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ORIGINAL ARTICLE

Thermal behaviour of insulation and phase change materials in buildings with internal heat loads: experimental study

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Abstract In recent years, the building sector is consuming high amount of energy; therefore, low energy buildings are promoted by the European Directives. In order to reduce the energy demand, improvements in the building envelope have been studied based on different aspects such as thermal insulation, thermal inertia and combining both of them. From the results obtained in the experimental set-up of Puigverd de Lleida (Spain) which analysed the thermal performance of different constructive systems, a similar methodology was used to consider internal heat loads, simulating scenarios with occupancy. This paper pretends to analyse the thermal performance of an insulated constructive system and another one with phase change materials (PCMs) located in the envelopes as passive cooling system. The experiments were done during the summer period. The results of the experimental campaign show that the insulation effect when internal gains are involved is harmful because heat loads cannot be easily dissipated to outdoors, increasing the energy consumption. Moreover, when adding PCM to an insulated constructive system, this effect is maximised because the PCM stores the heat produced by the inner loads and the external conditions; hence, the heat dissipation to the outer environment is limited.

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Introduction

The European Directive on the Energy Performance of Buildings (EPBD) suggests that all the EU member states should approve national plans and targets in order to promote the inclusion of very low and close to zero energy buildings (Directive 2010/31/eu). In recent years, 40 % of the global energy consumed in the European Union corresponds to the building sector, being the use of the HVAC systems an important fraction of this energy consumed. Consequently, the reduction of the energetic demand of the building became an important issue to overcome.

It is well known that there is a high potential in energy demand reduction with the improvement of building envelopes. An important amount of literature regarding the building envelope performance is related to the thermal insulation layer, as it is considered the most effective protection from the external conditions. Papadopoulos (2005) mentioned in a state of the art of insulation materials that the improvement in the thermal protection is the most cost-effective way to build or refurbish buildings with a reasonable energy consumption, satisfactory thermal comfort conditions and low operational costs. Also, guidelines and recommendations have been done by researchers, in a detailed and functional way for the practicing engineer and/or building owner. Al-Homoud (2005) presented an overview about the performance characteristics of common building thermal insulating materials. The author concludes that thermal insulation is more significant in buildings where there is a high demand of external load protection compared to those buildings with more internal load dominance.

Important energy savings have been quantified in the study of Cabeza et al. (2010) where the effect of the insulation in the building envelope was analysed. The authors experimentally registered an energy reduction of 64 and 37 % in the insulated buildings under summer and winter Mediterranean climate, respectively. Moreover, the location of the thermal insulation layer in the building facade is also a critical requirement for a better performance. Kossecka and Kosny (2002) concluded that the configuration with insulation in external walls can critically affect the thermal performance of the whole building, especially in continuously used residential buildings.

In addition, most of the building regulations were just focused on the insulation thickness to achieve a proper thermal resistance of the building components. Recently, some changes have been done in the building standards, such as in the Spanish one (CTE DB HE 2006). Some parameters related to the thermal inertia are taken into account for describing the materials used in the building envelope, i.e. thermal mass, specific heat capacity. These changes have been possible due to the demonstration of several published studies linked to the thermal inertia properties of materials and constructive systems which were not included in the building regulation. The design restrictions have to be focused not only on the thermal resistance but also on the thermal inertia, as well. Al-Sanea et al. (2012) recommended that building walls should contain a minimum amount of thermal mass to provide energy savings potential in buildings with continuously operating air conditioning.

Phase change materials (PCMs) have been widely studied for increasing the thermal energy storage capacity of the building envelopes Khudhair and Farid (2004), Zalba et al. 2003; Cabeza et al. 2011), which could offer an interesting solution to reduce the energetic demand of the HVAC systems (Sharma and Sagara 2005). This application is considered a passive solution, but PCM can also be implemented in active systems such as heating and cooling devices or domestic hot water equipment. Cabeza et al. (2007) tested the inclusion of micro-encapsulated PCM in a precast concrete cubicle. Results presented a 2-h delay of the maximum peak temperature in summer because of the Micronal PCM effect and also an internal temperature profile with lower fluctuations. Moreover, an experimental study of macro-encapsulated PCM implementation in the building envelope carried out by Castell et al. (2010) showed an energy consumption reduction of 15 % under summer conditions.

