Phase Change Material (PCM) composite insulating panel with high thermal efficiency

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Abstract: A new concept of wall system was developed and a numerical simulation of its dynamic thermal behavior was carried out. The new type of wall system consists of a composite panel with three functional layers. The external layer consists of conventional building materials impregnated with phase change materials (PCMs) and the internal layer consists of thermal insulation. Using two different types of PCMs with different values of the melting point a more effective management of the heating / air conditioning energy is achieved. A finite difference time-space discretization scheme was used in solving the transient heat conduction equation. A simplified model of PCMs’ thermal properties variation with temperature was considered neglecting effects such as supercooling and hysteresis. It was found that the layers of building material impregnated with PCMs contribute to attenuation of indoor temperature fluctuations and reduce the heating and cooling loads. Further investigation should identify the optimal parameters of the PCM layers (melting point, thickness) and should employ a more advanced mathematical model of the PCMs thermal properties.

Key words: Phase Change Materials, Building materials, Thermal energy efficiency

1. Introduction
Air conditioning and heating account for the highest percentage in the overall energy consumption of the built environment, especially in continental temperate climate with hot summers and cold winters. Management of the energy demand for air conditioning and heating and reducing the thermal energy exchanges with the ambient are essential requirements for improving the sustainability of the built environment.

Accurate knowledge of the cooling and heating load is essential in the building design phase for correct choice of building material and wall characteristics. Various theoretical and experimental techniques for evaluating the cooling and heating demand exist. Traditional theoretical models are Conduction Transfer Function (CTF) [1], based on physical properties of exterior walls and roof and thermal network model 2R2C [2]. Parameter estimation and optimization for the two models can be carried out experimentally or by means of more advanced techniques: artificial neural networks, genetic algorithms, support vector machine, etc.

Generally speaking the glazing area has the highest weight in the heat losses / gains balance of the building envelope. There are though situations in which the heat losses / gains through the building walls can exceed the value corresponding to the fenestration. Such situations occur in buildings with low glazing area or low ratio glazing area / walls exposed to the environment. In such cases the choice of an adequate building material for the exterior walls is essential in obtaining reasonable or good values of the built environment thermal efficiency.

In addition to the thermal insulation properties the thermal mass of the exterior walls is an important issue that influences the thermal energy exchange between the built environment and the ambient. Increasing the thermal mass can have positive effects especially on the thermal indoor comfort and on the energy demand for air conditioning / heating [3].

2. Description and mathematical modeling of the wall system
The proposed wall system consists of a sandwich-type panel and is shown in section in Fig. 1.

The functional layers of the new wall system are as follows: Layer 1, consisting of a building material impregnated with a phase change material (PCM) having the phase transition temperature range 25-29 °C; Layer 2, consisting of a building material impregnated with a PCM having the phase transition temperature range 19-23 °C; Layer 3, consisting of thermal insulation. Layers 4 and 5 don’t have a functional role in the thermal energy exchange...
between the environments separate by the wall system therefore they will not be included in the analysis.

![Fig. 1. Cross section of the new composite panel](image)

1 – External layer (exposed to environment); 2 – Internal layer (exposed to indoor space); 3 – Core layer consisting of thermal insulation; 4 – External surface layer (plaster, stucco, finish coat, sheathing); 5 – Internal surface layer (finish coat)

The structure and the characteristics of the new wall system were designed for the continental temperate climate with hot summers – with significant energy demand for air conditioning and cold winters with heating season extending on 4 months or more [4]. The building materials impregnated with PCM (PCBMs) were extensively investigated [5-7]. Gypsum wallboards impregnated with various PCBMs such as fatty acids, butyl stearate, butyl palmitate, etc. were reported to have good properties both in the respect of heat storage capacity and other physical properties (chemical stability, PCM liquid phase retention in the matrix material, stiffness, etc.). A detailed discussion and the choice of such building materials is not the main subject of this study, therefore a simplification will be made in modelling the complex thermo-physical properties of the building material impregnated with PCM since the objective of the study is to prove the viability of the new wall system.

