in terms of the reduction of thermal peaks. In Seville, in the months of July and August, the reduction of the thermal peaks were small, in most of the days did not reach 1 °C. All the studied cases achieved the largest peak temperature reductions between the last weeks of September and the end of October. In those weeks, the results vary considerably from day to day as shown in Fig. 10. October was the month in which the cases BA20w90s, MA20w90s and SE10w90s achieved the greatest monthly average of high temperature peak reduction as shown in Table 4. However, in the case of Soria the greatest reduction were achieved in July and August. The case BI30w70s show a reduction between 2.3 °C and 2.4 °C from July to October. Also in October, in four of the five analyzed cases there were reduction close to 5 °C, the exception was the case SE10w90s where maximal peak thermal reduction in this month was 4.4 °C. The influence of the 26 °C PCM drywall in the reductions of hours with temperatures below 21 °C are not as significant as the reduction of high temperature peaks. Therefore, in most of the cases the reductions of the daily temperature swings are similar to the decrement of high temperature thermal peaks as shown in Fig. 11.

4.2.7. Influence of the study variables on the thermal comfort

In order to determine the influence of each study variable, the thermal performance of the rooms was studied changing only one variable at a time. For example, to determine the influence of the WW ratio in the thermal comfort of rooms, the cases with the same Shading Factor (fs) and different WW ratio were compared. The influence of the fs on the thermal comfort of rooms without PCM was determined comparing the cases with same WW ratio and different fs. Additionally, the influence of the combination of both factors was verified, comparing the results in rooms with and without PCM drywall panels. Table 5 summarizes the findings of
the thermal simulation in relation to the influence on the thermal comfort of the variables of this study, first the effect of each one separately and them the combined effects.

5. Discussion

In an attempt to evaluate the influence of PCM drywall and the fenestration in building retrofitting in Spain, a comparative simulation works of rooms with and without PCM drywall panels was carried out. These works were preceded by a preliminary study. This preliminary study provided an initial idea of the inertia in the number of hours within the thermal comfort range due the correct use of the thermal mass. The results of the preliminary study and the results of the simulations are similar only in the cases with low WW ratio and low fs values, see Figs. 4b and 12a. The results of the simulations in Madrid, Barcelona and Bilbao with 10w10s are similar to the results of the preliminary study. In Seville, the cases with 10w10s present the greatest increase in the hours of thermal comfort in both studies. However, the simulation results were less promising than the preliminary study results.

The results of thermal simulations, shown in Table 5, corroborate that, in building rehabilitations, it is first necessary to study passive design strategies, such as the size of windows and their shading systems, whether if new materials such as PCM drywall panels will be used or not. In Barcelona, for example, analyzing the number of hours where the range of thermal comfort in rooms without PCM and with fs = 90, it was found that depending on the WW ratio used, the difference in results may vary by up to 28%. In this city, in rooms without PCM and a WW ratio of 50%, the number of hours of thermal comfort may vary by up to 33.7%, depending on the Shading Factor of glazing. The results in rooms without PCM with different combinations of WW ratio and fs show that the number of hours in comfort could be increased by more than 20%. In Barcelona, it could rise to 34.6%. The results also show that the thermal comfort conditions of existing rooms could be further enhanced with the use of PCM drywall. Comparing the worst combination of WW ratio and fs without PCM drywall, with an appropriate combination of these variables with PCM drywall, was found that the number of hours in the range of thermal comfort in all the cities could be increased by over 30%, and in Madrid the increment could be up to 49% comparing the cases MA50w90s and MA50w10s.

The thermal simulation results show that the use of 26 °C PCM drywall cold reduce both the high and low temperature peaks. However, the reduction of high temperature peaks was more significant: in some cases a reduction of 5 °C was achieved. PCM drywall panels also show greater effectiveness in reducing the number of annual hours with temperatures above 26 °C, more so than reducing the number of hours with temperatures below 21 °C. The reduction in hours with temperatures below 21 °C was not the most beneficial effect of the PCM drywall panels. However, in some cases in Bilbao, more than 500 h were added to the thermal comfort range. Similarly, in Soria there were cases in which over 400 h were added. In Seville, with warmer weather, the annual reduction of hours below 21 °C is negligible.

In relation to the enhancement of thermal comfort by the use of 26 °C PCM drywall panels in the Spanish territory, there is at least one case in all the analyzed cities in which more than 1000 h could be added to the thermal comfort range, see Table 4. The results varied depending on the climate zone and combinations of variables, but all of them show at least a slight improvement in comfort conditions due to the use of PCM drywall (see Fig. 12a). In three out of the 25 cases of Soria were found that the number of hours with temperatures below 21 °C increased: 53 h in S010w10s, 18 h in S03010s and 79 h in S020w30s. However, in these cases there was a larger reduction in hours with temperatures above 26 °C, resulting in a positive annual balance (as shown in Fig. 12a).

In four of the five cities studied, it was found that at least one combination of WW ratio and fs in which the use of PCM drywall could help maintain a comfortable temperature in the rooms for about 90% of the hours of the year. The exception was Seville where a
maximum of 74.9% of the hours within the range of thermal comfort was achieved (case SE10w10s with PCM).

