Study of improving the thermal response of a construction material containing a phase change material

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Abstract. The use of phase change materials (PCMs) for improving the thermal comfort in buildings has become an attractive application. This solution contributes to increasing the thermal inertia of the building envelope and reducing power consumption. A building element filled with a PCM and equipped with ventilation tubes is proposed, both for increasing inertia and contributing to refreshing building envelope. A numerical simulation is conducted by the finite element method in COMSOL Multiphysics, which aims to test the thermal behaviour of the developed solution. An experimental study is carried out on a concrete block containing a PCM with ventilation tubes. The objective is to see the effect of PCM coupled with ventilation on increasing the inertia of the block. The results show the ability of this new solution to ensure an important thermal inertia of a building.

1. Introduction
Nowadays, the energy problem in building is attracting more and more interest. The design, selection of building materials, as well as energy and thermal systems used are evolving very rapidly. It is indeed necessary to implement new solutions and structures to balance the available energy and occupant comfort. In new buildings, many reasons, namely the cost and space optimization, require the reduction of the wall thickness; it tremendously affects the thermal inertia and makes it insufficient to reduce the oscillations due to changes in outside temperatures. [1] Thus, most of the climate control systems of local consume large amounts of electricity.

The use of latent heat storage with phase change materials (PCMs) can respond largely to several problems. These materials provide a high storage density of energy and also a large amount of heat during the phase change process with a small change in the volume and temperature. Indeed, many studies have been conducted, including the incorporation of phase change materials in the walls. With this coupling, amortization of peak temperatures up to 4 °C [2].
The integration of PCM in the building envelope must face some constraints. Such as, the leakage problem when melting of the material. Several studies offer more innovative methods of incorporation for each application [3-10]. On the other hand, the PCMs are characterized by asymmetry between the energy stored and released, which requires a solution to extract more energy during the destocking cycle. The choice of PCM is also important as it is necessary that its melting temperature be near that of comfort and that the latent heat is large enough to store more energy.

As part of this work, we want to conduct a study on improving the thermal inertia of buildings by phase change materials (PCMs) with integrated ventilation. To this end, we propose a solution based on a building element "concrete block" filled with a polymer-paraffin composite material and equipped with ventilation tubes. Through this module, we aim to study the impact on the thermal inertia of a concrete block wall at summer discomfort conditions. The goal is to reduce the effect of the diurnal range of external temperatures, quantify the ability of these materials to store, restore energy and control the indoor temperature in buildings. Improved thermal release is performed by the nighttime ventilation.

The first part of this work is devoted to a numerical simulation with COMSOL Multiphysics software. A comparative study of different configurations can analyze the effect of the integration of PCM and ventilation tubes on the thermal behavior of the block. The second part will describe an experimental study to test the response of this solution on real plan. All results are analyzed and demonstrate the suitability of the new component to guarantee significant thermal inertia of a building.

## Nomenclature

### Latin letters

- $C_p$ specific heat at constant pressure (J/kgK)
- $h$ convective heat transfer coefficient (W/m²K)
- $k$ thermal conductivity (W/mK)
- $T$ temperature (K)
- $t$ time (s)
- $T_{sl}$ phase change temperature (K)
- $u$ velocity field (m/s)

### Greek letters

- $\rho$ density (kg/m³)

### Subscript

- $e$ external
- $f$ face
- $i$ internal
- $l$ liquid
- $PCM$ phase change material
- $s$ solid

## 2. Presentation of the studied problem

### 2.1. Description of the physical module

The physical module is based on a hollow concrete block, with the following dimensions: 50 cm x 20 cm x 9.5 cm. Consisting of 3 rectangular cavities whose geometric characteristics: length, width and height are respectively 13 cm, 6.5 cm and 17 cm. The three cavities are filled with a mixture of a paraffin and a styrene-type polymer. This mixture has a high mechanical stability in the temperature ranges used in the building, which is important to prevent leakage problems. The system has six PVC tubes which pass through the PCM and allows the passage of air through the module (figure 1). The choice of PVC tubes meets the constraints linked to the achievement of the experimental device. The increase in the exchange surface and the injection of air at a temperature below the melting point of the PCM, improves the system response during energy release.

