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The effectiveness of PCM wallboards for the energy refurbishment of lightweight buildings

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Abstract

In order to compensate for the small storage capacity of lightweight buildings, that usually suffer from pronounced overheating in summer, the incorporation of Phase Change Materials (PCMs) into the opaque envelope can be an effective way to enhance thermal inertia and to improve the thermal comfort. In particular, PCM wallboards are recommended during refurbishment, as they have a small thickness and can be easily applied on the inner surface of both the walls and the ceiling.
In this paper, a comprehensive study is presented about the effectiveness of PCM wallboards for improving summer thermal comfort in existing lightweight buildings. The study is based on dynamic simulations carried out with the software EnergyPlus on a sample office building. The analysis is repeated in four different locations, ranging from Southern Europe (Catania, Italy) to Northern Europe (Paris, France).
The results of the simulations may help designers to make the correct choices in terms of position of the PCM wallboards, scheduled rate of nighttime ventilation and value of the peak melting temperature for the specific PCM.

Keywords: Phase Change Materials, lightweight buildings, summer thermal comfort, strorage efficiency.

1. Introduction

Nowadays, there is a tendency to design buildings with light and thin envelopes, so as to reduce the weight, the cost of transport and the time for construction. Unfortunately, such modern lightweight buildings suffer from pronounced overheating in summer, especially those characterized by large glazed surfaces, hence by important solar gains.

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In order to compensate for the small storage capacity of lightweight buildings, the incorporation of Phase Change Materials (PCMs) into the opaque envelope can be an effective way to enhance thermal inertia and to improve energy performance, both in the construction stage and during refurbishment. Indeed, thanks to their high latent heat, PCMs can store a significant amount of thermal energy at daytime while melting, thus reducing the indoor air temperature swings produced by solar and internal gains. At night time, thermal energy is released and the material can restore its solid state; this stage can be enhanced by ventilating the building with fresh outdoor air.

Organic PCMs, such as paraffin, fatty acids and polyethylene glycol (PEG), are the materials most frequently used; they show good chemical stability, high latent heat and very limited super-cooling. Unfortunately, they have low thermal conductivity, which may reduce the penetration of the thermal wave into the core of the material and the full exploitation of its latent heat. Moreover, the greatest part of the common paraffinic PCMs are flammable, and they may not meet the strict low-flammability criteria set by the American Society for Testing Materials (ASTM). Possible solutions to limit flammability through the addition of fire retardants are discussed in [1].

The simplest and most widespread way of using PCMs in buildings consists in their impregnation into gypsum, concrete or other porous materials. However, micro-encapsulation techniques have been recently developed: these consist in enclosing the PCM in microscopic polymer capsules that form a sort of powder; the powder is then included in a container made up of PVC or aluminium [2]. The final product is generally distributed as a panel or wallboard, easy to be handled and installed, from which the PCM cannot leak; furthermore, the reduced size of the microcapsules enhances the full exploitation of the PCM, thanks to the large surface available for heat exchange. A detailed review about the most common PCMs and the technical solutions adopted for their application in buildings can be found in [3] and [4].

Now, in order to provide a comprehensive view about the use of micro-encapsulated PCM wallboards for refurbishing lightweight buildings, aimed to reduce the overheating due to solar gains, a case study is considered hereafter, based on the dynamic thermal simulation of a sample building. The study is extended to different climates in Europe, and highlights the essential role of night ventilation to maximize the effectiveness of this solution. Moreover, with the aim of making the study more general, two different real PCM wallboards are considered: however, no reference is made to their commercial name.

The first wallboard (called PCM-A in the following) includes an aluminium honeycomb matrix, filled with a compound containing 60 wt% of a paraffin wax, encapsulated within polymeric microspheres with a diameter of approximately 5 μm. The wallboard is sealed by two thin aluminium sheets, and its overall thickness is 20 mm, as described in [5]. The weight of the wallboards is around 11 $kg \cdot m^{-2}$.

The second wallboard (PCM-B) is made of a micro-encapsulated paraffin, different from the previous one, as described later. The final form of this wallboard is a flexible panel with a thickness of 5.26 mm, covered on both sides with a very thin aluminium sheet [6]; the final weight is 4.5 $kg \cdot m^{-2}$.

