Thermal Performance of Innovative Building Envelope Systems in Mediterranean Climate

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Abstract

Energy efficient buildings, besides saving energy, should provide adequate indoor thermal comfort. Hence, to maximize advantages, a balance between different energy efficient technologies and solutions must be found. In this sense, the European directives on the energy performance of buildings have defined a high standard of thermal insulation for buildings in order to comply with strict energy performance limits. However, several studies have highlighted that such an approach can have negative effects in summer, especially in the Mediterranean area, thus inducing an increase in the energy needs for cooling and a remarkable overheating.

In this context, the main objective of this study is to investigate the thermal performance of Vacuum Insulation Panels (VIPs) and Phase Change Materials (PCMs) when applied to the building envelope, and their ability to improve the building thermal behavior in the Mediterranean area. To this aim, a numerical model of a test room with standard construction technologies was implemented on Design Builder. This model was validated against experimental measurements available in the literature. Once the model was calibrated, a further series of simulations was performed by applying to the same test room the above-mentioned innovative building envelope systems. The simulations were run both in free-running conditions, in order to assess thermal comfort and thermal inertia of walls, and by assuming the presence of an HVAC system, to calculate the energy needs for space heating and cooling on a yearly basis.

The results highlight that, in summer, thermal discomfort and remarkable increases in the energy needs for cooling may occur when the building is retrofitted with VIPs, whereas better conditions are achieved with PCMs.

1. Introduction

The energy demand of buildings accounts for a remarkable part of the world energy consumption (Seong et al., 2013). Hence, improving the energy efficiency, while also providing indoor thermal comfort in buildings through high performance thermal insulation and sustainable materials, has a strategic role (Gagliano et al., 2016a).

In recent years, many developed countries have introduced programs directed at decreasing energy consumption and improving the carbon performance of buildings. Some researchers (Alotaibi et al., 2014; Alam et al., 2011; Thorsell, 2011) suggest the use of VIPs for highly energy efficient buildings. Indeed, VIPs can reduce the energy needs for the heating of a building from 158.7 to 127.5 kWh m^{-2}. A decrease of about 24 % can be achieved after retrofitting, due to a reduction in the transmission losses through the walls by 23 % (Johansson, 2014).

On the other hand, PCMs are innovative materials capable of storing or releasing thermal energy as latent heat. Since the amount of latent heat absorbed or released is much larger than the sensible heat, the application of PCMs in buildings has a significant potential to reduce both the peak heating and cooling loads, and the energy consumption (Seong et al., 2013; Bejan et al., 2016). The results of dynamic thermal simulations conducted on an office equipped with honeycomb PCM wallboards have shown a reduction in the peak operative temperature of about 1 °C during the summer period. Moreover, in the same study the peak surface temperature of the east wall decreases from 29.7 °C to 28 °C (Evola et

al., 2013; 2014). An experimental investigation carried out during two days in summer on a test room where PCM panels were superimposed on three walls, has highlighted that the indoor air temperature is about 1 °C lower when compared to the values measured before installing the panels (Kuznik et al., 2008; Kuznik et al., 2009). Simulations have shown a potential reduction by 2 °C in the peak indoor air temperature in a test room where microencapsulated paraffin was added to a 30 mm gypsum plaster during a week (Voelker et al., 2008).
In this framework, the present study aims at assessing the effectiveness of VIPs and PCMs in reducing the energy needs of a virtual office test room located in Southern Italy. Dynamic thermal simulations have been conducted both in free-running conditions, to assess the thermal comfort and thermal inertia of the walls, and by assuming the presence of an HVAC system to calculate the energy needs for space heating and cooling on a yearly basis.