The function of Layer 1 is to lower temperature variations in the wall system, and thus on the inside, during the hot season. On a typical summer day, the external surface temperature increases until it reaches the PCM phase transition. Further heat coming from the environment (radiation and convection) is accumulated without significant temperature rise during the phase change process. With proper design (thickness, PCM selection and mass concentration) melting of the PCM is completed by the time the heat transfer changes reverses due to the change in the environmental conditions. During the night the accumulated heat is released to the outside through the solidification process. The application of the insulation layer prevents the heat from being released to the indoor space during the PCM solidification process. Ideally, solidification of the PCM should be completed before the temperature rise on the next day. This completes the operating cycle of the system during the hot season.

The PCBM Layer 2 is active during the cold season by having a PCM with a phase change temperature ranging 19-22 °C (near target indoor value). The increase of the thermal mass has positive effect, namely reduces cycling of the heating equipment (reduces short cycle operation). By reducing the temperature gradient between layers 2 and 3 the heat loss to the ambient is also reduced. In case of excessive heat gains (solar radiation through glazing or internal gains) the PCBM layer can store the excess energy and release it during periods when heating is required.

The heat transfer process between the indoor environment and the ambient is modelled using the one-dimensional transient heat conduction equation with adequate boundary conditions:

\[
\frac{dt_{wall}}{d\tau} = \alpha \frac{d^2 t_{wall}}{dx^2} \tag{1}
\]

The boundary conditions are as follows:

Indoor environment:

\[ -k \frac{dt_{wall}}{dx} \bigg|_{x=0} = h_{\text{int}} (t_{wall,\text{int}} - t_r) \tag{2} \]

Ambient:

\[ -k \frac{dt_{wall}}{dx} \bigg|_{x=\delta} = h_{\text{ext}} (t_{\text{amb}} - t_{wall,\text{ext}}) \tag{3} \]

The initial condition for the transient conduction equation (1) is:

\[ \tau = 0, \ t_{wall}(x) = t_{wall,0} \text{, for } 0 \leq x \leq \delta \tag{4} \]

The boundary condition 3 considers only the contribution of convection, neglecting the thermal radiation.

Numerical solution of Eq. (1) with boundary and initial conditions (2), (3) and (4) respectively was developed using thermal electrical analogy [8]. In this method the wall cross section was divided into a
finite number of nodes. The heat flow inside the wall is governed by thermal resistances ($R_i$) connecting each node. The thermal mass of each node is characterized by its thermal capacitance ($C_i$). Schematic representation of the equivalent electrical network is shown in Fig. 2.

The energy balance equation for nodes $1...n$ is:

$$Q_{ht,j} = Q_{ht,j+1} + Q_{tm,j}$$  \hspace{1cm} (5)

$$Q_{ht,j} = \frac{t_{j-1} - t_j}{R_j}, \hspace{1cm} j = 1...n$$  \hspace{1cm} (6)

$$Q_{tm,j} = C_j \frac{dt_j}{d\tau}, \hspace{1cm} j = 1...n$$  \hspace{1cm} (7)

Figure 2. Thermal-electrical analogy used in numerical solving of Eq.1

For node 1 a radiation exchange term is considered:

$$Q_{ht,1} = \frac{t_0 - t_1}{R_1} + Q_{rad}$$

Thermal radiation term $Q_{rad}$ can be positive (gain) or negative (loss).

The expressions of thermal resistances and thermal capacitances occurring in Eqs. (6) and (7) are summarized in Table 1.

Table 1. Expressions of thermal capacitances and thermal resistances of the equivalent electrical network model

<table>
<thead>
<tr>
<th>Node</th>
<th>1</th>
<th>2...n-1</th>
<th>n</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R$</td>
<td>$\frac{1}{h_{ext} A_{wall}}$</td>
<td>$\frac{\Delta x_j}{k A_{wall}}$</td>
<td>$\frac{1}{h_{int} A_{wall}}$</td>
</tr>
<tr>
<td>$C$</td>
<td>$\rho_{wall} A_{wall} c_{wall} \Delta x_1$</td>
<td>$\rho_{wall} A_{wall} c_{wall} \Delta x_j$</td>
<td>$M_{air} c_{air}$</td>
</tr>
</tbody>
</table>

The convection coefficients $h_{ext}$ and $h_{int}$ were chosen according to ASHRAE recommendations [9] at 17 W/(m² K) and 8.3 W/(m² K) respectively.