2. Methodology

2.1. Characterization of the phase change material

The melting process of a real PCM used for building applications does not entirely occur at a given temperature, as for a pure PCM, but it is completed over a certain temperature range. In order to quantify the amount of heat absorbed by a PCM during phase change, the equivalent specific heat capacity C_{eq} is used. This parameter represents the thermal energy needed to produce a unit temperature variation in the unit mass of PCM at constant pressure:

$$C_{eq}(T) = \frac{\partial h(T)}{\partial T} \qquad (1)$$

As a rule, the evaluation of C_{eq} is performed through laboratory tests, by imposing a periodic temperature fluctuation to a PCM sample and then measuring its enthalpy variation. The equivalent heat capacity normally fits a Gaussian curve, with a maximum value occurring at the peak melting temperature T_P. As an example, Fig. 1 shows the curves of the equivalent heat capacity of the two PCMs mentioned above; the corresponding mathematical formulation is reported in [7] and [8], respectively.

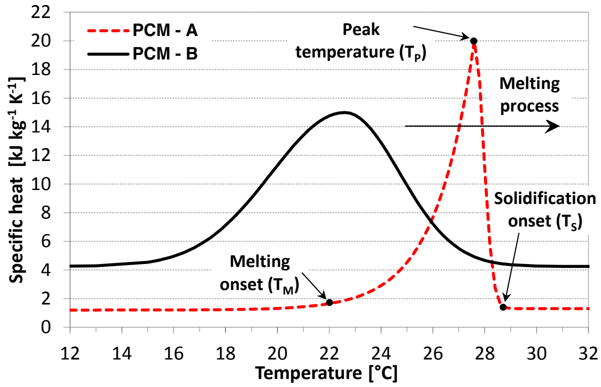

Fig. 1. Curves of the equivalent specific heat capacity for the two proposed PCMs

As one can observe, the melting process of PCM-A starts at T_M = 22°C and is completed at T_S = 28.5°C; moreover, after the peak temperature T_P = 27.6°C melting is achieved quite rapidly. On the other hand, Fig. 1 suggests that the behaviour of PCM-B is considerably different. In fact, the melting process is distributed over a temperature range wider than for PCM-A (i.e. from T_M = 17°C to T_S = 27°C), and the highest value of the equivalent heat capacity is lower than for PCM-A. Furthermore, PCM-B has a lower peak temperature (T_P = 22.6°C), which suggests that the exploitation of this PCM should benefit from lower indoor temperatures. On the whole, the latent heat of both PCM wallboards, i.e. the thermal energy needed to complete the whole melting process from T_M to T_S, is very similar when referred to the unit surface, as it amounts to 131.7 Wh·m^{-2} and to 134.0 Wh·m^{-2}, respectively for PCM-A and PCM-B.

Actually, according to the laboratory tests, the curves describing the equivalent heat capacity during the solidification phase do not correspond exactly to those determined for the melting phase and shown in Fig. 1; indeed, they are slightly shifted towards lower temperatures. This behavior, called *super-cooling*, is typical of the paraffinic materials; however, if one neglects it in the simulations, the reliability of the results is not affected significantly [9].

Another important parameter that characterizes a PCM is the thermal conductivity. The measured effective thermal conductivity of PCM-A is 2.7 W·m^{-1}·K^{-1}: this value is remarkably high, if compared to PCM-B, whose thermal conductivity varies between 0.18 and 0.22 W·m^{-1}·K^{-1}. This difference is imputable to the aluminium honeycomb matrix used in PCM-A, which allows heat to be easily transferred through the panel.

2.2. The evaluation of thermal comfort

In most of the research works available in the scientific literature and regarding the use of PCM wallboards for improving summer thermal comfort in buildings, the effectiveness of PCMs is measured by the indoor temperature drop achieved, during a short representative period, thanks to the application of the PCM, in comparison with the case without PCM.

However, it should be remarked that the room operative temperature, and not the indoor air temperature, is the parameter that directly affects the comfort sensation, as suggested by well-established comfort theories, reported in the International Standards ISO 7730 [10] and EN 15251 [11]. According to this approach, in this paper the discussion of the results is based on the values of the operative temperature T_{op} obtained from the simulations.