2. Methodology

In order to investigate the thermal performance of these innovative materials, the software used for dynamic thermal simulations is DesignBuilder (Design Builder, 2014). The model of the virtual test room was first validated against the experimental results of the survey conducted on a real prototype of the same test room located in Milan (Rossi, 2009), with an average error below 1 %. After the validation, the virtual test room was simulated in a different location, namely Cozzo Spadaro, near Syracuse (Southern Italy)
As well known, in summer the energy needs and the thermal behavior of buildings strongly depend on the thermal inertia of their envelope. Generally, traditional constructive systems based on double brick walls do not have adequate thermal inertia to maintain good indoor thermal conditions and to guarantee low energy needs for space cooling. In particular, the facades facing east and west receive, in summer, a high solar irradiance that is comparable to that received on the south-facing façade. Consequently, one way to increase their performance may consist in the adoption of materials operating as a barrier against the outer external forcing conditions, and capable of absorbing heat from the indoor spaces. Hence, VIPs and PCMs are proposed as potential solutions. Moreover, different ways to install these materials on the walls are considered in order to analyze the possible effects of their position in the walls.
Therefore, five scenarios are analyzed in the paper:

- the base case, with double brick walls;
- two cases with VIPs and PCMs placed on the inner side of the baseline wall;
- two cases with VIPs and PCMs placed on the outer side of the baseline wall.

The base case and all VIPs scenarios are simulated by using the Conduction Transfer Function (CTF) method, whereas for the PCMs scenario the finite difference method is adopted (EnergyPlus, 2011). The simulations of the test room are carried out with a frequency of 12 timesteps per hour.
The indoor thermal comfort conditions and the thermal inertia of the walls facing east and west are studied through free-running simulations (without HVACs) from July 24th to 31st, which is the warmest week in summer. In particular, the results of the simulations are analyzed in terms of indoor operative temperature, inner and outer surface temperature, Time Lag (TL) and Decrement Factor (DF) of the walls. It is useful to remember that TL is the time shift between the maximum outer and inner surface temperatures occurrence, while the DF can be defined as the ratio of the amplitude of the inner surface temperature fluctuations to the amplitude of the outer surface temperature fluctuations (Gagliano et al., 2016b).
On the other hand, to measure the indoor thermal comfort in summer the *Intensity of Thermal Discomfort* (ITD) is adopted. The ITD is defined by the integral, over a certain period P, of the positive difference between the current indoor operative temperature (T_{op}) and the threshold value T_{lim} = 26 °C, needed to have comfortable indoor conditions (Sicurella et al., 2012). Moreover, the energy needs for heating and cooling are calculated through a second series of simulations where a thermostat control is set for the entire heating (20 °C) and cooling (26 °C) season.

2.1 Properties of VIPs

VIPs are innovative insulating solutions consisting in an evacuated, open-pore core material surrounded by thin laminates, used to maintain a high level of vacuum (Alam at al., 2011).

Their insulating capability is approximately seven times better than conventional insulating materials, such as mineral wool or EPS. Indeed, according to Johansson (2014), their thermal conductivity can be even below 5 $mW{\cdot}m^{-1}{\cdot}K^{-1}$. Consequently, a mineral wool board with a thickness of 185 mm is equivalent to a 20-mm thick VIP (Alotaibi at al., 2014). In this study, the authors used the following values to describe the VIPs performance: λ = 7 $mW{\cdot}m^{-1}{\cdot}K^{-1}$, ϱ = 160 $kg{\cdot}m^{-3}$ and c_p = 800 $J{\cdot}kg^{-1}{\cdot}K^{-1}$

2.2 Modeling the PCMs

The thermal behavior of a PCM undergoing phase change can be described by means of the relation between temperature and enthalpy:

$$dh(T) = C_{eq}(T) \cdot dT \tag{1}$$

Here, the enthalpy is set as h = 0 kJ kg^{-1} at T = 0 °C, while C_{eq} is determined experimentally. The melting process occurs through a temperature range; the maximum equivalent heat capacity is measured at the so-called *peak melting temperature*.

