

Performance of Phase Change Materials for Cooling of Buildings in Mild Climates

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ABSTRACT

The effect of phase change material (PCM) integration in buildings is investigated in mild climates for the entirety of the hot season. The incorporation of PCMs in building materials is particularly interesting because it allows for the thermal storage to become a part of the building structure while being completely passive. Simulations in a typical single-family home are carried out, and the effect of incorporating PCMs in different building components is analyzed. Results show an important reduction in cooling energy.

1- INTRODUCTION

World electricity consumption is expected to double by 2025, increasing at a significant rate of 3.5 % per year. Furthermore, the demand for thermal comfort in both domestic and commercial buildings is currently rising. The additional energy demand significantly contributes to the increasing consumption with a peak demand in mild and hot climates. However, any action must start by reducing the level of energy consumption or at least delaying the peak demand.

To shift the peak energy demand (ideally few hours), the thermal mass of buildings can be used to store energy and lessen indoor temperature fluctuations. Nevertheless, the requirements of a thermally massive building often conflict with cost or aesthetics that require buildings to be increasingly lightweight. Incorporating phase change materials (PCMs) into buildings is a way to artificially increase the thermal mass of lightweight structures (Zhang et al, 2007). Heat storage can either take sensible or latent forms. Sensible storage is accomplished by increasing the temperature of the material, whereas latent heat storage is accomplished by changing the physical state of the material. To store the same quantity of energy, a smaller amount of material is required for latent storage. For example, a common building material, such as concrete can store about 1 kJ/kg when subject to a temperature increase of 1°C, whereas a PCM, such as calcium chloride hexahydrate can store/release up to 193 kJ/kg on complete phase transition (Kenneth and Gates, 2000). This huge increase of thermal storage capacity for PCMs and their almost isothermal discharge could be used to stabilize ambient temperatures inside buildings.

Currently, the available commercial micro-encapsulated PCMs are made with paraffin waxes embedded within small polymer spheres of about 10-20 μm in diameter. When in powder form, PCMs can be mixed directly into the building material or internal wallboard without risking leakage. The additional latent heat capacity for the distributed PCM increases the overall effective heat capacity when compared with sensible storage alone (Khudhair and Farid, 2004). The main advantage of setting a PCM in wallboards and incorporating it into the internal side of the external envelope of a building is to have a large surface in contact with the indoor air.

Recently, incorporating phase change materials (PCMs) in building materials to reduce the cooling needs has been investigated in many studies. An extensive literature review on micro encapsulated PCMs and the application in buildings can be found in (Osterman et al, 2012) or (Zhao and Zhang, 2011). However, these studies mainly address lightweight or reduced scale constructions (laboratory scale testing, (Tardieu et al, 2011)). Therefore, the obtained results cannot be generalized and are inconclusive regarding the benefits in real buildings and climates. Indeed, the experience conditions for the reduced scale generally lead to a large day/night temperature variation, which allows the PCMs to swing widely around the melting temperature. In this case, charge and discharge cycles are fully accomplished, and in turn, PCMs are in their optimum working mode. However, when simulating a long period (all the hot season for example), it is the average values that must be considered. A PCM can perform badly on a particular day, but might still perform well on average for the whole season.

With this work, our aim is to see how PCMs can reduce thermal loads in real buildings and how they can decrease fluctuation of indoor temperature to improve summer thermal comfort. Additionally, we will try to see if a unique optimum switch temperature exists and what parameters influence this temperature.

2- MATHEMATICAL MODEL

For the mathematical modeling, a nodal method was used. With nodal methods, a system is decomposed into isothermal (but not necessarily elementary) volumes. Each volume V_i is represented by a node with calorific capacity $C_i = \rho_i C_{p_i} V_i$. The heat exchange of a node with its neighbors is represented by thermal conductances (opposite to thermal resistances) characterizing different modes of heat transfer (conductive, convective, radiative and “fluid”). The energy conservation equation at node i connected to its neighboring nodes j and with a heat source $Q_i(t)$ is as follows:

$$C_i \dot{T}_i = C_i \frac{dT_i}{dt} = \sum_j G_{ij}^c (T_j - T_i) + \sum_k G_{ik}^r (T_k - T_i) + Q_i(t) \quad (1)$$