Nevertheless, the comfort requirements and the climatic conditions are still the main parameters that are taken into account in scientific studies, leaving a part the internal heat caused by the activity of a building. Occupancy, equipment and lighting are examples of internal gains of an office which affect strongly the thermal performance of the whole building and hence influence the comfort temperature. The heating and cooling demand is influenced by these internal gains and, hence, the HVAC system requirements too. Ballarini and Corrado (2012) presented a methodology to evaluate the thermal performance of a building in summer focusing in the insulation level. The results showed a weak influence of the whole envelope on the energy performance of an office building due to the high impact of the internal heat sources. On the other hand, in the residential building case, the whole envelope represented a fundamental contribution to the cooling energy demand.

Moreover, the influence of the thermal mass location in the envelope of a building with high internal heat loads during summertime was studied by Di Perna et al. (2011). In the experimental and parametric analysis, the authors concluded that the thermal inertia should be placed on the internal side of the building envelope and an insulation layer on the external side. However, in this paper, no details of the key parameters such as heat gains, schedule and ventilation are presented. Therefore, there is a need for a detailed study to evaluate the influence of internal heat loads in the overall thermal performance of a building.

Taking into account the previous experience obtained from the experimental installation of Puigverd de Lleida (Spain), the objective of this study is to analyse experimentally the thermal impact of the internal heat loads when insulation and PCM are placed in the external walls of the buildings. In order to focus this study on the performance of the cubicle constructive system, the heat gains due to the direct incidence of the solar radiation through the openings are not taken into account;

Fig. 1 Experimental set-up of Puigverd de Lleida

therefore, test cubicles were designed without windows. The experiments were done during the summer period to observe the effect of the insulation and the thermal inertia that the PCM is providing to the envelope. In this case, both materials are designed as passive systems in order to protect from the high outdoor temperatures in summer.

The inclusion of PCM in the building envelope increases the thermal energy storage capacity, and therefore, thermal loads are supposed to be absorbed. On the other hand, the PU insulation reduces the heat coming from the external conditions; however, the internal heat loads could be an inappropriate scenario for this constructive system, since heat cannot be easily dissipated.

Methodology

The experiments were done in the experimental facility of Puigverd de Lleida, Spain (Fig. 1). The area corresponds to the climate Csa according to the Geiger climate classification (Kottek et al. 2006). Three different cubicles with the same inner dimensions (2.4×2.4×2.4 m) and orientation (N-S, 0°), no windows, and an insulated metal door in the north wall were studied. The constructive system selected for the design of these three cubicles permits the evaluation and comparison of the incorporation of polyurethane and PCM in a conventional Mediterranean building.

The description of the constructive system and materials used in the construction of the cubicles are shown in Fig. 2. The three cubicles are built based on the traditional brick system which consists of two brick layers with an air gap between them. The cubicle called Reference (REF) cubicle has no insulation in its wall constructive system; on the other hand, the polyurethane (PU) cubicle is insulated between the brick layers with 5 cm of spray foam polyurethane. In the same way, as the previous cubicle described, the PCM (PCM) cubicle is insulated with polyurethane, but it also contains a PCM layer on the internal face of the insulation. The

