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Investigation into application of PCMs in lightweight buildings: annual energy performance simulation and economic evaluation under three European climates

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Abstract
The application of PCMs into a lightweight office building is examined under three locations: Rome, London and Vienna. The study analyzed the effect of PCMs during the whole four seasons. With the aid of EnergyPlus, the indoor temperature fluctuation reduction, the increase of comfort hours and the reduction in cooling and heating loads were compared. Different melting temperatures, thicknesses, orientations and quantities of PCMs were investigated. The results showed that 23°C is the PCM melting point that provides the highest energy savings in all the chosen climates. Moreover the simulations demonstrated that above 3cm the PCM performance increase slower and the suggested walls' orientations of PCM application are: east or west in Rome and south in London and Vienna. Finally payback periods of 4-11 years, correspondent to 15-30% annual energy savings, were predicted in Rome, whilst in London and Vienna 20 years were estimated as a minimum.

Keywords: PCMs, annual performance, temperate climate, EnergyPlus, Europe

1 Introduction

The environmental and energy crisis that nowadays' society is facing requires new solutions to minimize the dependency on fossil fuels and promote new sustainable approaches. The built environment in the developed nations is a major contributor of energy consumption and consequently it is also responsible for a considerable amount of greenhouse gas emissions. Thus, as an example, the European Commission imposed the NZEB target to be met by 2020, which requires new buildings to be "nearly-zero" energy buildings. The new restrictive regulations on buildings' performance, together with the increased occupants' comfort requirements for both heating and cooling, can be met by means of passive strategies to reduce energy demands and active strategies with the integration of renewable energy technologies to produce energy on site.

In this contest, ES (energy storage) systems can play an important role for both efforts: as a passive strategy in the type of *thermal energy storage* (TES), sensible or latent, to act on the principle of *thermal mass*; or as an application to active systems to make them more reliable and maximize their output by storing energy when their intermittent source of energy is not available.

Omitting the active systems applications which will not be presented in this paper, TES consists in the temporary storage of heat or cold for later use and can be *sensible*, when the temperature of the storage medium is varied during the process, or *latent*, when the substance changes phase at a nearly constant temperature.

The main advantages are the reduction of the indoor air temperature fluctuation, which causes discomfort and high dependency on mechanical heating/cooling, and/or the time shifting of peak loads.

While sensible TES are widely exploited with conventional materials such as concrete, brick, and stone which require massive constructions, latent TES, with the use of *phase change materials* (PCMs), have the advantage of storing larger quantities of heat in considerably lower mass so that they can be used in new lightweight constructions or for retrofitting design where space requirements are crucial.

2 Methodology

The aim of this study was to explore the outcome of the optimization of PCMs during a whole year rather than a single summer week. The optimization focused on the optimal melting temperature, thickness, orientation and quantity of PCMs. The parameters chosen for comparison are:

- Indoor operative temperature and temperature fluctuation reduction
- hours comfort according to ASHRAE 55-2004 thermal comfort model (ASHRAE, 2009)
- Cooling and heating loads reduction.

The study was conducted using EnergyPlus which was chosen among the other available software because it is fully able to simulate PCMs, it has been validated experimentally (Tabares-Velasco et al., 2012) and it is easily downloadable free of charge.

Three European cities were chosen for the simulations: London, Vienna and Rome. These locations represents three common climate types in Europe (Table 1) according to the Koppen-Geiger classification (Peel et al., 2007).

Table 1. Koppen-Geiger classification of the chose locations

Location	Zone	Description
Rome	Csa	Temperate-without dry season-warm summer
London	Cfb	Cold-without dry season-warm summer
Vienna	Dfb	Temperate-dry summer-hot summer

The building's model used for the simulations is a 50m^2 lightweight building with typical office internal gains, infiltration and ventilation (Table 2).

