HEFAT2014
10th International Conference on Heat Transfer, Fluid Mechanics and Thermodynamics
14 – 16 July 2014
Orlando, Florida

Application of PCM Embedded in a Floor Panel for Thermal Management of the Lightweight Envelope of Buildings

Laurent Royon *, Laurie Karim
Matière Système Complexe,
University of Paris Denis Diderot, UMR 7057 CNRS
Paris 75013,
France,

André Bontemps
Laboratoire Interdisciplinaire des Energies de Demain,
Université de Paris Denis Diderot, UMR 8236
Paris, 75013
France

E-mail: laurent.royon@univ-paris-diderot.fr

ABSTRACT

Implementation of Phase Change Materials (PCMs) into building components allows their thermal performance to be enhanced, reducing indoor temperature fluctuations and improving the occupant comfort. A practical problem to solve is the possibility of leakage when the PCM is under the liquid state. In this study, a new component using PCMs is described. This component is derived from an existing slab having cylindrical cavities which is used in floors/ceilings. The cavities are filled with a polymer-paraffin composite and leaks are avoided, due to, both the use of the composite and the insertion inside cavities. This study is based on numerical simulations whose results are compared to experimental ones with the same boundary conditions in order to validate the model. The PCM was introduced inside the cavities with an annular repartition and different percentages. A new indicator was introduced (PCM activity) that allows an evaluation of the amount of PCM to be used in such a component. With this indicator the optimal percentage of PCM has been determined.

INTRODUCTION

To reduce the energy dependence of buildings, it has become necessary to explore and develop new materials or constructive systems that meet the requirements needed to promote both energy conservation and sustainability in construction. One way to reduce energy consumption is to exploit heat storage, especially in climates where daily temperature variations require both heating and cooling over the same 24 hours period. Because of their high storage capacity in the narrow temperature range, phase change materials (PCM) in active and passive cooling/heating of buildings are the most efficient ways to store thermal energy. Different research projects have been developed since the last decade including (i) direct incorporation or impregnation of the construction material, (ii) incorporation of PCM capsules in building components, (iii) manufacturing new panels with PCMs to replace classic wallboards and, (iv) incorporation in a heat exchanger plate to improve performance of a HVAC system. Most of projects can be found in recent reviews ([1] – [7]).

Nevertheless, the different techniques presented in published studies have limited success because it is difficult to incorporate these phase change materials into existing building materials. The main cause is the conditioning of the phase-change element, which must be completely sealed to prevent leakage of the product during the melting process.

One kind of PCM, called shape-stabilized PCM, does not require any encapsulation, because of the presence of a polymeric matrix. This compound can keep its shape stabilized even when the PCM state changes from solid to liquid.

Compared with conventional PCM, shape-stabilized PCM reduces the liquid PCM leakage danger, the additional thermal resistance and container cost. This material can be shaped into spheres, cylinders and plates or added into panel structure to be directly used as floor or wallboard. In recent years, some researchers have studied the preparation method and the thermal properties of several shape-stabilized PCMs [8–11]. This option permits easily their incorporation into light building components, which have cavities (cinder block, hollow brick, for example), without additional precaution of encapsulation. Though their integration has been investigated in numerous studies, these components were mainly devoted to walls. to our knowledge the integration in floors or ceilings has rarely been studied ([12-17]). Some authors also have studied performances of ceilings cooled with PCM slurries ([18]).

This study concerns a new construction element: a hollow concrete floor panel filled with tailor-made shape-stabilized PCM. Its thermal response with prescribed periodic boundary conditions was investigated experimentally and numerically as described in our previous paper [19]. The analysis of data demonstrates the suitability of this new component to guarantee significant thermal comfort and thermal inertia of a building. For a hollow floor panel completely filled with PCM, the temperature fluctuations applied to the surface of one side are significantly reduced at the surface of the other side and thereby improving the thermal comfort. Nevertheless, the numerical model shows that only a small part of the PCM is used during the imposed thermal cycle. The next step of this research is to quantify the amount of PCM to be introduced into the floor panel. Then, this study aims at determining the optimal amount for a prescribed distribution of PCM and for a given thermal cycle. An annular configuration of PCM inside the cavity has been adopted because it offers the best surface / volume ratio for the heat transfer point of view.