The melting temperature of used composite is 28 °C, which corresponds to the limit value for summer comfort in hot climates, the object of this study is to show the effectiveness of this configuration developed for smoothing solar influence on the temperature of the building envelope.
2.2. Modelling and simulation parameters

Modelling thermal system was undertaken using the simulation software based on the finite element method, COMSOL Multiphysics. To study the behaviour of the system, a three-dimensional modelling (3D) was developed. The equation in partial derivatives that governs the model is:

\[
(\rho C_p)(\frac{\partial T}{\partial t} + u \nabla T) = \nabla (k \nabla T)
\]  \hspace{1cm} (1)

Where \(k\), \(C_p\), \(u\) and \(\rho\) are respectively the thermal conductivity, the specific heat, the velocity field and the density of the different materials in the structure. The phase change is taken into account through the specific capacity of the material. The apparent heat capacity method is used in the resolution of the heat equation in the PCM. For simplicity, the thermal expansion of PCM and concrete was not considered. Only conduction heat transfer mode was considered inside the PCM. The melting/solidification process of the mixture is taken into account in the simulation by integrating experimental characteristics.

To simulate the system, discomfort conditions of a Mediterranean climate in summer are imposed. Outside, solar flux and a sinusoidal temperature (20-39 °C). Inside, the ambience is expected to be maintained at a comfortable temperature of 25 °C with a climate control system (see figure 2). The exchanges by convection with surrounding environments are included on both surfaces, internal and external, with convective coefficients assumed to be constant (\(he=17\) W/m\(^2\)K and \(hi=8\) W/m\(^2\)K). The injection of air through ventilation is from when the outside temperature is strictly less than 28 °C (PCM melting temperature) because a breakdown during the day will load the PCM further. The evolution of the temperature in different parts is controlled by sensors placed primarily on the external and internal faces of the block and in the PCM.

The mesh used is a non-uniform triangular one applied to the uppermost surface of the block and extruded onto the rest of the geometry. The thickness of the PVC tubing is equal to 1 mm, this small size has influenced the choice of the mesh because it requires that the region near the tubes is meshed much more finely than other regions. The model is a mesh that consists of about 900000 triangular elements.

3. Numerical results and discussions

We present the evolution of temperature on the inner side of the block depending on the configuration: concrete block without PCM, with PCM, with PCM and ventilated tubes, the flux variation on the inner surface and the assessment of energy requirements to maintain the temperature of thermal comfort.

The first step of the study is to analyse the influence of the configuration of the thermal response that occurs on the inside of the block. Figure 3 shows the variation of temperature on the inner side of the
block for the three configurations (without PCM, with PCM, with PCM and ventilation tubes) in a point. The comparison between the case without PCM and PCM with ventilation tubes, shows that stabilization of the minimum temperature passes from one day to four days, the integration of PCM impose the regulation of the temperature around the phase change temperature ($T_{sl}$), and the addition of ventilation lowers the maximum temperature of 6 °C on the inner side.

![Figure 3. Evolution of the temperature on the inner side of the block for each configuration](image)

By comparing the minimum temperature evolution between the case without PCM and PCM with ventilation tubes, it can be seen that the stabilization of the temperature is delayed by three days. The integration of PCM imposes the regulation of the temperature around the phase change temperature ($T_{sl}$), and the addition of ventilation decreases the maximum temperature of 6 °C on the inner side.

![Figure 4. Variation of the flux on the inner side of the block.](image)

Figure 4 presents the evolution of the flux density on the inner side of the block. The sign convention chosen is relative to flux entering or exiting with respect to the normal of the surface. Thus, if the flux is positive that it leaves the wall and it helps to increase the temperature inside. The effect of storage/release reduces flux exchanged through the wall. Comparing the three configurations, the addition of PCM stabilizes the minimum flux outgoing of the surface, while the intra-ventilation decreases the maximum flux which leaves the surface.

The intra-ventilation influences the response during the destocking cycle, the comparison between the case with closed tubes and ventilated tubes shows that the decrease in the volume of PCM in the concrete block through the addition of tubes does not much influence on thermal response, by against the injection of air reduces the temperature within of PCM, which should quickly lead to saturation.

![Figure 5. Temperature distribution on a section plane.](image)

Figure 5 shows the temperature distribution on a section plane. The analysis is made at the 6th day, the instant corresponds to the ventilation stop. The comparison of the isotherms in both cases shows that the
flow of air through the tubes provides a more uniform distribution, which promotes rapid destocking into the PCM.

Figure 5. Distribution of temperature fields at t = 167.5 hours: a) closed tubes, b) ventilated tubes.

Figure 6 shows the distribution of temperature fields in the concrete block (in both cases: tubes closed and ventilated tubes) when the outside temperature and the solar flux reach their maximum values. The evaluation of temperature fields corresponds to the sixth day, the increase in the thermal inertia of system is significant because the maximum temperature decreases from 52 to 47 °C. In figure 6.b, the temperature fields between the inner face and the tubes becomes more homogeneous and will vary slightly.

Figure 6. Distribution of temperature fields at t = 150 hours: a) closed tubes, b) ventilated tubes.