The PCMs adopted in this study consist of wallboards developed at CSTB (Centre Scientifique and Technique du Batiment), the performance of which is described in Evola at al. (2011). They are included in an aluminium honeycomb matrix, which contains 60 % of micro-encapsulated paraffin with a diameter of approximately 5 µm (Micronal T23 produced by BASF). Two thin aluminium sheets close the panel, the overall thickness of which is 2 cm (Hasse at al., 2011). According to the experimental measurements, the peak melting temperature is 27.6 °C for these PCM wallboards. However, since this temperature is quite low when compared to the thermal conditions expected in the case study, the real wallboards may not operate appropriately. Hence, the authors decided to consider a fictitious PCM wallboard in the simulations: they are exactly the same as the real honeycomb panels, but their melting curve is shifted in order to obtain a peak temperature of 30 °C.

The corresponding curve for Eq. (1) is depicted in Fig. 1. The melting process corresponds to the segments with the highest gradient: It begins at 27 °C and ends at 33 °C.

The honeycomb PCM panel has ρ = 545 $kg{\cdot}m^{-3}$ and λ = 2.7 $W{\cdot}m^{-1}{\cdot}K^{-1}$, which is imputable to the aluminum honeycomb matrix. Thanks to the aluminum honeycomb, the heat flux easily transfers through the panel, thus allowing the PCM included in the structure to work effectively.

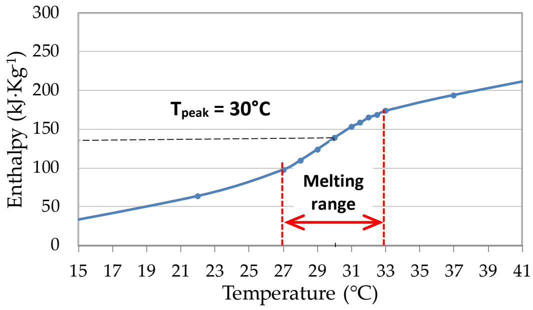


Fig. 1 – Enthalpy per unit mass for the PCM wallboards

3. Test Room

The test room (Fig. 2) has a gross surface area of 5.00 x 5.00 m and a height of 3.00 m. There are no obstructions and shields on all the outer sides. The façade facing south has a window measuring 3.00 x 1.35 m, that is to say 30 % of the external surface of the wall. The main geometric features of the building are reported in Table 1. In the simulations, the test room is located near Syracuse (lat. 36.7° N, long. 15.1° E, alt. 51 m). This area has a mild climate with hot dry summers and moderately cool winters.

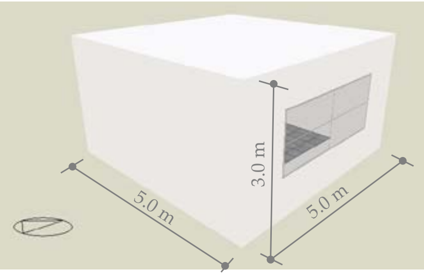


Fig. 2 – 3D model of the test room

Table 1 – Geometric features of the building

Geometric features			
Heated gross volume	V	58	m^3
Total external surface	S	85	m^2
Shape factor	S/V	1.70	m^{-1}
Net floor area	S_n	19.40	m^2

In summer, the average outdoor temperature ranges from 22 °C to 33 °C. In winter, the outdoor temperature varies from 5 °C to 15 °C, while in spring and autumn the climate is mild and the temperature fluctuates from 10 °C to 26 °C.

The test room was with an office program from Monday to Friday from 9:00 to 18:00. The internal loads are characterized by occupants, computers and lighting systems for a total of 380 W with a density of 15 $W·m^{-2}$. The occupancy density is 0.08 $people·m^{-2}$; lighting and office equipment power density is 8 $W·m^{-2}$. The air change rate is 0.5 $vol·h^{-1}$, without mechanical ventilation systems. The test room is equipped with a heating system represented by a natural gas boiler (η = 0.85), and a chiller for cooling purposes with COP = 2.50 in order to keep the indoor air temperature equal to 20 °C in winter and 26 °C in summer, respectively. The heating system is switched on during the occupancy period from December 1st to March 31st, whereas the air conditioning system operates from June 1st to September 30th.