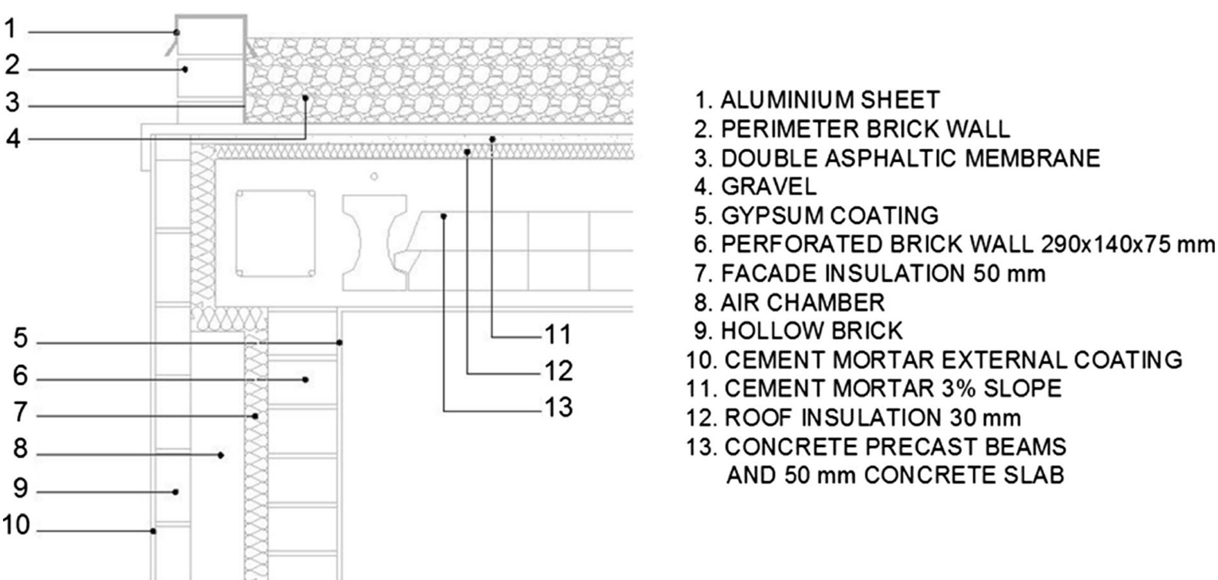

Fig. 2 Section of the constructive system of the cubicles

PCMs are macro-encapsulated in aluminium panels which are implemented in the southern and western walls and in the roof. The total amount of PCM for each wall/roof is 33 kg. Physical properties of the PCM provided by the manufacturer are presented in Table 1.

A domestic heat pump (Fujitsu Inverter ASHA07LCC) was installed in each cubicle to cover the cooling demand. The internal loads existing in a real building were simulated using an infrared radiator HJM mod. 301 (Fig. 3). Moreover, a timer is programmed to control these loads in order to provide a thermal scenario similar to an office profile (9–14 and 16–19 h). This heat load scenario considers the case of an office with one person, a computer with screen and the lighting, and the heat loads are determined following ASHRAE standards (Ashrae handbook fundamentals 1997), resulting in 330 W (57.3 W/m^2).

The cubicles were strongly instrumented to be able to measure and to evaluate their thermal performance. A data logger facility registered the following parameters every 5 min:

- Temperature of internal wall surfaces (east, west, north, south, roof and floor) and also external south wall temperature
- Indoor temperature and humidity of the cubicle
- Electrical energy consumption of the heat pump

In addition, weather conditions including solar radiation, outdoor temperature and humidity, and wind velocity and direction were also registered.

Sensors used for wall temperature measurements are Pt-100 DIN B, calibrated with a maximum error of ±0.3 °C. Indoor temperature and humidity conditions are measured with ELEKTRONIK EE21 with an accuracy of ±2 %. The energy consumption of the heat pump is registered by an electrical network analyser (Circutor MK-30-LCD).

During the summer period, two sets of experiments were performed in the experimental installation:

- Internal loads and free floating conditions: no cooling system was used during these experiments. The evolution of the internal temperatures of the cubicles was compared.
- Internal loads and controlled temperature: heat pumps were used to set the internal temperature of the cubicles, and their energy consumptions were compared.

Table 1 Physical properties of PCM

Property	RT-27
Melting point (°C)	28
Congealing point (°C)	26
Heat storage capacity (kJ/kg)	179
Density (kg/L)	
Solid	0.87
Liquid	0.75
Specific heat capacity (kJ/kg K)	
Solid	1.8
Liquid	2.4
Heat conductivity (W/mK)	0.2

In order to analyse the performance of the thermal insulation and the PCM when internal loads are simulated inside the cubicles, the experimental results are compared with the results of a previous study carried out using the same experimental facility (Cabeza et al. 2010; Castell et al. 2010).

Results

Internal loads in free floating conditions

The thermal evolution of the different internal environments under free floating conditions is presented in