Table 2. Internal gains and ventilation settings

Object	Settings
People	6.7 W/m^2; 12m^2/person
Clothing	1.3clo in winter; 0.8clo in spring and autumn; 0.6clo in summer
People activity	117W/person equivalent to 1.1MET
Lights	10 W/m^2
Equipment	15 W/m^2
Infiltration	0.5 ACH
Ventilation	12 L/s per person
night ventilation	10 ACH in Rome, 5ACH in London and Vienna (active in summer)

The PCM used in the simulations is an organic paraffin encapsulated in a light and flexible mat to be applied between the insulation and the internal plasterboard (Phase Change Energy Solutions, 2013). The product is available in three melting

temperatures: 23, 25 and 27°C, which will be referred in the paper as PCM-23, PCM-25 and PCM-27.

The economic analysis was carried out using the payback period as a method of evaluation, calculated with the following formula.

$$\textbf{Payback}\ period\ [\textbf{years}] = \frac{\textbf{PCM price}\ [€/m^2] \times \textbf{area of PCM}\ [m^2]}{\textbf{energy savings}\ [\textbf{KWh/years}] \times \textbf{electricity price}\ [€/\textbf{KWh}]}$$

3 Results and discussion

3.1 Reduction of uncomfortable hours and indoor temperature fluctuation

The simulation results proved that in all the three chosen locations the application of PCMs improved the building's performance by progressively increasing the number of comfortable hours -according to ASHRAE 55 thermal comfort model- compared to the baseline case without PCM when the melting temperature is reduced from 27°C to 23°C. The improvement for the uncontrolled building occurs especially during spring and autumn and temperature fluctuation reduction is visible during the whole year. As an example, Figure **1** shows hourly temperatures and number of uncomfortable hours with and without PCM in the Vienna case study.