Furthermore, in the attempt of having a more comprehensive view about the effect of PCMs on thermal comfort, not only limited on a few days but also accounting for the behaviour over the whole summer season, the indicator called *Intensity of Thermal Discomfort* (ITD) can be adopted. This indicator is defined as the time integral, over the occupancy period P, of the positive difference between the current operative temperature and the upper threshold for comfort (see Eq. 2).

$$ITD = \int_P \left(T_{op}(\tau) - T_{lim}\right)^+ d\tau \tag{2}$$

The ITD represents an effective way to quantify the uncomfortable thermal sensation due to overheating: indeed, it measures at the same time the intensity and the duration of the thermal discomfort perceived by the occupants [12]. In Eq. (2), the value of the threshold temperature T_{lim} depends on the choice of a specific thermal comfort theory. In this work, the adaptive approach is used, as described in the Standard EN 15251; hence, the threshold value is not constant in time, but it is determined daily as a function of the running mean outdoor air temperature.

2.3. The evaluation of the PCM efficiency

In order to accurately assess the performance of a PCM, it is necessary to understand whether and to what extent its latent heat is effectively exploited. To this aim, it can be useful to calculate the *Frequency of Activation* (*FA*), i.e. the percentage of time within a given period during which the PCM is actually undergoing phase change [7]. This occurs between T_M = 22°C and T_S = 28.5°C for PCM-A, and in the range 17°C ÷ 27°C for PCM-B (see Fig. 1).

The *FA* can provide important information: when its value is low, it means that the PCM remains in its liquid or solid phase for a long time, thus its latent heat capacity is not exploited. An ideal application of a PCM should imply *FA* = 100%, but this is not easy to accomplish, as the activation of the PCM is highly influenced by many circumstances.

However, not all the conditions inside the melting range have the same importance in terms of inertial potential, since the heat capacity of a PCM is strongly dependent on its temperature. As an example, the equivalent specific heat capacity of PCM-A at the peak temperature T_p = 27.6°C is almost 5 times as high as at 25°C, and vice versa (Fig. 1). Consequently, at 25°C the PCM-A, despite being activated, has a storing capacity 5 times lower than at T_p = 27.6°C. Yhe Frequency of Activation itself is obviously not capable of accounting for this difference.

Therefore, it appears suitable to introduce a new indicator called *PCM storage efficiency*, that measures the ratio of the thermal energy E_{st} actually stored by the PCM to its maximum storage capacity, i.e. its latent heat L, as defined in Eq. (3). Since the PCM is subject to daily temperature cycles, the actual energy storage E_{st} must be evaluated over the period P = 24 hours [7].

$$\eta_{\mathrm{PCM}} = \frac{E_{st}}{L} = \frac{\int_P \left(C_{eq} \cdot \frac{dT_{PCM}}{d\tau} \right) d\tau}{\int_{T_m}^{T_s} C_{eq}\left(T\right) dT} \tag{3}$$

3. Case study

Figure 2 shows the sample building considered in this investigation: it is conceived as a module of a typical office building, with a large glazed surface protected by movable blinds, a concrete frame, a well-insulated envelope and very light partition walls to separate the different offices. This typology of building normally suffers from significant overheating in summer; thus, a good strategy for its refurbishment could be the application of PCM wallboards on the inner surface either of the partition walls or of the ceiling, thus enhancing the building thermal inertia.

The main façade of the building is due south-west; the size of each room is 5 m by 3.5 m, with a height of 2.5 m. Floors and ceilings are made of a non-insulated concrete slab as thick as 200 mm (U-value = 2.8 W·m^{-2}·K^{-1}); the internal partitions are composed by two plasterboards with a 40-mm layer of glass wool in between. The façade has a 100-mm layer of heavy-weight concrete, with an outermost layer of glass wool (70 mm); its U-value is 0.68 W·m^{-2}·K^{-1}.

In addition, each window measures 1.5 × 1.7 m^2, and is provided with an aluminium frame (10 cm in width) and a 4-16-4 double glazing with air filling (U-value = 2.7 W·m^{-2}·K^{-1}). External venetian blinds are also available; these are kept open during the simulations, unless the incident solar radiation on the glazing gets higher than 250 W·m^{-2}. The space behind the rooms at each floor hosts a large corridor and a series of specular rooms facing north-east. Finally, the rooms are considered occupied from 08:00 to 18:00 (occupancy rate = 0.12 people/m^2), and present overall sensible internal loads as high as 360 W, due to people, artificial lighting and electric appliances.