G_{ij}^c and G_{ik}^r are conductive (or convective) coupling conductance and radiative conductance, respectively. When applied to all nodes, the energy conservation equation leads to a set of nonlinear, yet ordinary algebraic-differential equations. A dynamic solver is then used for the transient resolution. This type of method provides a very powerful tool for modeling complex systems with heterogeneous interactions, such as a building, and the precision is within the limit of validity of the isothermal assumption of the chosen nodes. In our case, the main advantage of those methods is the ability to consider the wallboard as an isothermal single node and then not necessarily solve the melting front position. The modeling of latent heat change use only its effective capacity C_{ef} , which is temperature dependant. It is treated as non-linear, such as others temperature dependant physical properties or conductances (natural convection or radiation for example). The actual solvers are robust and can deal with the very sharp evolution of C_{ef} .

The encapsulated PCMs are particularly candidates for this type of modeling because they are randomly mixed with gypsum to form a homogeneous material. The heat capacity is the sum of the capacities of the constituents (sensible and latent) as shown by (Shukla et al, 2012) and the density is the weighted average of densities.

3- PCM CHARACTERIZATION

Among key parameters for PCM simulation, thermal properties such as switch temperature and the enthalpy variation with temperature of are of primary importance. From the enthalpy variation $h=f(T)$, which can be determined by several methods, such as Differential Scanning Calorimetry (DSC) or T-history, the effective capacity, $C_{ef}=f(T)$ is a follows:

$$C_{ef} = \frac{\partial h(T)}{\partial T} \quad (2)$$

Because the model takes into account the phase change by the variation of the heat capacity during the phase transition, it is necessary to know its explicit variation versus temperature. There are several representations for this variation of C_{ef} . (Feustel, 1995) gave a simplified representation with an exponential symmetrical shape:

$$C_{ef} = C_{sl} + \frac{\Delta H}{2} \frac{2\beta / \tau}{\text{Cosh} \left[\frac{2\beta}{\tau} (T - T_m) \right]} \quad (3)$$

Where C_{sl} is the liquid phase heat capacity; ΔH the fusion latent enthalpy and T_m is the melting temperature (or switch temperature), β is a shape parameter and 2τ is a range where 99% of the phase change occurs (melting or freezing). The solid-solid peak transition is neglected because the temperature is not relevant for the wall's operating temperature. The representation is also using equal capacity values for liquid and solid phases. No hysteresis was also assumed between melting and freezing, which is generally the case with organic PCMs. In fact, in our calculations, a slight hysteresis (a shift of approximately 1°C) had practically no effect on long-term simulation if the switch temperatures are close to the optimum values.

Different values for the conductivity of gypsum with PCMs are found in the literature ranging from 0.15 W/mK to 0.6 W/mK mainly because different conductivities of the gypsum matrix are reported. A conductivity of 0.3 W/mK is considered for this work and the change of phase of the PCM do not have a substantial influence on thermal conductivity of the wallboard (Jaworski and Abeid, 2011).

4- THE CASE STUDY MODEL

Among numerous factors that influence energy consumption and performance of buildings with PCM integration, the following main parameters are identified:

- Local construction systems (envelope and windows).
- Local climate: solar irradiation and ambient outdoor temperature.
- Internal loads: the personal occupancy and electrical appliances (lights, TV, computers, etc.).

The case study involves a typical residential single-family house with an area of approximately 104 m² area, two bedrooms, one living room, one kitchen, one bathroom and one storage room.

Two windows (simple glass $U=4.4 \text{ W/m}^2\text{K}$) are located in the north and south walls and the window-wall ratio (WWR) is approximately 12% (see figure 1 for the sketch). The constructive system is typical of the Mediterranean countries with a relatively heavy envelope (solid concrete end-terrace roof and measonry brick walls). Windows are shaded is by roof eaves and shutters (shading factor $f_s=0.5$) in the summertime and the solar absorptivity is assumed 0.5 for the roof and the walls.