Fig. 3 Infrared radiator HJM mod. 301

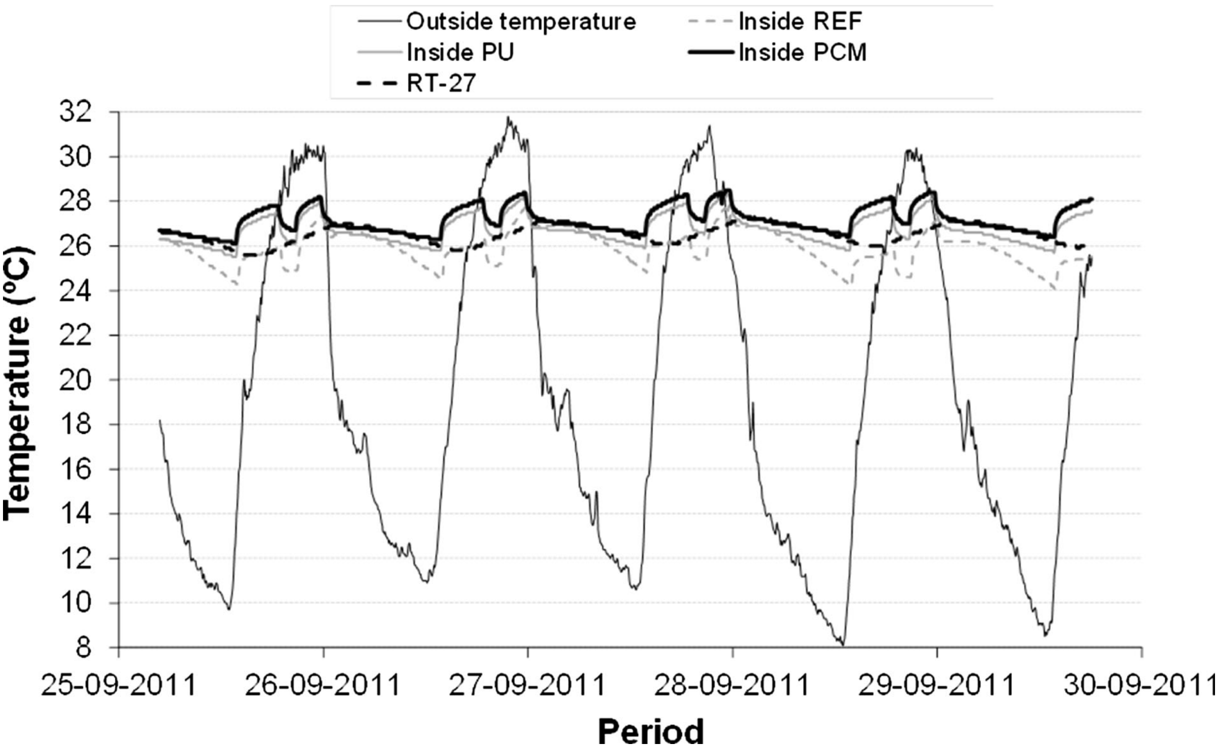

Fig. 4 Free floating with internal loads: inside and outside temperatures

Fig. 4. First phenomenon observed is that both cubicles with insulation have low temperature oscillations (28 to 26 °C) when compared to the reference one (28 to 24 °C). These high temperature gradients were expected in the reference cubicle, considering that the heat produced during the office profile can be easily released to outdoors at night-time.

In the free floating experiment, it can also be observed that the heat released during the occupancy period is transferred to the outer environment at a different rate depending on the thermal transmittance (U-value) of the cubicle envelope. The U-value of the cubicles was calculated in a previous study with experimental and theoretical methods (Table 2) (de Gracia et al. 2011). The polyurethane and PCM cubicles have the same U-value; therefore, one could think that they should have similar thermal profiles. However, the thermal inertia provided by the PCM must also have an effect. This effect is observed in the internal temperature of the PCM cubicle, which is always slightly higher than the polyurethane one.

Table 2 U-value calculations

	U-value (W/m^2 K)	
	Theoretical	Experimental
REF	1.21	1.04
PU	0.38	0.30
PU + PCM (RT-27)	0.38	0.30

From de Gracia et al. 2011

Figure 5 presents the daily thermal behaviour of the internal temperatures for each cubicle. Both insulated cubicles start at the same temperature when the internal loads switch off at 19.00 h, and during the night, the inside temperature of the cubicles decreases while heat is being released to outdoors. RT-27 temperature profile is also presented in Fig. 5, where it can be seen that the temperature of the PCM is always in the phase change range (26–27 °C). Therefore, the temperature drop in the PCM cubicle is slower due to the higher amount of heat stored in the PCM through the phase change. Moreover, after the night period and when the daily cycle starts again, the internal temperature of the PCM cubicle is around 0.5 °C above that of the PU one due to limited heat dissipation to the outer environment of the internal loads. Therefore, the PCM cubicle temperature is higher than that of the PU one during the whole office profile.