nomenclature

$a,\overline{a}$	[-]	indicator of activity of PCM
C_p	[J/kgK]	specific heat capacity
e	[m]	slab thickness
k	[W/mK]	thermal conductivity
h	[W/m^{2}K]	convective heat transfer coefficient
L	[m]	length
Nu	[-]	Nusselt number
Ra	[-]	Rayleigh number
t	[s]	time
X	[m]	horizontal coordinate
y	[m]	vertical coordinate

Greek symbol

β	[K^{-1}]	thermal coefficient of volume expansion
μ	[Pa.s]	dynamic viscosity
ξ	[K]	temperature amplitude
ε	[-]	emissivity
ρ	[-]	density
σ	[m]	Stefan-Boltzman constant
φ	[h]	time lag
χ	[m^2/s]	thermal diffusivity

Subscripts

max	cycle
m	maximum
onset	mean
endset	beginning of apparent specific heat increase
	end of apparent specific heat decrease

MAIN PHYSICAL PROPERTIES OF THE NEW PCM FLOOR COMPONENTS

Photography of the floor panel, which is commonly used for lightweight building, is presented in Fig.1. The alveolar floor is a concrete slab with dimension (28cm x 28 cm x 7.1 cm) and eight cylindrical holes with diameter of 2.5 cm and a length of 28 cm. The studied sample is a floor panel at 1:5 scale (Fig. 1). To develop a floor panel with high thermal capacity, a shape-stabilized PCM is introduced inside each cavity. The slab without PCM will be considered as the reference slab.

Figure 1 View of the floor panel at 1:5 scale

The PCM is a shape-stabilized paraffin material, where the polymeric matrix fixes the paraffin into compact form, even after its melting. More details about this material can be found in [19]. The phase change state appears around 27°C (Fig. 2) and the latent heat of melting is about 110 kJ/kg.

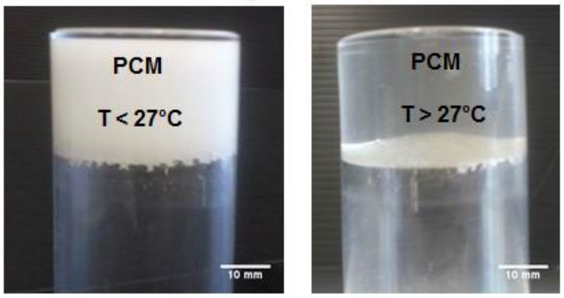

Figure 2 View of PCM in solid state (on the left) and in liquid state (on the right).

Thermophysical properties of the concrete and PCMs were measured and are given in Table 1. The thermal conductivity of the PCM is less than the concrete, and therefore, the PCM acts as a good thermal resistor at a steady state condition. However, the thermal mass of concrete is higher than liquid or solid

PCM, and therefore the concrete is a better heat absorber at transient conditions.

	Density ρ kg/m^3	Specific heat capacity C_p J/(kg K)	Thermal conductivity k W/(m.K)
PCM			
$T < 27,5°C$	850	2800	0.28
$T > 27,5°C$	780	2500	0.18
Concrete $T = 25°C$	2127	918	1.00

Table 1. Thermo-physical properties of the PCM and concrete

THERMAL PERFORMANCE OF THE PCM FLOOR PANEL

The sensation of comfort is related, among others, to ambient temperature level, mean radiative temperature and temperature fluctuations inside a building space [21, 22]. The surface temperature of walls and ceilings/floors contributes to thermal comfort through the three preceding conditions then, it is instructive to study the thermal performance of a PCM floor panel under fluctuating boundary conditions in accordance with a realistic situation. As discussed by Nicol [22] "If a change occurs such as to produce discomfort, people react in ways which tend to restore this comfort". A way to avoid such changes and such a reaction is to increase thermal inertia which damps any change which can occur. In a periodic variation, if the peak to peak variation is less than 1 K, there will be no influence on the comfort [21].

In this objective, a periodic variation of temperature (between 22 and 35°C) has been imposed on the lower face of a sample of a floor panel filled with PCM and the temperature on the upper face has been measured and compared to the one observed for a reference slab without PCM. This following section presents the numerical model developed to simulate the thermal behaviour of the floor.

In order to simplify the analysis, the following assumptions were made: (1) heat transfer through the floor is two-dimensional and purely diffusive; (2) thermal physical properties of the building components are considered constant except the specific heat of PCM during melting or thawing process; (3) the thermal expansions of PCM and concrete are not considered.