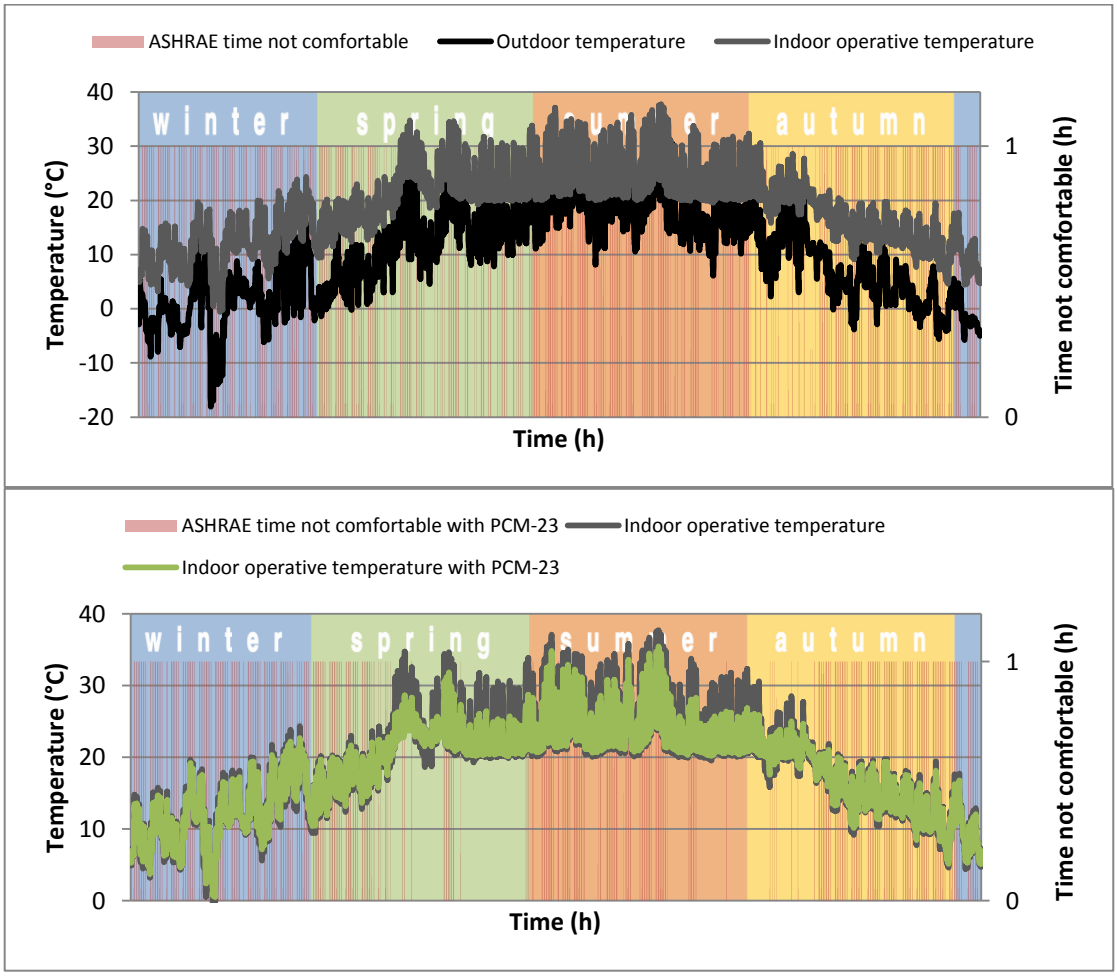

Figure 1. Comparison of indoor temperatures with and without PCM: Vienna case study

Despite of this, severe cold conditions in winter and the problem of overheating in summer are not resolved from the application of phase change materials, due to indoor temperature being significantly below or above the melting

temperature of the phase change material, hence the implementation of a HVAC is needed for all the case studies analysed.

3.2 Reduction of cooling and heating loads

The simulation of the model using different thermostats to maintain the indoor temperature within progressively restrictive ranges of 20-26°C, 21-25°C and 22-24°C, showed that the PCM with a melting temperature of 23°C is also the most efficient to reduce both cooling and heating loads, being in the middle of the imposed comfort ranges.

In the Rome case, the application of PCM accounts for 30% of annual cooling load reduction and 37% of annual heating load reduction. In London the percentage of cooling loads savings is higher and the percentage of heating lower than the Rome case: 57% and 11% respectively. The same results were observed in the Vienna case study where cooling loads were reduced by 37% and heating loads by 5% only. The reason for the low performance during the cold period of the year in London and Vienna is related to the rigid climate conditions that are not present in Rome. In fact in Rome, where winter temperatures are the highest of the three locations, indoor temperature exceed the heating setpoint of 20-22°C, allowing the PCM to absorb heat keeping the temperatures higher at night so that the next day lower energy is required to keep the room comfortable. In London and Vienna this does not happen because of the lower outside temperature, thus the indoor temperature stay nearly equal to the setpoint temperature and the PCM does not change phase. Therefore to achieve energy savings during the cold season in these locations, a phase change material with a lower melting temperature of 21°C or less may be used, or other passive strategies to gain heat in winter may be implemented.

3.3 The effect of PCM thickness

Another conclusion, that is valid in all three locations, regards the effect of PCM's thickness, simulated from 1cm to 6cm, on the building's annual energy savings. In all case studies, an appreciable difference was measured from 1cm to 3cm of phase change material, with increasing energy savings proportional to increasing thicknesses; while beyond 3cm the energy savings increase slower for greater thicknesses (Figure **2**).