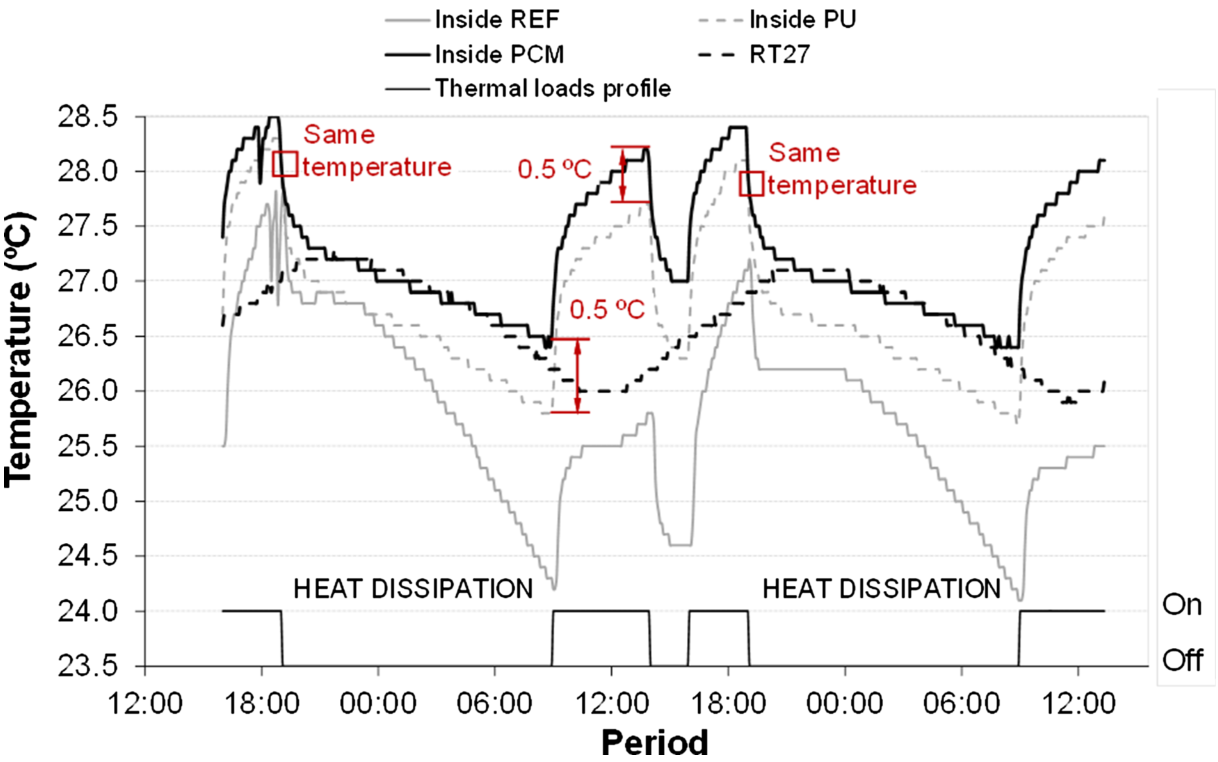

Fig. 5 Free floating with internal loads: internal temperature of the cubicles during a given day

On the other hand, in the case of the reference cubicle, the temperature decreases faster than in the other cubicles during the heat dissipation period due to a higher heat transfer rate.

Internal loads under controlled temperature conditions

In controlled temperature experiments, the energy consumption of the heat pumps of all the cubicles is compared. Several experiments have been performed with different temperature set points in order to analyse the PCM performance at various temperatures and therefore at different phases (solid or liquid). All the experiments were carried out for 10 days, but just the last 5 days were analysed to avoid the different initial conditions.

Moreover, the weather conditions were registered during all the experiments, and the results are presented in Table 3.

Due to the lack of insulation, REF cubicle, as it was expected, is the one that consumes the most in

Table 3 Weather conditions during the experiments

Experiment	Temperature (°C)			Solar radiation		Humidity (%) average
	T_{max}*	T_{min}*	$T_{average}$	Daily solar energy average (MJ)	Daily irradiance average (W/m^2)	
Set point 20+TL	40.2	13.9	26.3	21.4	478	55.5
Set point 20	38.0	9.9	24.3	29.4	542	59.7
Set point 22+TL	30.4	11	21.4	25.0	445	49
Set point 24	35.5	11.8	23.3	22.7	374.9	68.1
Set point 24+TL	34.2	8.6	22	23.0	415	52.1
Set point 27+TL	35.2	14.2	24.2	28.3	532	56.9
Set point 29+TL	38.6	15.9	27.7	27.5	491	53.5

all the experiments (Fig. 6). Moreover, the insulation effect is reflected in the PU cubicle, presenting lower energy consumption in comparison to the REF one. On the other hand, the PCM cubicle consumption is always above that of the PU one. Finally, an effect of the temperature set point can also be observed. While, in the experiments with set point at 20 and 29 °C, PU and PCM cubicles have almost the same energy consumption, the difference among them is higher in the experiments where the set point is 22, 24 and 27 °C (Table 4).