Node $n$ of the network corresponds to room temperature described by the energy conservation equation assuming a lumped parameter model:

$$C_n \frac{dt_n}{d\tau} = \frac{t_{n-1} - t_n}{R_n} - Q_{C/H}$$  \hspace{1cm} (15)

$Q_{C/H}$ is the heat flow removed / introduced by the air conditioning / heating equipment.

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Node $n$ of the network corresponds to room temperature described by the energy conservation equation assuming a lumped parameter model:

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The convection coefficients $h_{ext}$ and $h_{int}$ were chosen according to ASHRAE recommendations [9] at 17 W/(m² K) and 8.3 W/(m² K) respectively.

The energy balance equations for the entire network results in the following system of first order differential equations, written in matrix form:

$$\{dt_{wall}/d\tau\} = [A] \cdot \{t_{wall}\} + [B]$$  \hspace{1cm} (16)

Where $[A]$ is a $n \times n$ matrix given by:

$$[A] = \begin{bmatrix}
    -\frac{1}{C_1} & \frac{1}{R_1} & 0 & 0 & \cdots & 0 \\
    \frac{1}{C_2 R_2} & -\frac{1}{C_2} & \frac{1}{R_2} & \cdots & 0 & \cdots & 0 \\
    \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots \\
    0 & 0 & \cdots & \frac{1}{C_{n-1} R_{n-1}} & \cdots & 0 \\
    0 & 0 & \cdots & 0 & \cdots & \frac{1}{C_n R_n} & \cdots \\
    \frac{1}{C_2 R_2} & \frac{1}{C_2} & \frac{1}{R_2} & \cdots & \frac{1}{C_{n-1} R_{n-1}} & \cdots & \frac{1}{C_n R_n}
\end{bmatrix}$$  \hspace{1cm} (17)
And $[B]$ is a $n \times 1$ matrix given by:
\[
[B] = \begin{bmatrix}
\frac{1}{C_i R_i} t_{\text{amb}} + \frac{1}{C_i} Q_{\text{rad}} \\
0 \\
0 \\
\vdots \\
-\frac{Q_{C/H}}{C_v}
\end{bmatrix}
\] (18)

The set point indoor temperature values for the cold and hot season were chosen 20 deg. C and 25 deg. C respectively. The cooling / heating loads defined as the heat flow removed respectively introduced in the room in order to maintain the set point temperature values were calculated using an innovative approach, based on the PID controller principle:
\[
Q_{C/H}(\tau) = K_p e(\tau) + \frac{1}{T_i} \int_0^\tau e(\xi) d\xi + T_d \frac{de(\tau)}{d\tau}
\]

Where $e(\tau)$ is the error, defined by:
\[
e(\tau) = t_{\text{SET}} - t_n
\]

The tuning of the PID controller parameters $K_p$, $T_i$ and $T_d$ was achieved by manual method. The maximum value of the error $e(\tau)$ was approximately 0.1 corresponding to the following values of the PID controller parameters:
\[
K_p = -500 \\
T_i = 0.025 \\
T_d = 0.1
\]

The sign convention for $Q_{C/H}$ was positive for cooling load and negative for heating load.

The total wall thickness $\delta$ is divided into $\delta_1$ corresponding to the PCBM Layer 1, $\delta_2$ corresponding to the thermal insulation and $\delta_3$ corresponding to the PCBM Layer 2.

The simplified approach used in the mathematical modelling of the PCBM thermal properties is described in the next section.

Outside the phase transition temperature range the value of the PCBM i.e. with PCM in either solid or liquid phase, the specific heat capacity can be considered as the weighted average of the specific heat capacity values for the building material and for the PCM. The equivalent specific heat capacity of the PCBM in the phase transition temperature range must take into account the sensible heat capacity of the building material and the latent heat of the PCM. Drakwa et al [10] used a Gaussian distribution shape of the effective heat capacity of the PCBM. Various values of the Gauss function standard deviation parameter were tested. Little difference was found in terms of indoor temperature profile for a room built of PCBM. A simplified profile of the effective heat capacity will be used in this paper considering three levels of the effective heat capacity value as shown in Fig. 3.

The onset and end phase transition temperature values are presented in Table 2.