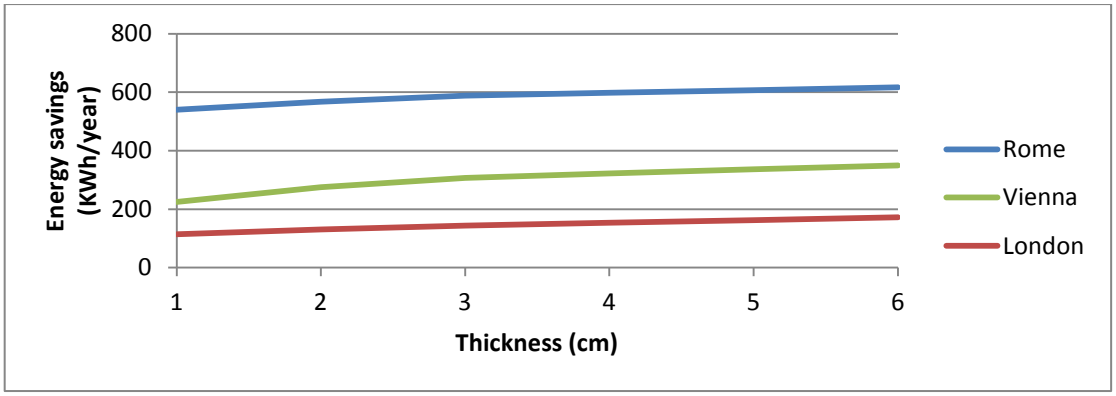

Figure 2. Effect of PCM thickness

This is probably related to the cycle of charging and discharging the heat: for low thicknesses, the phase change material cycle fast whilst beyond 3cm, although more heat can be absorbed, it is possible that the PCM does not undergo a completely melting or solidification. Thus, since a thicker phase change material corresponds to a higher capital cost, PCMs with thickness higher than 3cm would be less cost effective and it are not recommended.

3.4 The effect of orientation and quantity of PCM

It was observed that the effect of quantity is not linear because the sum of annual energy savings achievable by different surfaces with phase change material is not equal to the energy savings achievable by each surface with PCM applied singularly. For this reason the study on the effect of orientation was limited, since the geometry of the model is not symmetrical and windows are present on the south wall. Nevertheless it was possible to note that the east and west walls with PCM provide higher energy savings per square meter than the south wall, due to the highest incident solar radiation on these walls during the overheating period, but overall the difference between each orientation did not prove to be significant. Therefore, since the PCM layer is applied beyond the insulation, it can be assumed that external heat gains have little influence on the performance compared to internal heat gains in the simulated model. However, if a best orientation for the PCM application has to be suggested, south is recommended to cut heating loads because it receives more solar radiation during winter and east and west to cut cooling loads during summer, whilst the north orientation, although it still provides benefits, it has to be the last choice. Consequently, the application of PCM on south walls is recommended for cold locations such as London and Vienna, while east and west application for temperate locations such as Rome, where summer energy consumptions are more critical than winter's.

3.5 The economic outcomes

Finally, the economic analysis on the application of PCM under the three different chosen locations was assessed estimating the payback period of the investments. The calculations showed that reasonable payback periods within 4 and 11 years, correspondent to energy savings within 15-30% of annual energy savings, are possible in the Rome case, whilst under climatic conditions of London and Vienna the investment is paid back not earlier than 20 years. This result is related to the fact that the chosen phase change materials especially reduce the cooling loads rather than the heating loads and in Rome energy consumption is higher for cooling rather than for heating, while in the other two locations is the opposite. Moreover the heating load reduction is significant only in the Rome case because, as already mentioned, indoor temperatures may reach the lowest melting point of 23°C, whereas in the other locations they stay below the melting point. Thus, it was concluded that the application of PCMs on this study is cost effective in the Rome case study solely.

Figure **3** reports the payback period against the energy savings of each combination of melting temperature, thickness and surface application for the Rome case study. In the graph, the colours represent the different melting temperatures: the green symbols represent the PCM with a melting temperature of 23°C, the reds 25°C and blues 27°C. The difference of thickness is represented by the dimension of the symbols, progressively increasing for higher thicknesses.