As it was previously seen in the free floating experiments, the heat from the external summer conditions and the heat provided by the internal loads are affecting the PCM layer. The PCM is storing the heat coming from the external environment and the heat produced by the internal loads. This heat stored by the PCM is not rejected to the external ambient, and therefore, it must be absorbed by the heat pump, causing an increase on the energy consumption in order to achieve the desired thermal set point. In experiments with set point of 22, 24 and 27 °C, the difference between the consumption of PU and PCM cubicle is higher because the RT-27 is inside its phase change range. Therefore, the PCM is partially or completely melted and the cubicle envelope has a higher thermal inertia compared to the PU one. On the other hand, when the PCM is not working within its phase change range, its stored energy is reduced and so is the heat pump consumption.

Table 4 presents the energy consumption of each experiment as well as the energy reduction that the PU and PCM cubicle achieved compared to the REF one. These energy savings are calculated for each experiment and the values differ depending on the temperature set point. The PU cubicle has energy savings of around 21 % in experiments at 20 and 22 °C. As long as the set point temperature is increasing, the difference is getting higher, from 39.3 % at 24 °C to 46.7 % with a set point of 29 °C.

Table 4 Energy consumption values of the controlled temperature experiments for cooling

		Energy consumption		Energy savings (%)
		Accumulated (kWh)	Daily (kWh/day)	
Set point 20 °C	REF	22.19	4.44	0
	PU	17.61	3.52	20.63
	PCM	18.09	3.62	18.49
Set point 22 °C	REF	12.60	2.52	0
	PU	9.96	1.99	20.92
	PCM	10.95	2.19	13.04
Set point 24 °C	REF	9.20	1.84	0
	PU	5.58	1.12	39.30
	PCM	6.53	1.31	29.00
Set point 27 °C	REF	6.95	1.39	0
	PU	4.69	0.94	32.52
	PCM	5.49	1.10	21.02
Set point 29 °C	REF	8.27	1.65	0
	PU	4.41	0.88	46.72
	PCM	4.77	0.95	42.27

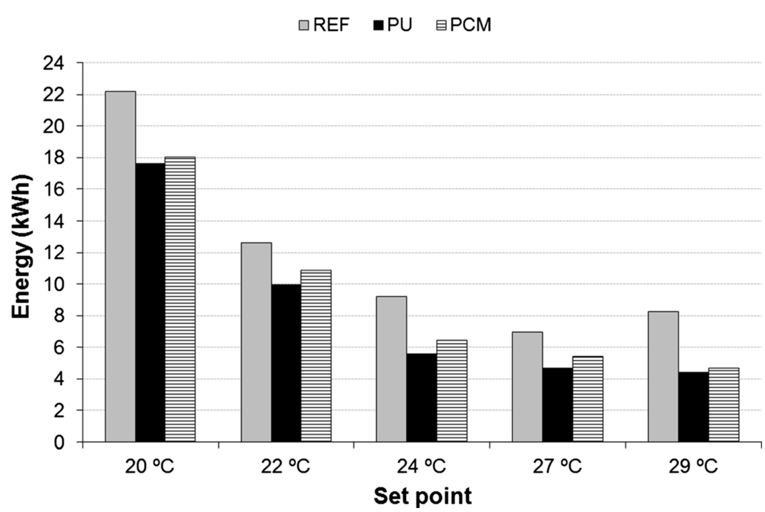

Fig. 6 Accumulated energy consumption of the controlled temperature experiments for cooling