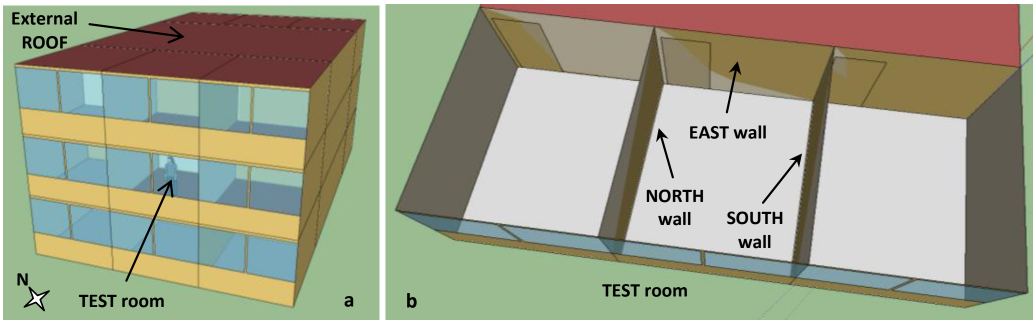

Fig. 2. (a): model of the simulated building. (b): partition walls covered with PCM wallboards

As far as ventilation is concerned, a constant air change rate $n = 0.5\ h^{-1}$ is considered for hygienic purposes. In order to check the effect of night ventilation on the performance of the PCM wallboards, an additional night ventilation rate is introduced between 21:00 and 06:00, with an air change rate $n = 4\ h^{-1}$ or $n = 8\ h^{-1}$.

The dynamic simulations needed for this study are carried out on EnergyPlus version 7.0 over the whole summer period (June - September) in free-running conditions. Firstly, the weather data of Milan (Lat. 45°27'N, Italy) are used, as an example of continental climate; in a second stage, other locations in Europe are considered. Three series of simulations are performed:

1. without PCM wallboards
2. PCM wallboards placed on the inner faces of the three partitions in the test room (Fig. 2)
3. PCM wallboards placed on the inner surface of the ceiling in the test room.

4. Results and discussion

4.1. Effect of the PCM wallboards on the thermal comfort

The profile of the indoor operative temperature in the test room, provided by the simulations with and without PCM wallboards for two sunny days in July, is shown in Fig. 3. In the cases with PCM, the wallboards containing PCM-A or PCM-B are applied on the inner surface of all the partition walls; all curves refer to Milan and to a ventilation rate $n = 4\ h^{-1}$ at night (from 21:00 to 06:00).

As shown by the diagram, the installation of the PCM wallboards yields a reduction in the peak operative temperature of about 0.5°C for both materials. On the other hand, in the central hours of the day (from 12:00 to 16:00) this reduction keeps around 1.0°C when using PCM-A, that seems more effective than PCM-B in reducing the indoor operative temperature swings.

However, as explained in Section 2.2, the ITD indicator can be very useful to provide more information about the improved thermal comfort determined by the installation of the PCM wallboards. Thus, this indicator is exploited hereafter to underline the role of the night ventilation as well as the effect of the position of the wallboards.

The main results of this analysis are reported in Fig. 4, and still refer to the city of Milan. The first message conveyed by Fig. 4 is that the PCM wallboards are far more efficient if applied on the partition walls than on the ceiling. As an example, with reference to $n = 4\ h^{-1}$, the application of PCM-A on the partition surface would yield a reduction by 51.0% in the seasonal ITD if compared to the case without PCM, while the improvement would only amount to 9.5% if the wallboards are applied on the ceiling. The difference between the two cases is remarkable

These results can be partially justified by the larger surface area available on the partitions (27 m^2) than on the ceiling (17.5 m^2). However, it is also true that the partitions – but not the ceiling – are directly hit by the solar radiation during the day; this determines a faster and more intense melting of the PCM, hence a more effective exploitation of its latent heat. One more simulation was devoted to the case where all the surfaces are covered by PCM (partitions plus ceiling): the results were very close to those obtained with the PCM placed only on the partitions.