3.1 Building Components

The building envelope of the test room in the base case is characterized by opaque vertical closures made by double brick walls with internal air gap and an overall thickness of 30 cm. The outer layer of the wall is in plaster with solar absorbance α = 0.60 and thermal emissivity ε = 0.90. The properties of the double brick walls are reported in Table 2; the air gap has a thermal resistance of 0.18 $m^2·K·W^{-1}$. A traditional slab with concrete and brick (thickness 20 cm) characterizes the flat roof and the floor.

Table 2 – Thermal properties of double brick walls

Layers	**s** m	**λ** $W·m^{-1}·K^{-1}$	**ρ** $kg·m^{-3}$	**C_p** $J·kg^{-1}·K^{-1}$
Outer Plaster	0.015	0.25	900	1000
Hollow brick	0.12	0.39	716	840
Mortar	0.01	1.00	1800	1000
Air gap	0.06	-	-	-
Hollow brick	0.08	0.40	775	840
Plasterboard	0.015	0.25	900	1000

The window has an aluminum frame without thermal break (U_f = 5.9 $W·m^{-2}·K^{-1}$), and two glasses (s = 6 mm) separated by an air gap (s = 12 mm); the glazing has U_g = 2.78 $W·m^{-2}·K^{-1}$ and SHGC = 0.70.

The U-value and the surface mass (SM) of the building components are reported in Table 3.

We validated the results of the simulation conducted on the base case with the measured data (24th–31st July) coming from an actual test room located in Milan (Rossi, 2009).

Table 3 – U-values and SM of the building components

	U ($W·m^{-2}·K^{-1}$)	SM ($kg·m^{-2}$)
Wall	1.02	160
Roof	1.84	332
Ground floor	1.98	332
Window	3.25	-

3.2 Solutions for Wall Insulation

We considered four configurations in the application of VIPs and PCMs respectively, to the inner and the outer surface of the standard wall in the test room (Fig. 3). The application of a 2 cm continuous layer of VIPs, either on the inner or the outer surface of the wall, allowed for the reduction of the U-value by 74 %.

Therefore, the U-value of the wall after retrofitting is 0.26 $W·m^{-2}·K^{-1}$. On the contrary, PCMs do not significantly reduce the U-value of the wall compared to the base case; indeed, the new value is 1.00 $W·m^{-2}·K^{-1}$.

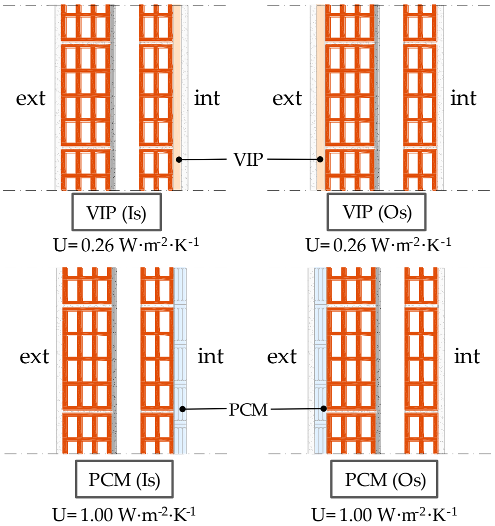
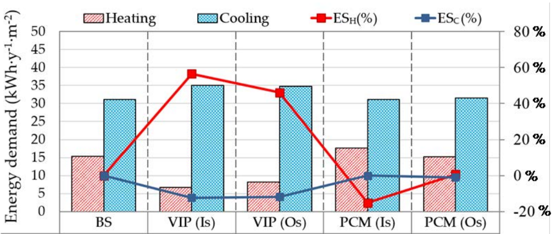


Fig. 3 – Wall configurations with VIPs and PCM on the inner surface (Is) and outer surface (Os)

4. Results

4.1 Energy Comparison

The energy needs for space heating and cooling in the different scenarios are shown in Fig. 4. Here, the energy savings in the heating period (ES_H) and in the cooling period (ES_C), compared with the base case, are also reported.