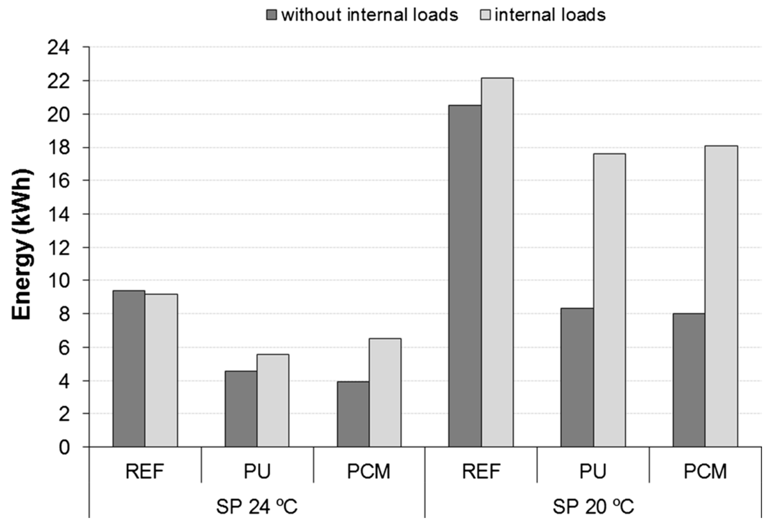

Fig. 7 Accumulated energy consumption of the controlled temperature experiments for cooling with and without internal loads

Discussion

Once the experiments with internal heat gains are analysed, the values are compared with the results obtained in previous studies, where the same experiments were done without internal loads (Fig. 7). Table 5 summarises the energy consumption values for both experiments. Experiments with a set point of 20 and 24 °C are presented, since they correspond to the minimum and maximum differences in behaviour between the PU and PCM cubicles, as seen in Table 3.

In the experiment with a set point temperature of 24 °C, the energy savings registered in the PU cubicle are reduced from 51 % (without internal heat gains) to 39.3 % (with internal heat gains) in comparison to the REF cubicle. Moreover, when another experiment with set point of 20 °C is compared, it can be seen that, again, having the occupancy loads increases the energy consumption of the PU cubicle, having 20 and 59 % of energy savings with internal gains and without, respectively. The effect of the insulation layer is beneficial when reducing the heat coming from the outdoors but, at the same time, is acting as a barrier for the internal heat dissipation.

Furthermore, the PCM cubicle shows a similar effect. In the experiment with a set point temperature of 24 °C,

Table 5 Comparison between experiments for cooling with and without internal heat loads

			Energy consumption (kWh)	Energy savings (%)[a]	Improvement PCM (%)[b]
SP 24 °C	Internal loads	REF	9.20	0	–
		PU	5.58	39.30	0
		PCM	6.53	29.00	–16.98
	Without internal loads	REF	9.38	0	–
		PU	4.58	51.12	0
		PCM	3.91	58.33	14.75
SP 20 °C	Internal loads	REF	22.19	0	–
		PU	17.61	20.63	–
		PCM	18.09	18.49	–2.70
	Without internal loads	REF	20.53	0	–
		PU	8.34	59.39	–
		PCM	8.03	60.89	3.71

[a] Compared to REF cubicle

[b] Compared to PU cubicle

the energy savings registered in the PCM cubicle are reduced from 58 % (without internal heat gains) to 29 % (with internal heat gains) in comparison to the REF cubicle. In addition, the PCM cubicle presents an energy reduction of 15 % compared to the PU one in the case with no heat gains. However, the including internal loads cause a negative energetic performance, resulting in energy consumption 17 % higher than that of the PU cubicle. These results corroborate those observed in the PU cubicle, where the protection from the high external temperatures is working properly. Nevertheless, when internal gains are taken into account, the PU insulation and the PCM layer have an inappropriate performance because of its low dissipation capacity.

Conclusions

The thermal performance of two different constructive systems is experimentally analysed in summer conditions and with high internal heat loads. Three cubicles with the same dimensions were compared under Csa climate (according to the Geiger climate classification) to determine the effect of internal loads in the behaviour of thermal insulation and thermal inertia (using PCMs).

During the free floating experiments, the internal ambient temperatures showed that the PCM cubicle had low dissipation capacity of the heat loads. The PCM stored the heat and maintained the indoor temperature at higher values than in the other cubicles, which reduces significantly the thermal comfort of the building. This behaviour was also seen in the controlled temperature experiment, where the PCM cubicle always consumed more energy than the PU one due to the higher operation of the heat pump to achieve the comfort temperature.

Moreover, a comparison between the results obtained with and without internal heat loads demonstrated the high influence of the internal gains in both polyurethane insulation and PCM systems. When comparing the energy savings achieved by the inclusion of PU insulation in comparison to the REF cubicle, this is reduced from 60–65 % (without internal heat loads) to 39–20 % (with internal heat loads). In the experiments performed for this study, the cubicles are dealing with the heat coming from outside and the internal heat gains. In the case of the PU cubicle, the insulation is preventing the internal ambient from the high external temperatures but, at the same time, is an obstacle to dissipate the internal gains to outdoors.