HEAT TRANSFER MODEL OF THE PCM FLOOR PANEL

The numerical simulation analysis was carried out with the commercial code Comsol Multiphysics® software [23] to simulate the thermal behaviour of the floor. This software was used to create and to mesh the geometrical model of the floor and to solve the heat equation. Only conduction heat transfer mode was considered inside the floor, even during the melting or solidification processes. Indeed, the polymer prevents natural convection inside the PCM. The governing equation considered was the classical energy balance equation, in absence of heat source expressed as:

$$\rho\, C_p\, \frac{\partial T}{\partial t} + div\left(-k\, \overrightarrow{\nabla T}\right) = 0 \tag{1}$$

where k, C_p, ρ are respectively the thermal conductivity, the specific heat and the density of the different materials in the structure. The material parameter values that are assigned to both the concrete and the PCM can be found in table 1. The specific heat C_p obtained by calorimetry for heating at 0.125°C/mn is taken into account for the simulation. For simplicity, the thermal expansion of PCM and concrete was not considered. For modelling the phase-change problem, the effective heat capacity method is used here by considering the experimental PCM's specific heat.

The model is a mesh that consists of about 4000 triangular elements. A mesh convergence study has been carried out to ensure the accuracy of the finite element results. The geometry as well as the boundary conditions for the heat equation are depicted in Fig. 3.

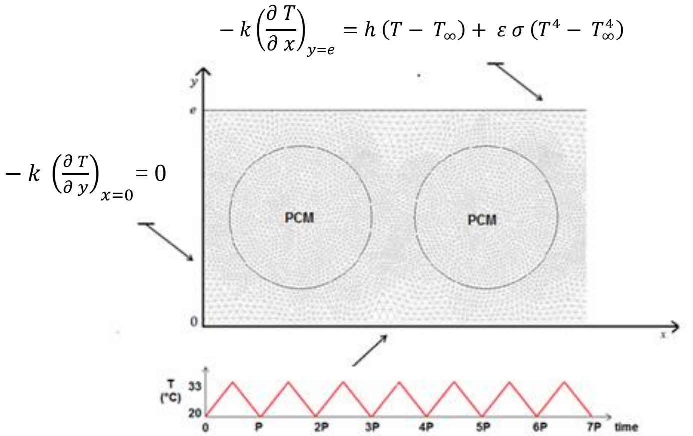

Figure 3 Representative domains used for the two-dimensional numerical model

The upper surface of the floor is subjected to radiative and free convection boundary conditions.

$$-k\left(\frac{\partial T}{\partial y}\right)_{y=e} = h\,(T - T_\infty) + \varepsilon\,\sigma\,(T^4 - T_\infty^4) \tag{2}$$

where h is the free convective heat transfer coefficient and ε the emissivity of the concrete. T and T_∞ are the temperature on the upper surface of the floor and far from the floor respectively. For eq. (2), the used value of emissivity is 0.9 (in accordance with the emissivity of the black paint put on the surface of the slab); the order of magnitude of the heat transfer coefficient h has been estimated considering a natural convection heat transfer, by using the adimensional correlations valid for a horizontal plane [24].

$$Nu = 0.54\, Ra_L^{1/4} \qquad for \;\; 10^4 < Ra < 10^7$$
$$Nu = 0.15\, Ra_L^{1/3} \qquad for \;\; 10^7 < Ra < 10^9 \qquad (3)$$

where the Rayleigh number is given by:

$$Ra = \frac{g\,\beta\,\rho}{\mu\,\chi}\, L^3\, (T - T_\infty) \qquad (4)$$

In this formula, g is the gravitational acceleration and, β is the volume expansion coefficient, ρ the density, μ the dynamic viscosity and χ the thermal diffusivity of air. For a mean air velocity of 0.6 m/s above the floor measured with a hot-wire anemometer, and considering the length L of the floor as a characteristic length, the heat transfer coefficient h varies slightly and has been chosen equal to 3.5 Wm^{-2} K^{-1}.

At the lower surface, a Dirichlet boundary condition is imposed corresponding to an external cyclic linear variation of the temperature between 20 °C and 35 °C. The duration of a heating–cooling cycle was fixed to 58 min in order to take into account the dimension of the sample (scale 1:5). In scale 1:1, the floor panel would be submitted to heating–cooling period of 24 h.