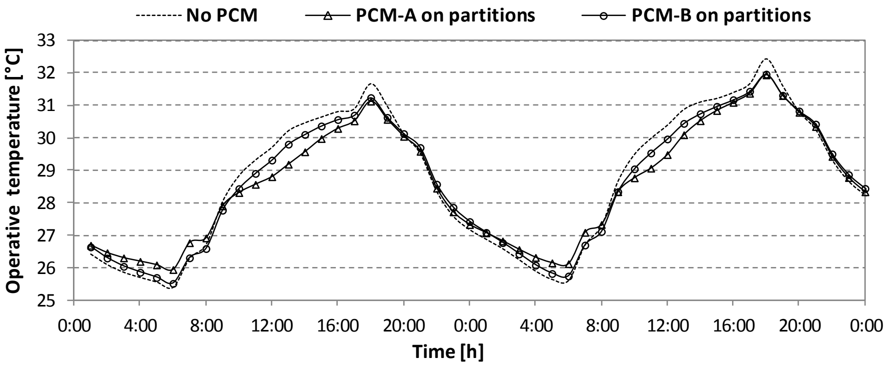

Fig. 3. Effect of the PCM wallboards on the indoor operative temperature (Milan, $n = 4\ h^{-1}$ from 21:00 to 06:00)

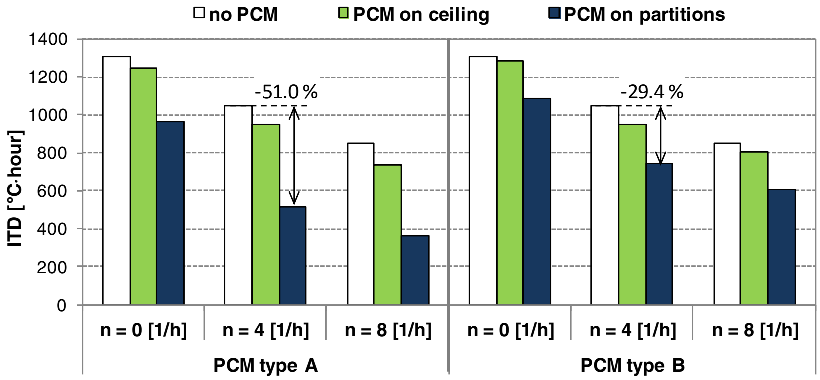

Fig. 4. Comparison based on the ITD measured over the whole summer season (Milan).

Another key message emerging from the simulations is the importance of a good night ventilation strategy, as this boosts the discharge of the heat absorbed during daytime. Indeed, Fig. 4 shows that the ITD is very sensitive to *n;* however, a saturation effect seems to occur, thus it is not recommendable to go beyond $n = 8\ h^{-1}$, since the benefit on the indoor summer thermal comfort tends to vanish.

It is also understood that such intense ventilation can only be practiced in tertiary buildings, that are supposed to be not occupied at night; furthermore, if the ventilation is procured by mechanical means, an accurate calculation of the electricity consumption should be made to avoid severe penalties to the benefits discussed so far.

Finally, the results reported in Fig. 4 confirm that the wallboards containing PCM-B are not as effective as PCM-A in reducing the intensity and the duration of the thermal discomfort perceived in the test room. As an example, when $n = 4\ h^{-1}$ and the PCM wallboards are applied on the partitions, the reduction in the ITD remarked in Milan in comparison with the case without PCM is 51.0% for PCM-A and only 29.4% for PCM-B.

The main reason is that the phase change for PCM-B occurs over a range of temperatures quite lower than for PCM-A (see Fig. 1). Hence, in the presence of the high temperatures usually measured in summer in free-running lightweight buildings, the storage capacity of PCM-B cannot be exploited as effectively as for PCM-A. Further investigations on this point are presented in the following section.

4.2. Correlation between climate and PCM effectiveness

The results reported in the previous section suggest that the wallboards containing PCM-A can allow a significant improvement in the summer thermal comfort for a typical lightweight office building located in Milan (Italy, continental climate). Now, it is interesting to investigate whether such favorable outcomes hold true also in other climatic contexts.