Similarly, the PCM cubicle registered an improvement of 15 % in energy consumption comparing to the PU cubicle without internal loads. When occupancy loads are included, the PCM is punishing the energetic performance of the cubicle and it consumes 17 % more than the PU.

As a conclusion, it is demonstrated that the inclusion of PCM in the building envelope as a passive system for reducing the summer temperature peaks is not recommended in a building with high internal heat loads unless proper natural ventilation for PCM and internal ambient discharge can be programmed. Furthermore, the PU insulation layer is not working properly when dissipating the heat gains and this is reflected on the registered higher energy consumptions.

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References

Al-Homoud, M. S. (2005). Performance characteristics and practical applications of common building thermal insulation materials. *Building and Environment, 40*, 351–364.

Al-Sanea, S. A., Zedan, M. F., & Al-Hussain, S. N. (2012). Effect of thermal mass on performance of insulated building walls and the concept of energy savings potential. *Applied Energy, 89*, 430–442.

American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc. (1997). Ashrae handbook fundamentals. In R. A. Parsons (Ed.), *Nonresidential cooling and heating load calculations* (pp. 28.7–28.16). Atlanta: SI Edition.

Ballarini, I., & Corrado, V. (2012). Analysis of the building energy balance to investigate the effect of thermal insulation in summer conditions. *Energy and Buildings, 52*, 168–180.

Cabeza, L. F., Castellón, C., Nogués, M., Medrano, M., Leppers, R., & Zubillaga, O. (2007). Use of microencapsulated PCM in concrete walls for energy savings. *Energy and Buildings, 39*, 113–119.

Cabeza, L. F., Castell, A., Medrano, M., Martorell, I., Pérez, G., & Fernández, I. (2010). Experimental study on the performance of insulation materials in Mediterranean construction. *Energy and Buildings, 42*, 630–636.

Cabeza, L. F., Castell, A., Barreneche, C., de Gracia, A., & Fernández, A. I. (2011). Materials used as PCM in thermal energy storage in buildings: a review. *Renewable and Sustainable Energy Reviews, 15*, 1675–1695.

Castell, A., Martorell, I., Medrano, M., Pérez, G., & Cabeza, L. F. (2010). Experimental study of using PCM in brick constructive solutions for passive cooling. *Energy and Buildings, 42*, 534–540.

De Gracia, A., Castell, A., Medrano, M., & Cabeza, L. F. (2011). Dynamic thermal performance of alveolar brick construction system. *Energy Conversion and Management, 52*, 2495–2500.

Di Perna, C., Stazi, F., Ursini Casalenab, A., & D'Orazio, M. (2011). Influence of the internal inertia of the building envelope on summertime comfort in buildings with high internal heat loads. *Energy and Buildings, 43*, 200–206.

Directive 2010/31/eu of the European Parliament and of the Council of 19 May 2010 on the energy performance of buildings. Available from: http://www.epbd-ca.eu. Accessed Oct 2014.

Khudhair, A. M., & Farid, M. M. (2004). A review on energy conservation in building applications with thermal storage by latent heat using phase change materials. *Energy Conversion and Management, 45*, 263–275.

Kossecka, E., & Kosny, J. (2002). Influence of insulation configuration on heating and cooling loads in a continuously used building. *Energy and Buildings, 34*, 321–331.

Kottek, M., Grieser, J., Beck, C., Rudolf, B., & Rubel, F. (2006). World Map of the Köppen-Geiger climate classification updated. *Meteorologische Zeitschrift, 15*, 259–263.

Papadopoulos, A. M. (2005). State of the art in thermal insulation materials and aims for future developments. *Energy and Buildings, 37*(1), 77–86.

Sharma, S. D., & Sagara, K. (2005). Latent heat storage materials and systems: a review. *International Journal of Green Energy, 2*(1), 1–56.

Spanish government. (2006). *Código técnico de la Edificación: Documento básico HE ahorro de energía*. Resource document. http://www.codigotecnico.org/web/recursos/documentos/DB_HE_abril_2009.pdf. Accessed 17 Feb 2007.

Zalba, B., Marín, J. M., Cabeza, L. F., & Mehling, H. (2003). Review on thermal energy storage with phase change: materials, heat transfer analysis and applications. *Applied Thermal Engineering, 23*, 251–283.