An insulated boundary condition is imposed on the other lateral boundaries. The floor is initially considered at a constant temperature of 20°C.

SIMULATION RESULTS

The numerical results are presented in Fig. 4 for a floor panel completely filled with PCM and a floor panel without PCM. Solid lines represent the computational results. One can observe that the upper surface temperature in contact with ambient air of the room reaches periodic steady state very rapidly for the reference floor panel and after a certain time (about 4 cycles) for the PCM's floor panel. This result is an indicator of the level of inertia of these two panels. When the temperature reaches this periodic steady state, it means that the amount of the energy transferred to the model during the charging phase is equal to the amount of energy taken from the model during its discharging. The upper mean temperature seems to be the same for the two floor panels.

The presence of the PCM appears principally on the amplitude $\xi$and the time lag φ of thermal wave measured at the upper surface. An analysis of data shows that:

- the temperature amplitude ξ of the upper surface temperature is reduced down to around 2°C when the floor panel is filled with the PCM,

- the initial slope of the upper surface temperature is lower for the floor panel with PCM,

- the time lag φ is higher for the floor panel with PCM,
- at the end of 7th cycle during the discharging period, temperature equilibrium is reached more slowly with the floor filled with PCM because of its high thermal inertia.

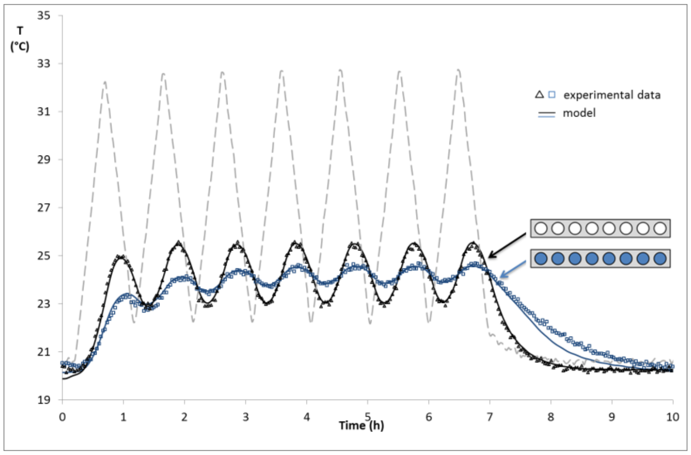

Figure 4 Temperature at the surface of the floor panel

Such results show that thermal comfort will be improved due to a decrease of the fluctuation of the surface temperatures of the floor panel and the increase of the time lag by the incorporation of PCM.

MODEL VALIDATION

In order to validate the model, an experimental device has been developed to apply identical temperature variation to the floor panels with and without shape-stabilized PCM. One side of the floor panel is located in close contact with a heat exchanger, fed by a thermo-regulated water flow. The bath is programmed to produce a prescribed heating–cooling cycle of 58 min between 20°C and 33°C. The opposite side is adjacent to a room in which ambient temperature is kept quasi-constant at T_∞=18.5 °C. On each side of the floor are placed temperature and heat flux sensors. Thermocouples (type K) were calibrated with a specific device. More details are presented in [19, 20].

The experimental and the simulated results were compared in Fig. 4. Circles represent the experimental data. A good agreement is found between simulation and measurements for the floor without PCM. For the floor filled with PCM, one can observe that the level of the temperature oscillation obtained by the model is higher than that obtained experimentally. Amplitude of the oscillations obtained by simulations is lower than amplitude of experimental oscillations. Two reasons can explain the slight discrepancy between simulation and experimental data. Firstly, the possibility that the thermal insulation of the sides of the slab is not perfect. Secondly, the possibility that the model only considers single value of the specific heat $C_p(T)$ variation during the melting phase. Indeed, the calorimetric study has shown that the melting temperature and freezing temperature of the shape-stabilized PCM are different (see [19]). This hysteresis phenomenon is not considered in the simulation model and can explain the disagreement.