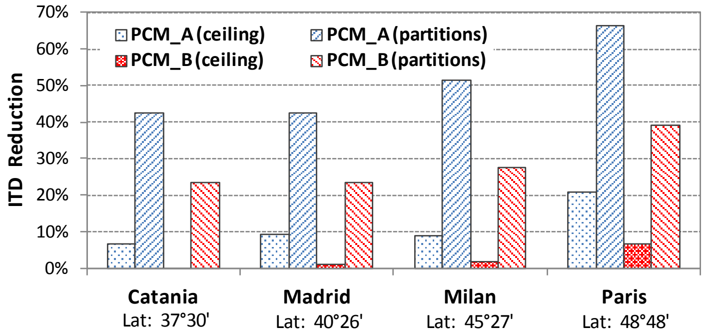

Fig. 5. Reduction in the ITD in relation to the site (n = 4 h^{-1})

As shown in Fig. 5, the effectiveness of PCM-A in reducing the Intensity of Thermal Discomfort in the test room is not the same for all the sites considered. Apparently, a certain correlation emerges between the ITD reduction and the latitude of the site. Indeed, the highest values of the ITD reduction occur in northern Europe (66.2%, Paris), whereas the least satisfying results are those concerning southern Europe, i.e. around 42% in Catania (Southern Italy) and Madrid (Spain). In addition, an average effect is observed in central Europe (51.0%, Milan), as already remarked in Fig. 4.

Such a tendency can be easily justified if one thinks that the high solar irradiance occurring in summer at low latitudes may produce a too intense PCM melting at daytime, especially if the glazed surface is high. Furthermore, at night, as the outdoor air temperature is on average quite high, there is a low potential for refreshing the room and discharging the heat absorbed by the PCM, that cannot be completely solidified. On the contrary, at high latitudes the PCM melting process might be often not complete, whereas solidification at night is easily achieved.

In any case, the installation of the wallboards on the ceiling are far less effective than on the partitions, whatever the latitude of the site.

4.3. The PCM storage efficiency

As explained in Section 2.3, the Frequency of Activation (*FA*) can provide interesting information about the operation of a PCM wallboard. The results obtained in this case study in terms of *FA* are shown in Fig. 6. Here, it is possible to observe that the wallboards containing PCM-A seem to work very well in Paris, as the PCM is almost always activated throughout the season (*FA* = 96%). On the contrary, the same wallboards keep very often in the liquid phase if installed in Catania, where the activation of the PCM is by far less frequent than in other sites (*FA* = 35%), due to the severe climatic conditions in summer. As concerns PCM-B, FA is always lower than for PCM-A.

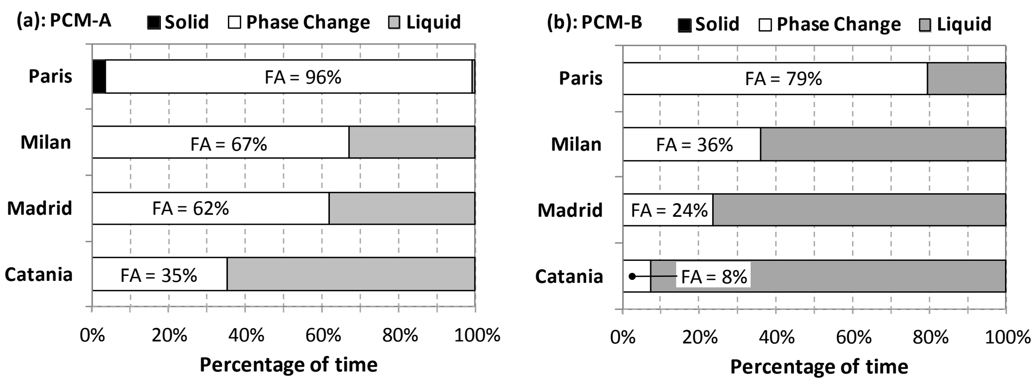

Fig. 6. Average Frequency of Activation of the PCM wallboards (July and August, n = 4 h^{-1})

On the other hand, the average values of the daily PCM storage efficiency are reported in Table 1. Here, a distinction is also made between the wallboards applied on the partitions and those installed on the ceiling. The values of this indicator are usually significantly lower than *FA*: as an example, the average storage efficiency is η_{PCM} = 42.6% for PCM-A in Paris, even if the PCM turns out to be activated for more than 90% of time (*FA* = 96%, see Fig. 6a). Very low values of η_{PCM} occur for PCM-B, ranging from 19.7% to 35.1% when installed on the partition walls and from 7.6% to 13.9% when installed on the ceiling. According to these figures, the effectiveness of the PCM wallboards seems not to be very satisfying, despite their frequent activation.