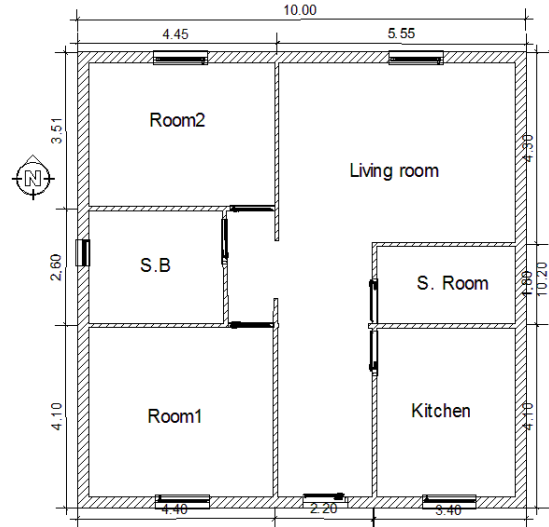


Fig 1. Sketch of the building model.

Exterior walls are traditional double brick walls with a 5 cm air gap (see table 1 for thermal characteristics of building components). The levels of insulation seem to be lower compared to those in continental climates, but they are sufficient for the Mediterranean region. PCM (when being present) of varied switch temperature between 24°C and 32°C is embedded in the wallboard of gypsum plaster of 15 mm nominal thickness. They contain between 0% (no PCM) and 30% mass fraction of encapsulated paraffin and are set into the internal face of the walls or the ceiling.

Table 1. Thermal characteristics of the building components.

	Roof	Ext. Wall	Floor	Glass
U-value [$\text{W/m}^2\text{K}$]	1.26	1.23	2.41	4.40

The study is carried out for the city of Djelfa, Algeria a typical Mediterranean city with a sub-continental climate: a mild-warm climate and relatively hot and dry summer. When the indoor temperature exceeds 26°C , cooling is activated and split system room air conditioners with 100 W/m^2 power are used. Thermal loads for occupancy and appliances are omitted to obtain a non perturbed comparison for PCM efficiency. For the same reason, only the absolute indoor temperature (and not operative or adaptive temperatures) is considered. The internal convection coefficient is difficult to determine because deviations of more than 100% can be found in the literature (David et al 2011). In this study, $h=8.3 \text{ W/m}^2\text{C}$ is used for vertical walls (according to ASHRAE recommendations, Diaconu and Cruceru, 2010) and $h=3 \text{ W/m}^2\text{C}$ for ceilings (stratified hot air on top) as average values for combined transfer coefficients (convective and radiative).

5- RESULTS AND DISCUSSION

The year round cooling performances of a PCM are evaluated. However, only the summer period is considered, i.e., June, July, August and September (the period from June 1st to September 30 is also generally the period where the differentiated electricity price for on peak and off-peak period exist in many countries). Two very simple indicators are used.

The first indicator is for a passive house (free cooling without air conditioning) with a “discomfort index” I_{sum} (Zhang et al 2007, modified by scaling it for the considered period):

$$I_{sum} = \frac{\int_{season} (T_{in} - T_{set}) dt}{Season} \quad \text{when } T_{in} > T_{set} \quad (4)$$

This indicator shows how long (and how much higher) the indoor temperature is above the comfort temperature, which is assumed to be 26°C (overheating). The second indicator is for an air-conditioned house and shows the primary energy demand Q_c , or the quantity of primary energy that needs to be removed from the indoor building by an active cooling system to confine the indoor air temperature to a maximum of $T_{set}=26^\circ\text{C}$.

$$Q_c = \int_{season} q_c dt \quad (5)$$

Figure 2a shows the indoor temperature with a 30% PCM fraction weight and $T_m=25^\circ\text{C}$ and figure 2b shows $T_m=27^\circ\text{C}$ ($\Delta H=160 \text{ kJ/kg}$). From those figures, we can see that for $T_m=25^\circ\text{C}$, the PCM performs well early in the hot season in June and in late September, but less so in the middle of the hot season (the hottest days). With $T_m=27^\circ\text{C}$, the PCM seems to work mainly in the middle of the hot season (July and August). The adjustment of the switch temperature permits to control of which days of the hot season are concerned by PCM action.