The model gives the opportunity to access to the quantity of PCM in the melting process during the thermal cycle. To this end, we defined an indicator a which evaluates the activity of the PCM. As the PCM presents a large melting temperature range, the material can be considered in a melting state between the temperature T_{onset} (=25.8°C) and the temperature T_{endset} (=28°C). So, the percentage of "active" paraffin inside the cavity is evaluated by the PCM volume which temperature is between T_{endset} and T_{onset}. Fig 5 illustrates this variation during the seven successive thermal cycles. First, one can observe that the PCM's ability to store heat is far from its maximum; a does not exceed 66%. Secondly, starting the third cycle, the indicator a does not return to zero. This signifies that accumulated latent heat during the increase of temperature is not entirely released at the end of the thermal cycle. The PCM is thus only partly used. This will be discussed in section 4. Therefore the thickness of PCM to be implemented in the floor panel should be optimized; a parametric study of the amount of PCM to be implemented is proposed in section 4 for a ring configuration.

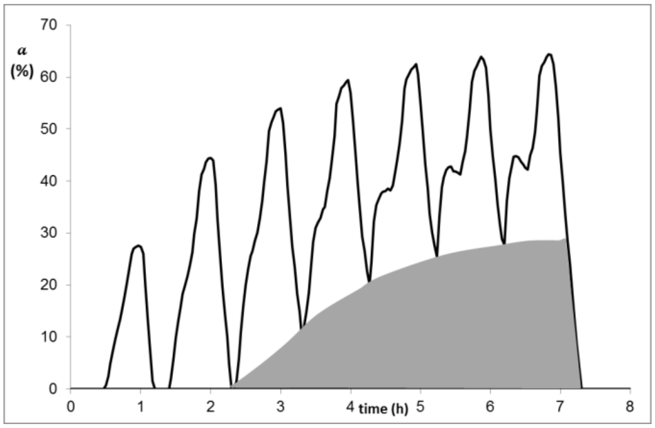

Figure 5 Percentage of "active" PCM during the thermal cycle

OPTIMIZATION OF THE PCM AMOUNT IN THE FLOOR PANEL

The amount of the PCM in the hollow floor panel is investigated here in ring configuration for the same boundary conditions as in section 3.2. Parametric analysis is carried out aimed at understanding what amount of PCM assures optimum performance of comfort. Six annular configurations defined by their volume fraction of PCM have been studied (see Fig. 6). The mean temperature T_m, the temperature amplitude ξ and the time lag φ of the floor panel with various layers of PCM are analyzed in comparison with the reference floor panel. Such parameters can be considered as good indicators of thermal comfort obtained at the surface of the floor panel.

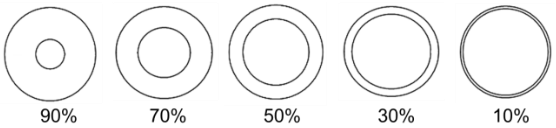

Figure 6 Schematic representation of the six annular configurations of PCM studied

Fig. 7, Fig. 8 and Fig. 9 show respectively the mean temperature T_m, the time lag φ and the surface temperature fluctuation amplitude ξ as function of the percentage of PCM. On one hand, one observes that T_m decreases with the amount of PCM until an optimum near 50%-60% of PCM and then, a slight increase appears. A difference of about 1°C is observed between the floor panel with 50% PCM and the reference floor panel. By contrast, the time lag is clearly increased (more than 40%) when the panel is included with PCM for any amount of PCM. On another hand, the thickness of the PCM ring impacts notably the temperature amplitude ξ as illustrated in Fig.8. The amplitude ξ decreases gradually with the amount of PCM to about 50%-75% of PCM and then seems to reach a plateau. Beyond this critical concentration range, the addition of PCM has no more effect on the decrease of surface temperature fluctuation ξ.