There were no cases where the maximum benefit of the PCM drywall was achieved and, where in turn, a maximum reduction in the number of hours out of the thermal comfort range was reached. However, there were some cases in Soria and Bilbao with results closed to this possibility. In the case SO50w40s, when the room is retrofitted using PCM drywall, 87.1% of the annual hours are within the thermal comfort range and in turn a potential increment of 1559 h within the range of thermal comfort was registered. Similarly in the case B150w30s with PCM drywall, 87.9% of the hours were in thermal comfort, and there was potential to increase the thermal comfort range to 1629 h.

In the other hand, there cases were the use of PCM drywall cannot be justified, due to the small benefits that could be obtained. For example, in all the cities studied the rooms with WW ratio = 10 and F = 10 the results shown a low level of improvement by the use of PCM drywall, being SO10w10s the worst case. In this case, the reduction of hours with temperature above 26 °C did not reach 100 h per year, and as explained before, the number of hours with temperatures below 21 °C was increased. However, in Seville the smallest benefits were obtained in a room with high WW ratio and high Fs values. For example, in case SE50w90s, the reduction of hours with temperatures above 26 °C did not reach 300 h per year.

In building retrofitting is not common to change the sizes of the openings. However, in some cases due the change of use, the necessity of increased daylight or views to the outdoors, new windows are added, or the existing ones are enlarged. In these cases, the proper sizing of PCM surface can also help to absorb the excess of heat gains due to the increased glazing area, and even be able to achieve more hours of comfort than those obtained before rehabilitation. This possibility was corroborated with the results of the present study; in many cases, it was found a greater number of hours with temperatures above 26 °C in rooms without PCM than in the rooms with PCM even with larger glazing.

The results presented in this paper have the typical limitations of studies based on numerical analysis or building simulations. These limitations as usual are related to simplifications in the method of calculation. So it is necessary to continue the experimental phase of the research, to validate or adjust the results obtained so far. The simulation results show the effect of the PCM on the air temperature, in the surface temperatures and also in the operative temperature of the rooms on an hourly basis. However, there are other effects that could influence indoor thermal comfort that cannot be observed with the simulations, such as the possible reduction in air thermal stratification since the software provides only one temperature value per room. Kuznik et al. observed for the first time that the PCM wallboard panels enhance the natural convection mixing in the air, avoiding uncomfortable thermal stratifications [19].

6. Conclusions

The influence of the use of PCM drywall and the fenestration in building retrofitting, in Spain, has been studied. The PCM drywall panels are designed to improve thermal performance of buildings with low thermal mass, especially those located in areas with high diurnal temperature range. PCM drywall panels are relatively lightweight, have low thickness, are easy to install, can replace the existing interior finishing or be placed over them; these characteristics make these panels particularly suitable for building retrofitting. A comparative study on the influence of the study variables in five Spanish cities was carried out. The influence of the fenestrations was evaluated using the WW ratio and the Shading Factor as variables.

In all studied cases, it was found that the PCM drywall could help to increase the number of hours within the thermal comfort range, reducing thermal peaks, smoothing the daily temperature swing and increasing the number of hours within the range of thermal comfort. However, the influence of the 26 °C PCM drywall on the thermal comfort was not the same in all cities. Cases in Seville showed better performance with low WW ratio. In Bilbao and Soria the best results were obtained with a high WW ratio. In Madrid and Barcelona was found high potential of increment of hours within the range of thermal comfort and a significant reduction in hours with temperatures above 26 °C. Regarding the reduction of hours
below 21 °C, cases in Soria and Bilbao obtained the best results, followed by others in Madrid and Barcelona. The effect of reducing the thermal peaks by the use of 26 °C PCM drywall in some cases was up to 6 °C. Likewise, the reduction of internal temperature swing in some cases reached 60%. In all the cities, there were cases in which the number of hours in thermal comfort may be potentially increased in more than 1000 h. In one of the Bilbao cases, it was found that the potential increase of hours in thermal comfort may reach 1600 h. However in some of the cases, the use of PCM drywall cannot be justified, due the negligible results obtained.

In rehabilitation projects, in which it is necessary to increase the size of the windows, the use of PCM drywall could also be useful. The results of this study show that with the proper sizing of PC drywall surfaces, the excess heat due to the increased glazing area may be absorbed by the PCM, getting in some cases even more hours of thermal comfort than those achieved before the rehabilitation.

It is necessary to keep in mind that the viability of the passive utilization of PCM drywall depends on the diurnal thermal variability, as well as the appropriated thermal energy charge and discharge. Therefore, the orientation of the rooms and their ventilation possibilities, as well as glazing types, sizes and solar protection are fundamental elements to take into account in the planning of the use PCM drywall. The results of the simulations bring a preliminary idea of the influence of the PCM drywall and fenestrations on the thermal comfort in retrofitted buildings. However, further research, with full scale cells or in real buildings is necessary to quantify the improvements in the thermal comfort conditions and determine the energy savings due to the use of PCM drywall panels.

References