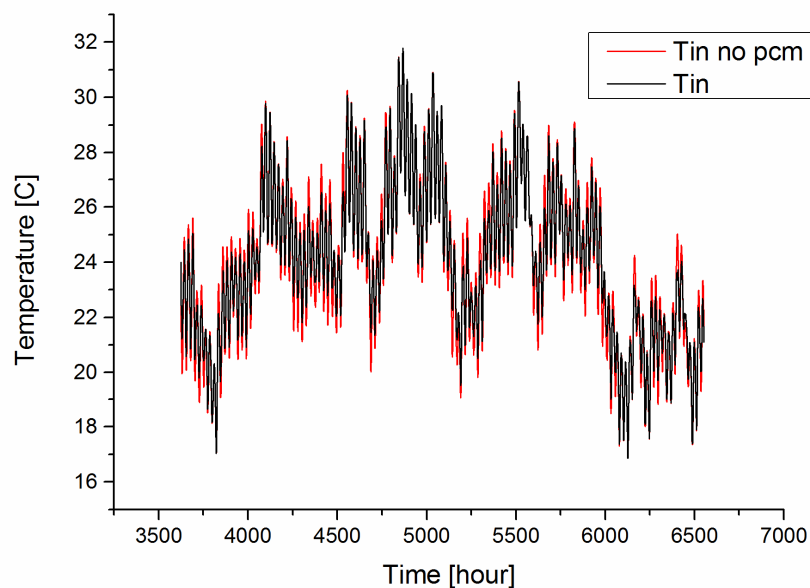


Fig 2a. Evolution of the indoor temperature without and with PCM, $T_m=25^\circ\text{C}$.

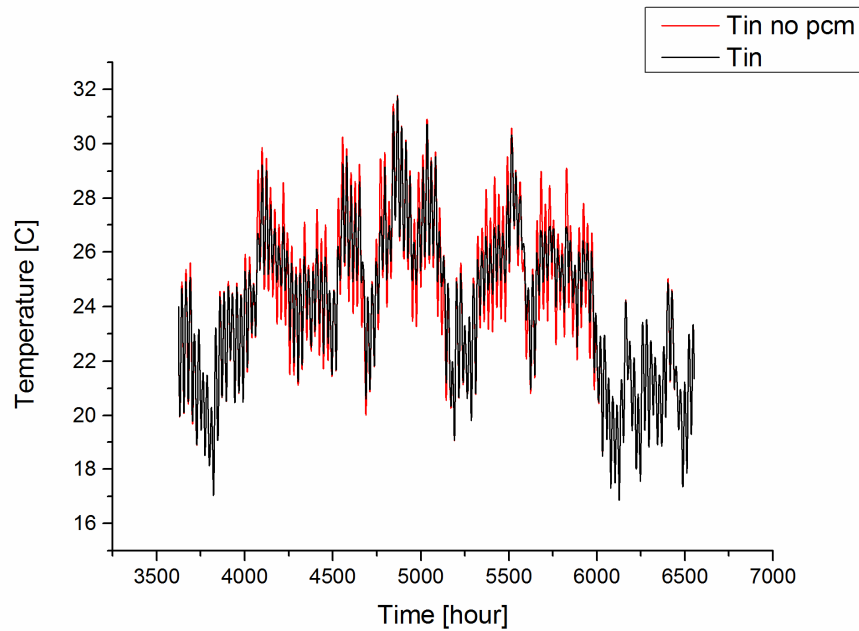


Fig 2b. Evolution of the indoor temperature without and with PCM, $T_m=27^\circ\text{C}$.

Table 2 shows the discomfort index I_{sum} and the cooling load Q_c for a PCM set on the internal face of walls and the ceiling for different switch temperatures and for a PCM fraction weight of 30% and with $T_{\text{set}}=26^\circ\text{C}$. It is clear with those two indicators that the optimum switch temperature is between 26 and 27°C . However, a switch temperature close to this range would provide slightly different results. The maximum reduction on cold demand with the incorporation of PCMs is about 20% which is in the average of results found by the others studies.

Table 2. Discomfort index and cooling load variation with switch temperature T_m
($W_t=30\%$, $\tau=3$)

	No PCM	$T_m=25^\circ\text{C}$	$T_m=26^\circ\text{C}$	$T_m=26.5^\circ\text{C}$	$T_m=27^\circ\text{C}$	$T_m=28^\circ\text{C}$	$T_m=29^\circ\text{C}$
I_{sum}	0.642	0.557	0.524	0.514	0.508	0.514	0.530
Q_c [kWh]	1384.01	1171.36	1111.24	1106.50	1118.07	1160.02	1175.85

It is interesting to see if this optimum switch temperature is the same for both components (walls and ceiling). Table 3 shows the two indicators with PCM only set on the walls and Table 4 shows those with PCM only set on the ceiling (internal face). The results show that the optimum switch temperature is approximately 26°C for the walls and approximately 31°C for the ceiling. This is because the walls and the roof do not receive the same amount of solar irradiation and consequently, do not operate at the same temperature.