Table 1. Average values of the PCM storage efficiency (n = 4 h^{-1})

	PCM type A		*PCM type B*	
	On partitions	On ceiling	On partitions	On ceiling
CATANIA	35.0%	9.9%	19.7%	7.6%
MADRID	41.0%	14.0%	19.9%	7.6%
MILAN	42.1%	14.6%	24.4%	9.4%
PARIS	42.6%	20.7%	35.1%	13.9%

The reason for this apparently reduced PCM potential can be found by looking at Fig. 7, where each point describes the mean operating conditions of a wallboard over a day in summer.

The highest values of the daily storage efficiency for PCM-A (between 60% and 70%, see Fig. 7a) pertain to those days where the average temperature of the PCM wallboards is very close to the peak melting temperature. This corresponds to what already remarked by Neeper [13]. However, this condition occurs only occasionally in July and August; on the contrary, the daily temperature of the PCM is frequently either too low (in Paris) or too high (in Catania). As a general rule, the farther from T_P is the daily average PCM temperature, the lower is the daily PCM storage efficiency.

When looking at PCM-B, the situation is more unsatisfying: here, all the points regarding Catania are very close to the upper limit of the melting range, thus the daily storage efficiency always keeps between 15% and 25% (see Fig. 7b). Better results are observed in Paris; nevertheless, the daily values of η_{PCM} hardly exceed 50%.

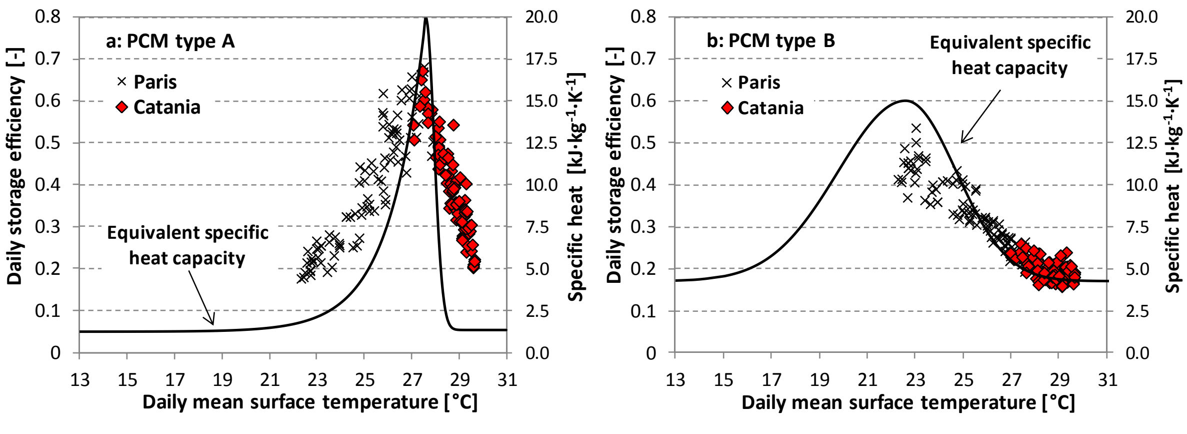

Fig. 7. Average daily PCM temperature vs. average daily storage efficiency.
Each point represents the mean value for all partitions (July and August, n = 4 h^{-1})

5. Conclusions

This paper discusses the effectiveness of PCM wallboards as a technique for improving summer thermal comfort in existing lightweight buildings. The investigation is extended to two different types of PCM and to several different climatic conditions.

The results confirm that the use of wallboards made of micro-encapsulated paraffinic PCMs is a promising and effective solution for the energy refurbishment of existing lightweight buildings. However, the ability of a PCM to improve summer thermal comfort in buildings is strictly related to the possibility of exploiting its latent heat capacity; to this aim, a parameter called PCM storage efficiency has been introduced and calculated in this paper.

According to the results, the main variables that affect the PCM storage efficiency are: (i) the position of the PCM wallboards within the room, (ii) the rate of nighttime ventilation and (iii) the value of the peak melting temperature for the specific PCM. However, the convenience of PCMs in existing buildings must be carefully considered also in relation to the local climate.

What has been outlined in this paper may help designers to make the correct choices in this direction.

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