	BS	VIP (Is)	VIP (Os)	PCM (Is)	PCM (Os)
Heating	15	7	8	18	15
Cooling	31	35	35	31	31
ES_H(%)	0	57 %	46 %	-15 %	1 %
ES_C(%)	0	-12 %	-12 %	0 %	-1 %

Fig. 4 – Energy needs for space heating and space cooling

The results highlight that the application of VIPs allows for a significant reduction in the energy needs in the heating period. This is certainly due to the remarkable insulating capacity of the VIPs if compared to traditional insulating materials.

In particular, VIPs placed on the inner surface produce ES_H = 57 %, which is higher than the case where VIPs are placed on the outer surface (ES_H = 46 %). On the contrary, VIPs involve an increase in the energy needs during the cooling period in both scenarios (ES_C = -12 %). In fact, a highly insulated envelope does not promote heat dissipation, and determines overheating into the building in hot summer days.

Overall, the use of PCMs does not change the energy needs significantly. The only exception occurs in winter when the PCM is placed on the inner side (ES_H = -15 %). Indeed, the HVAC system imposes a constant value of indoor temperature (20 °C and 26 °C in the heating and cooling period), which is well below the melting temperature of the PCM. Therefore, the PCM remains in its solid phase almost the entire day. The exception that has been pointed out is probably due to the high thermal conductivity of the PCM, which also reduces the indoor surface temperatures, as shown in the following section.

4.2 Evaluation of Indoor Thermal Comfort

The operative temperature (T_{op}) within the test room was through simulations in free running conditions from July 1st to 31st. The main results are reported in Table 4.

As shown in Table 4, the operative temperature in the base case ranges from a minimum value of 28 °C to a maximum value of 34.1 °C. On the other hand, VIPs are generally responsible for an increase in both the minimum and the maximum values. In particular, when the VIPs are placed on the inner surface, the maximum operative temperature increases from 34.1 °C to 35.2 °C; when the VIPs are placed on the outer surface, the maximum operative temperature keeps almost the same as in the base case, but the minimum value increases by 1 °C. These results can be explained by considering that VIPs act as a barrier to the heat flux transferred from the inside to the outside, thus causing overheating. The overheating effect is also shown by the ITD value that increases by 17 % if compared to the base case. Hence, VIPs seem not to be suitable in hot climates. Furthermore, the PCM panels placed on the inner surface reduce the maximum operative temperature from 34.1 °C to 32.9 °C, with a decrease of 1.2 °C. This result is achieved thanks to the heat storage capacity of the PCM. In fact, in this case without thermostat controls, the PCM can reach the melting temperature range, thus it can be effectively exploited. If we look at ITD, this reduces by 2 %. Instead, the PCM placed on the outer surfaces does not offer significant improvement compared to the base case, as it cannot interact with the indoor environment. In this case, the ITD slightly increases.

Table 4 – Main results in terms of indoor thermal comfort.

		T_i (°C)	T_{op} (°C)	ITD (°C·h)
Base case (Bs)	Max	34.8	34.1	2631
	Min	27.9	28.0	
VIP (Is)	Max	35.8	35.2	3183
	Min	28.3	28.4	
VIP (Os)	Max	34.8	34.1	3137
	Min	28.8	29.0	
PCM (Is)	Max	33.6	32.9	2590
	Min	28.7	28.9	
PCM (Os)	Max	34.6	33.9	2669
	Min	28.3	28.1	

Overall, the proposed solutions for the retrofitting of the walls provide worse conditions in terms of summer thermal comfort, with the only exception of the PCM placed on the inner side.

4.3 Dynamic Thermal Behaviour

Time Lag and Decrement Factor were in relation to the inner (T_{si}) and the outer (T_{so}) surface temperatures, based on hourly simulations in free running conditions during the period from 1st to 31st July. Fig. 5 and Fig. 6 illustrate the hourly profiles of T_{si} and T_{so} for the walls facing east during three summer days (July 27th–30th). The results, also including the walls facing west, are shown in Table 5. As reported in Fig. 5, in the base case the east wall has a maximum outer temperature $T_{so,max}$ = 44.4 °C, which occurs at 10:00 am; the peak temperature on the inner surface ($T_{si,max}$ = 33.8 °C) is attained at 17:00. Thereby, in this case the TL is about 7 hours, while DF = 0.22 (see Table 5). The minimum values of T_{so} and T_{si} occur at 6:00 am and 9:00 am, and are about 23°C and 28 °C respectively.