Table 3. Discomfort index and cooling load variation with switch temperature T_m
PCM set on the walls ($W_t=30\%$, $\tau=3$)

	No PCM	$T_m=25^\circ\text{C}$	$T_m=26^\circ\text{C}$	$T_m=27^\circ\text{C}$	$T_m=28^\circ\text{C}$
I_{sum}	0.642	0.560	0.530	0.529	0.555
Q_c [kWh]	1384.01	1178.17	1127.06	1172.42	1282.25

**Table 4. Discomfort index and cooling load variation with switch temperature T_m
PCM set on the ceiling ($W_i=30\%$, $\tau=3$)**

	No PCM	$T_m=28^\circ\text{C}$	$T_m=29^\circ\text{C}$	$T_m=30^\circ\text{C}$	$T_m=31^\circ\text{C}$	$T_m=32^\circ\text{C}$
I_{sum}	0.642	0.591	0.571	0.556	0.553	0.562
$Q_c[\text{kWh}]$	1384.01	1258.00	1201.59	1161.31	1154.00	1178.75

Note that even if the areas (and then the PCM quantities used) for the ceiling and the walls are equivalent (102 m^2 and 113m^2 , respectively) and the received irradiation is different, the PCM perform in the same way (16.5% and 18.5% in reduction of the cooling demand, respectively). In fact, the ceiling receives more solar irradiation than external walls but has in revenge a weak convection heat transfer coefficient compared to the walls.

6- CONCLUSION

The incorporation of encapsulated PCMs in building materials such as gypsum wallboards was investigated for the entirety of the hot season to reduce cooling energy or enhance thermal comfort. The PCMs are found to perform well a reduction of approximately 20% for cooling energy. This PCMs performance is realized even in mild climates characterized by low day/night temperature swings, which make night time ventilation less efficient for discharging the PCM. Anyway, the reduction of the cooling energy is obtained with relative large quantity of PCM. A local economic efficiency analysis must confirm the process profitability.

The PCMs have better performance on surfaces that undergo the widest temperature variation. Incorporating PCMs on the ceiling give the best compromise gain/cost and is relatively easy to realize even in existing houses. This shows their potential use for refurbishment of actual buildings which is the weak point of all energy conservation policies.

REFERENCES

- Diaconu B. and M. Cruceru, 2010. "Novel concept of composite phase change material wall system for year round thermal energy savings". *Energy and Buildings*, 42, 1759-1772.
- Jaworski M. and S. Abeid, 2011. "Thermal conductivity of gypsum with incorporated phase change material (PCM) for building application". *Journal of power technology*, 91, 49-53.
- Kenneth I. and J. Gates, 2000. "Thermal Storage for Sustainable Dwellings". *International Sustainable Building proceedings*, Maastricht, Netherlands.
- Khudhair A.M. and M.M. Farid, 2004. "A review on energy conservation in building applications with thermal storage by latent heat using phase change materials". *Energy Conservation and Management*, 45, 263-275.
- Osterman E., V. Tyagi, V. Butala, N. Rahim and U. Stritih, 2012. "Review of PCM based cooling technologies for buildings". *Energy and Buildings*, 49 37-49.
- Shukla N., A. Fellahi and J. Kosny, 2012. "Performance characterization of PCM impregnated gypsum board for building applications". *Energy procedia*, 30, 370-379.
- Tardieu A., S. Behzadi, J. Chen and M. Farid, 2011. "Computer simulation and experimental measurement for an experimental PCM-impregnated office buildings". *Proceedings of building simulation 2011: 12th conference of international building performance simulation association*, Sydney.
- Zhao C. and H. Zhang, 2011. "Review on microencapsulated phase change materials (MEPCMs): Fabrication, characterization and applications". *Renewable and sustainable Energy Reviews*, 15, 3813-3832.
- Zhang Y., G. Zhou, K. Lin, Q. Zhang and H. Di, 2007. "Application of latent heat thermal energy storage in buildings: State-of-the-art and outlook". *Building and environment*, 42, 2197-2209.