The diagram in figure 7 describes a simplified energy balance in all three cases, this assessment is based on the average values of the exchanged flux densities for a day. Thus, the calculation is made from the 5th day. The outer face absorbs more energy because the thermal capacity of the system increases more with the PCM. The energetic balance on the concrete block without PCM confirms the low inertia of this element. The case with the PCM shows that it absorbs additional heat. Activating a night ventilation cancels 53 kJ of the outgoing heat of inner face.
Integrating the flux density curves through time on periods when the temperature of the inner surface is higher than the temperature of thermal comfort, it is possible to estimate the energy requirements for maintaining the temperature of comfort.

Except for the configuration without PCM, the flux passing through the concrete block always reaches the interior ambience. For both configurations: with PCM, with PCM and ventilation tubes, the results for a day, show that for a concrete block with PCM, we will need 600 kJ of energy and only 355 kJ for a concrete block with the tubes (with an air velocity of 1 m/s) (figure 8). Adding tubes with ventilation of 1 m/s saves around 245 kJ/day of energy needed to cancel the heat flux that comes from the inner face.

4. Experimental study and results
An experimental bench is developed to study the thermal response of the block filled with PCM and ventilating tubes (see figure 9). The experimental device includes a concrete block consisting of three cavities, six PVC tubes with a diameter of 2 cm, a heating system based on a resistance made of silicone having the shape of a plate, K-type thermocouples connected to the acquisition system, small ventilators are connected to tubes and a polystyrene insulation system has been put in place to limit heat loss and ensure a unidirectional transfer. The adopted heating type is considered to reflect the real conditions: sunshine and convection directly on the face of the block. That is to say, we choose the temperature margins to be applied through the control of the power resistors.
The same experimental bench can be adapted to test the response of a concrete block without PCM with the same conditions. On the realized experimental bench, two configurations are mainly studied: concrete block without PCM and concrete block with PCM and the ventilated tubes. Depending on the condition of the tubes, we can differentiate between three modules: closed tubes (without flow), open tubes (natural convection) and tubes with ventilators (forced convection).

The two resistors are adjusted to generate a power of 462 W/m², a sufficient power to bring the outer surface at a temperature equal to 65 °C after five hours of heating. The heating film is adopted to simulate solar gain, it can take into account solar and convective flow directly on the surface. A dynamic study was adopted on 24 hours, the experimental protocol involves applying a rise of temperature from 20 to 65 °C and subsequently the cooling cycle for each case studied (with or without ventilation). For the case with ventilation, injection of air is carried out after stopping heating. The ambient temperature varies slightly between 20 and 21 °C.

Figure 9. Photography of the experimental device.

Figure 10. Schematic representation of the experimental setup.

Figure 11 shows the evolution of the temperature of the inner and outer face for the four configurations. The storage in the PCM increases the phase shift and achieves about the maximum temperature after two hours on the heated face. On the inner side, the phase shift is of about four hours. The exchange within the PCM through the flow of air in the tubes contributes more to quickly reach
saturation. With an air speed of about 1 m/s, a slight variation in temperature is noticed, the final stabilization begins after 22 hours of the global experience time. Thermal stresses used in numerical simulation are periodic conditions that largely reflect reality. For the real conditions of solar flux and external temperature, an estimated equivalent flux (the sum of the radiation and convection that is added or subtracted depending on the time) is imposed on the system. However, the experimental device adopted aims eventually to regulate the flow to simulate the same situation as the reality namely impose an equivalent flux density. At the present stage of the device, a density ramp is imposed but not yet the reality in function of time (rise and descent). The current work therefore focuses on the heating portion but cooling is without control and represent our work prospects.

5. Conclusion

The objective of this study is the development of building components incorporating a phase change material coupled with a ventilated tubes to improve thermal inertia of the walls and comfort inside the buildings. This study is a preliminary step to test the feasibility of this solution before proceeding to final optimization. The developed configuration is based on the coupling of a paraffin-polymer mix with ventilation tubes in a concrete block. To optimize the system response, a numerical simulation in 3D was conducted using the COMSOL Multiphysics software. A comparative analysis of different configurations shows the contribution of this coupling to improve the thermal response. However, analysis of the saturation of the system shows that the PCM does not release all the heat stored. An optimizing the geometry of the tubes relative to the speed is necessary to get to the removal more energy.

An experimental study was conducted to highlight the thermal behaviour of the block containing the PCM with ventilation tubes. The results confirmed that the insertion of the paraffin with the tubes helps stabilize temperature on the inner side and to increase the thermal inertia. In outlook, we will consider to test the influence of the change in air velocity as well as better control the temperature imposed by the heating system.

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