When the VIP is placed on the inner side, the T_{so} assumes the same trend as in the base case, but the peak of T_{si} increases by 1.1 °C. The maximum T_{si} value is $T_{si,max}$ = 34.9 °C and occurs at 16:00; as reported in Table 5, TL = 6 h and DF = 0.26. Instead, the scenario with the VIP on the outer side provides a significant increase in the maximum outer temperature, compared to the base case. Indeed, $T_{so,max}$ increases from 44.4 °C to 47.9 °C.

The profile of T_{si} remains almost the same, with the only exception of the minimum value, which increases by 1.6 °C compared to the base case. It has to be highlighted that this scenario is able to attenuate the peak of the heat wave better than a standard wall (DF = 0.13). According to these results, the placement of the VIP layer on the outer side offers better performance in terms of dynamic behaviour.

The performance of PCMs is reported in Table 5. When the PCMs are placed on the inner side, the peak inner surface temperature decreases by about 1.4 °C, irrespective of the exposure, and the outer surface temperature is quite similar to that of the standard wall.

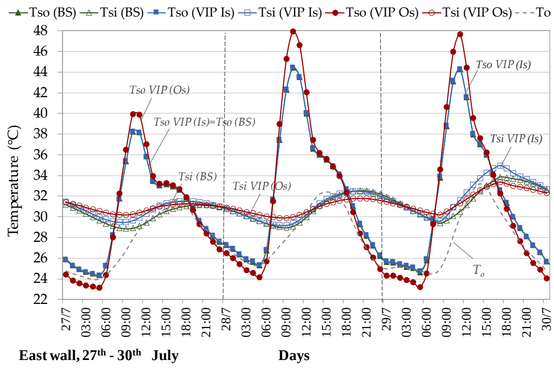


Fig. 5 – Inner and outer surface temperature of east wall (VIP)

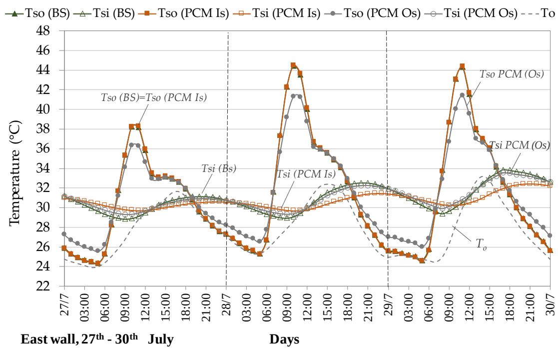


Fig. 6 – Inner and outer surface temperature of east wall (PCMs)

Table 5 – Surface temperatures and dynamic thermal parameters

		$T_{so,max}$ (°C)	$T_{si,max}$ (°C)	TL (h)	DF (-)
Base case (Bs)	East	44.4	33.8	7	0.22
	West	44.8	33.7	4	0.20
VIP (Is)	East	44.4	34.9	6	0.26
	West	44.8	34.8	2	0.24
VIP (Os)	East	47.9	33.4	7	0.13
	West	47.4	33.3	2	0.12
PCM (Is)	East	44.5	32.4	10	0.09
	West	44.9	32.4	7	0.08
PCM (Os)	East	41.4	33.5	7	0.24
	West	42.9	33.2	3	0.19

In fact, the PCM is able to delay and attenuate the heat wave better than the other solutions thanks to its ability to store heat and release it afterwards.

Hence, with reference to the east wall (Fig. 6), $T_{so,max}$ occurs at 10:00 am and $T_{si,max}$ occurs at 20:00, so TL = 10 hours while DF = 0.09.