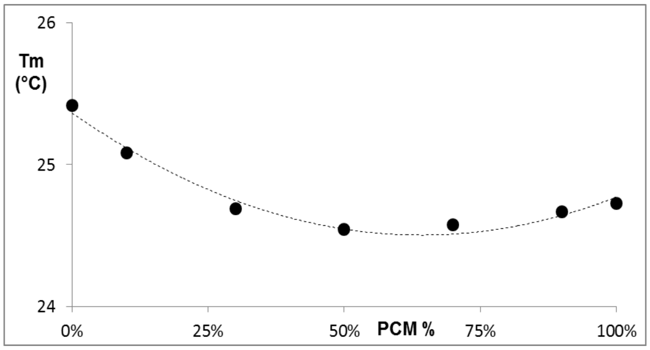

Figure 7 Mean Temperature T_m for the different configurations studied

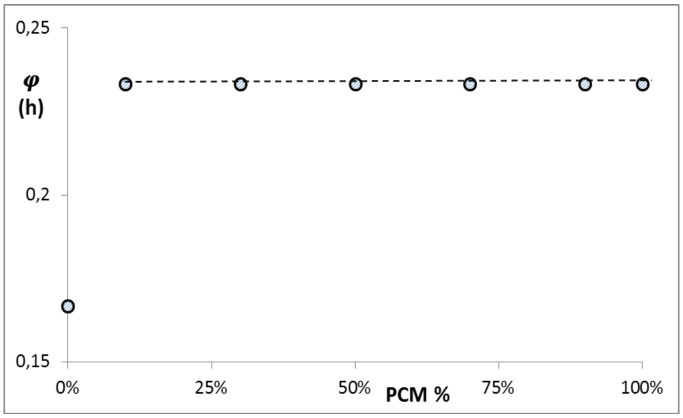

Figure 8 Time lag φ for the different configurations studied

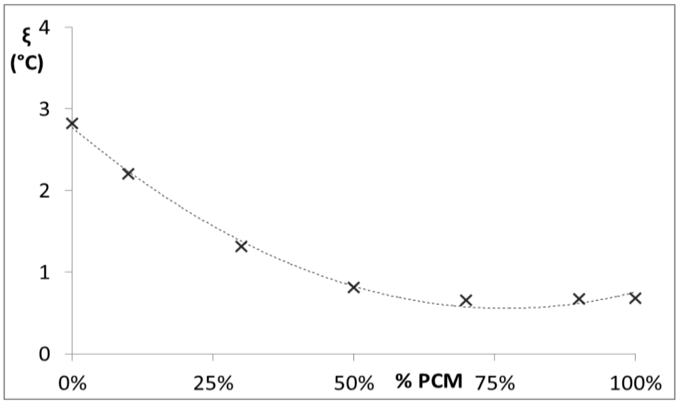

Figure 9 Temperature amplitude ξ for the different configurations studied

Results show that lowest surface temperature T_m, as well as lowest fluctuation ξ can be obtained for PCM concentration ranging from 50% to 100 %. This fluctuation is less than 1 K as recommended in the ThermCo report [21]. Let's now consider the instantaneous activity of PCM defined by the indicator a to determine more precisely the optimal concentration. The amount of PCM which is active (as defined in 3.3) during seven successive thermal cycles is presented in Fig. 10 and 11. For rings with PCM percentage equal to, or more than 70%, the indicator a does not return to zero which confirms that one part of the latent heat is unusable during the cycle. For other configurations, indicator a shows a full storage-release of latent heat.

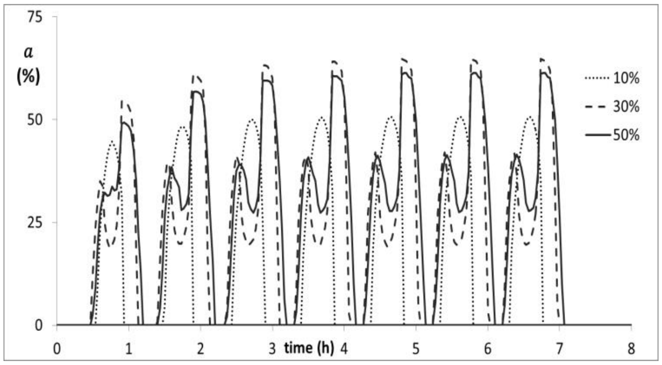

Figure 10 Instantaneous activity a of PCM during the seven thermal cycles for 10%, 30%, 50% PCM concentrations.

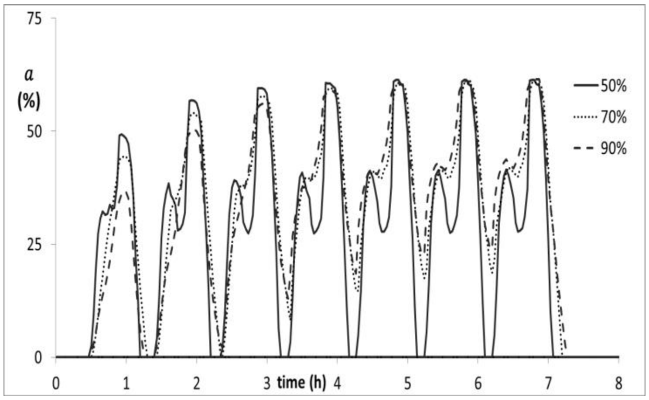

Figure 11 Instantaneous activity a of PCM during the seven thermal cycles for 50%,70%, 90% PCM concentrations.