Table 2. The phase transition onset and end temperature for the two PCBM layers

<table>
<thead>
<tr>
<th>PCBM Layer 1</th>
<th>PCBM Layer 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>$t_{\text{onset}}$</td>
<td>$t_{\text{end}}$</td>
</tr>
<tr>
<td>25</td>
<td>29</td>
</tr>
</tbody>
</table>
The characteristic values of the thermophysical properties for the PCBM and thermal insulation are presented in Table 3.

Table 3. Thermophysical properties and layer thickness of the three functional layers

<table>
<thead>
<tr>
<th>Layer</th>
<th>Effective heat capacity (J/(kg K))</th>
<th>Thermal conduction coefficient (W/(m K))</th>
<th>Density (kg/m³)</th>
<th>Layer thickness (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Solid phase</td>
<td>Liquid phase</td>
<td>Phase transition</td>
<td></td>
</tr>
<tr>
<td>Layer 1</td>
<td>800</td>
<td>800</td>
<td>6800</td>
<td>0.15</td>
</tr>
<tr>
<td>Layer 2</td>
<td>820</td>
<td>820</td>
<td>6000</td>
<td>0.15</td>
</tr>
<tr>
<td>Layer 3</td>
<td>1130</td>
<td></td>
<td></td>
<td>0.03</td>
</tr>
</tbody>
</table>

3. Results and discussion

A test room with the dimensions 28 x 10 x 3 and wall thickness 0.20 m was considered. All four lateral walls were considered exterior walls and the heat exchange through floor and ceiling was not considered in the analysis.

In order to assess the effect of the PCM presence in the structure of the building material two situations were considered. The first situation considered the wall system described in section 2 without PCM, considering gypsum wallboard as building material for Layers 1 and 2 and expanded polystyrene as thermal insulation. The second situation considered gypsum wallboards impregnated with a PCM for Layers 1 and 2, resulting in a significant increase of the effective heat capacity in the phase transition temperature range. Identical geometrical characteristics and thermal insulation material as in the first situation were considered.

A simulation for an year (8760 h) time span was carried out, first not considering the AC / heating system in order to assess the effect of PCM presence in the building material structure. The weather data was generated using TRNSYS Type 109-TMY2 for Bucharest (Romania).

The indoor temperature profile in the two cases (with PCM and without PCM in the structure of Layers 1 and 2) is shown in Fig. 4. In the case of the climatic conditions considered significant attenuation of the indoor temperature fluctuations is achieved especially during winter (approx 5 deg. C).

The indoor temperature profile in the case of cooling is presented in Fig. 5.

The cooling load for the two cases is shown in Fig. 6.

The maximum value of the cooling load decreased approximately three times in the case of the wall system with PCMs compared to the case without PCMs and the annual amount of energy for cooling decreased from 255 kWh/year to 150 kWh.
The maximum value of the heating load (shown in Fig. 7) decreased from approximately 1800 W to 1600 W and the annual energy consumption for heating decreased from 4141 kWh/year to 3992 kWh/year.

![Graph showing heating load with and without PCMs](image)

4. Conclusion

The energy performances of a new composite wall system with two layers containing PCMs were investigated by means of numerical simulations. A simple model for the thermal properties of the building material containing PCMs was used. The simulations showed that the energy performance increased by applying building material with PCM compared to a wall system without PCM and identical geometrical characteristics and insulation material. The two layers of building material impregnated with PCM attenuated successfully the temperature fluctuations during both cold and hot season. The minimum temperature value increased with approximately 5 deg. C and the maximum decreased with approximately 3 deg. C compared to the wall system without PCM. Both AC and heating energy demand values decreased in the case of the wall system with building materials containing PCMs. Maximum values of the cooling and heating loads also decreased resulting in downsizing the cooling / heating equipments.

Further investigation is required for optimization of the composite panel characteristics. The optimum phase change temperature range for each PCM building material layer should be identified by means of further simulations. A more realistic approach should take into account the thermophysical properties of the PCM building material and a more accurate mathematical model for the heat transfer in the composite panel. Finally, a more detailed model of the thermal exchange between the environment and the building considered should be used resulting in a more accurate estimation of the energy performance.

Other aspects of the new composite panel implementation should be analysed: cost, life cycle assessment, soundproofing and fireproofing.

References