On the other hand, the PCMs placed on the outer side provide a significant reduction in the peak outer surface temperature. Indeed, in the east wall $T_{so,max}$ decreases from 44.4 °C (base case) to 41.4 °C (see Table 5), which means a reduction by 3 °C. In this case, the profile of T_{si} is unchanged compared to the base case, as the PCM mainly accomplishes its action on the outdoor wall surface. Overall, the dynamic parameters gained from the simulations for all scenarios are reported in Table 5.

In the base case, the east and west walls show low TL values (7 and 4 hours, respectively) and DF = 0.20, because of their low surface mass. The peak values of outer and inner surface temperature are 44.8 °C and 33.8 °C, respectively. For the other solutions, the worse condition is the one where VIPs are placed on the inner side, because in this case the inner surface temperature increases by 1.1°C with great fluctuations.

On the contrary, the optimal solution is when PCM panels are placed on the inner side, which shows TL = 10 h and DF = 0.09, with a reduction in the peak inner surface temperature of about 1.4 °C. Both the solutions with VIP and PCMs on the outer side do not provide any significant contribution to the reduction of the inner surface temperature. Furthermore, it can be highlighted that the VIPs on the outer side overheat the outer surface of the walls by about 3 °C, while the PCM panels on the outer side reduce the peak outer surface temperature by about 3 °C.

5. Conclusions

The results show that the innovative solutions considered in this study (VIPs and PCMs) may be useful in the Mediterranean climate, but only if placed on the right side of the walls.

In particular, VIPs are very useful to reduce the heating energy needs: in this paper, the heating energy demand is reduced by 57 % and 46 % if they are placed on the inner or the outer side, respectively. However, the cooling energy needs increase by about 12 % compared to the base case.

As concerns the selected PCM, in this specific case it is not recommended with HVAC systems because in this case the set point imposed by the HVAC systems (20 °C in winter and 26 °C in summer) is lower than the melting temperature of the PCM, thus it cannot activate. Indeed, the results show that the energy demand for heating and cooling with the PCM panels are almost the same when compared to the base case.

However, if PCMs were used into a mixed-mode building with 28 or 30 °C cooling setpoint, they would be capable to activate and the application could work well.

The simulations in free-running conditions have highlighted that both the solutions with VIPs and PCMs on the outer side are the worst ones for indoor comfort conditions in summer. Placing the VIPs on the inner side leads to very high fluctuations in the indoor operative temperature (from 28.4 °C to 35.2 °C) compared to the case with PCMs placed on the inner side (from 28.8 °C to 32.9 °C). That is why the PCM panels placed on the inner side can be regarded as the optimal solution.

Nomenclature

Symbols

C_{eq}	Equivalent heat capacity ($J \cdot kg^{-1} \cdot K^{-1}$)
Cc_p	Specific heat ($J \cdot kg^{-1} \cdot K^{-1}$)
DF	Decrement factor (-)
ES	Energy saving percentage (%)
h	Enthalpy ($J \cdot kg^{-1}$)
ITD	Intensity thermal discomfort (°C·h)
s	Thickness (m)
S	External surface (m^2)
S_n	Net floor area (m^2)
SHGC	Solar Heat Gain Coefficient (-)
SM	Surface mass ($kg \cdot m^{-2}$)
T	Temperature (°C)
TL	Time lag (h)
U	Thermal transmittance ($W \cdot m^{-2} \cdot K^{-1}$)
V	Heated gross volume (m^3)

Greek letters

α	Solar absorptance (-)
ε	Thermal emissivity (-)
λ	Thermal conductivity ($W \cdot m^{-1} \cdot K^{-1}$)
ρ	Density ($kg \cdot m^{-3}$)
τ	Time (h)

Subscripts/Superscripts

C	Cooling
f	Frame
g	Glazing
H	Heating
i	Indoor
M	Melting point
max	Maximum
min	Minimum
o	Outdoor
op	Operative
si	Inner surface
so	Outer surface

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