Mean activity of PCM during the thermal cycle can be defined by the following expression:

$$\overline{a} = \frac{1}{t_c}\int_{t_0}^{t_0+t_c} a\,dt \qquad (5)$$

where t_0 and t_c are the temperatures at the beginning and at the end of a cycle respectively.

The calculation of this mean activity during a period is carried out in accounting for the "available" PCM, i.e. the PCM which can both melt and solidify. Considering figure 5 for a PCM concentration of 100 %, it is seen that one part of the PCM does not recover the solid state from the 4th to the 7th cycle. The PCM remains in the liquid state as shown in the grey part of the figure. This PCM is not available to store latent energy. Then, the mean activity is calculated in considering only the part of the curve of the instantaneous a which is above the grey zone. To calculate $\overline{a}$ as a function of PCM concentration we have chosen the 6th period because, it is close to the equilibrium plateau and it is not affected by the end of the oscillation process.

The variation of this parameter $\overline{a}$ as a function of the percentage of PCM inside the alveolar floor panel is presented in Fig.12. One can observe that an annular ring with 50% of PCM is the configuration for which the latent heat is optimally stored. Beyond 50% the PCM is not completely restored in its solid state

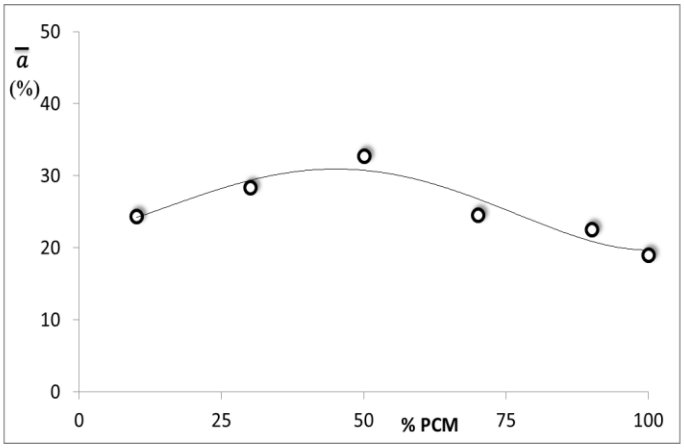

Figure 12 Parameter $\overline{a}$ as a function of the percentage of PCM

The performed analyses confirm that for a certain set of climatic conditions and building envelope materials, there is a quantity of PCM that assures optimum comfort performance. Such performance is related to maintaining temperatures within the temperature melting range of PCM for a given period of time.

The model can be considered as a tool to provide information on the amount of PCM to be implemented as well as on the distribution of PCM in the floor. It will also be of particularly great importance to derive the optimum choice in term of PCM properties in order to maximize the stored energy for a given set of boundary conditions.

CONCLUSION

The use of intermittent energy sources as solar heating, night cooling …etc for conditioning the interior space of a building encourages us to optimize the choice of construction materials. In this study, we have presented a way to artificially increase the thermal inertia of a building to regulate its internal temperature. This has been achieved by incorporating a PCM inside elements of constructions, in this case a slab serving as a floor and/or ceiling. This fusible material is, in fact, a home-made mixture polymer - paraffin which avoids any exudation of the paraffin [19]. The studied slab is an industrial hollow panel currently used in building construction, having cylindrical cavities. These cavities have been filled up with PCM. Inside the cavity an annular repartition has been adopted to obtain the best surface/volume ratio.

We have carried out a numerical simulation with the Comsol Multiphysics® software. Our model has been validated with experimental data. The performance of this panel for an annular repartition has been calculated as a function of the PCM percentage inside the cavity. For this purpose, a periodical temperature variation has been applied on one side. The temperature has been determined on the other side and it was shown that, for a filling concentration of 50% or more, its amplitude was divided by three compared to the applied oscillation. To evaluate the optimal amount of PCM we have introduced, a new indicator, the PCM activity, which represents the percentage of PCM available for latent heat storage. For our geometry and given boundary conditions we have found a 50 % value, in accordance with the amplitude attenuation.

ACKNOWLEDGEMENTS

This work was partially funded by Bouygues Pole Ingenierie Materiaux. The authors would like to thank P. Gegout and F. Barberon (Bouygues Pole Ingenierie Materiaux), for their advises and the helpful discussions on this work.