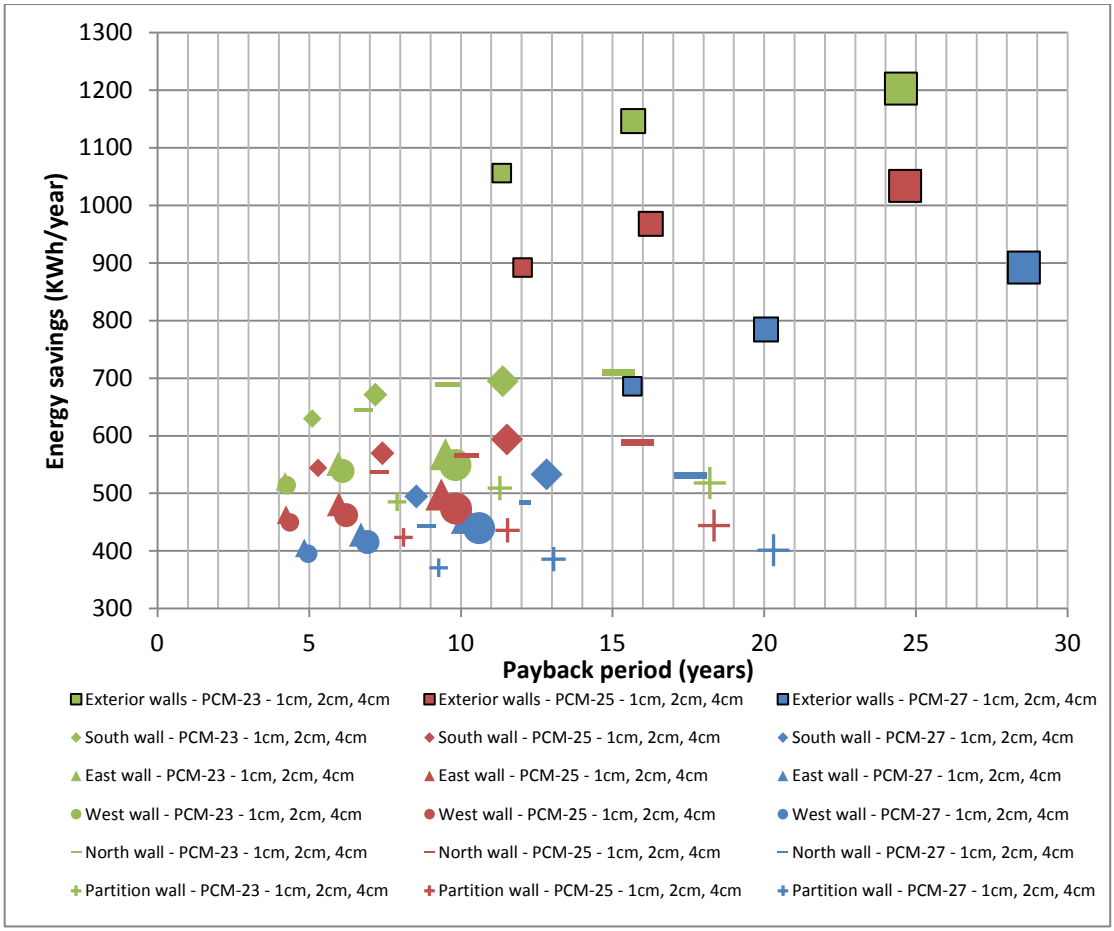

Figure 3. Energy savings against payback period: Rome case study

5 Conclusions

The performance evaluation of phase change materials applied to a lightweight building under the climatic conditions of Rome, London and Vienna was assessed through EnergyPlus software. The results for all the chosen locations showed that 23°C is the PCM melting point that provides the highest energy savings when the HVAC's thermostat is set to maintain the temperature within 20°C and 26°C. Moreover it was highlighted that above 3cm the PCM performance increase slower and the suggested walls' orientations of PCM application are: east or west in Rome and south in London and Vienna. Finally reasonable payback periods of 4-11 years, correspondent to 15-30% annual energy savings, were predicted in Rome, whilst in London and Vienna the investment of PCM is paid back not earlier than 20 years.

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