REFERENCES

[1] B. Zalba, J.M. Mari, F. Cabeza, H. Mehling, Review on thermal energy storage with phase change: materials, heat transfer analysis and applications, *Applied Thermal Engineering*, 23, 2003, pp 251–283.

[2] A.M. Khudair, M.M. Farid, A review on energy conservation in building applications with thermal storage by latent heat using phase change materials, *Energy Conversion and Management*, 45, 2007, pp 263 – 275.

[3] V.V. Tyagi, D. Buddhi, PCM thermal storage in buildings: A state of art, *Renewable & Sustainable Energy Reviews*, 11, 2007, pp 1146 – 1166.

[4] V. Sharma, V.V. Tyagi, C.R. Chen, D. Buddhi, Review on thermal energy storage with phase change materials and applications, *Renewable & Sustainable Energy Reviews,*13, 2009, pp 318 – 345.

[5] Y. Dutil, D.R. Rousse, N. Ben Salah, S. Lassue, L. Zalewski, A review on phase-change materials: Mathematical modeling and simulations, *Renewable & Sustainable Energy Reviews*, 15, 2011, pp 112 – 130.

[6] N. Soares, J.J. Costa, A.R. Gaspar, P.Santos, Review of passive PCM latent heat thermal energy storage systems towards buildings' energy efficiency, *Energy and Buildings*, 59, 2013, pp 82 – 103.

[7] G. Ziskind, Phase change materials: Recent advances in modeling and experimentations, Heat Transfer in Components and Systems for Sustainable Energy Technologies: Heat-SET 2007 April 18 to April 20 2007, Chambéry, France.

[8] H. Ye, X. Ge, Preparation of polyethylene-paraffin compound as a form-stable solid-liquid phase change material, *Solar Energy Mater, Solar Cells*, 64, 1, 2000, pp 37–44.

[9] M. Xiao, B. Feng, K. Gong, Preparation and performance of shape stabilized phase change thermal storage materials with high thermal conductivity, *Energy Conv. Management,* 43, 1, 2002, pp 103–108.

[10] K. Kaygusuz, C. Alkan, A. Sari, O. Uzun, Encapsulated Fatty Acids in an Acrylic Resin as Shape-stabilized Phase Change Materials for Latent Heat Thermal Energy Storage, *Energy Sources*, 30, 2008, pp 1050-1059

[11] K. Chen, X. Yu, C. Tian, J. Wang, Preparation and characterization of form-stable paraffin/polyurethane composites as phase change materials for thermal energy

storage, *Energy Conversion and Management*, 77, 2014, pp 13 -21.

[12] X. Xu, Y. Zhang, K. Lin, H. Di, R. Yang, Modeling and simulation on thermal performance of shape-stabilized phase change material floor used in passive solar buildings, *Energy and Buildings*, 37, 2005, pp 1084 – 1091

[13] M. Koschenz, B. Lehmann, Development of a thermally activated ceiling panel with PCM for application in lightweight and retrofitted buildings, *Energy and Buildings*, 36, 2004, 567-578.

[14] R. Ansuini, R. Larghetti, A. Giretti, M. Lemma, Radiant floors integrated with PCM for indoor temperature control, *Energy and Buildings*, 43, 2011, pp 3019 – 3026.

[15] J. Mazo, M.Delgado, J.M. Marin, B. Zalba, Modeling a radiant floor system with Phase Change Material (PCM) integrated into a building simulation tool: Analysis of a case study of a floor heating system coupled to a heat pump, *Energy & Buildings*, 47, 2012, pp 458 – 466.

[16] N.A. Yahaya, H. Ahmad, Numerical Investigation of Indoor Air Temperature with the Application of PCM Gypsum Board as Ceiling Panels in Buildings, *Procedia Engineering*, 20 (2011) 238-248.

[17] S. Jeon, J.-H. Lee, J. Seo, S.-G. Jeong, S. Kim, Application of PCM thermal energy storage system to reduce building energy consumption, *Journal of thermal analysis and calorimetry*, 111, 2013, 279 – 288.

[18] X. Wang, J. Niu, Performance of cooled-ceiling operating with MPCM slurry, *Energy Conversion and Management*, 50, 2009, pp 583 – 591.

[19] L. Royon, L. Karim, A. Bontemps, Thermal energy storage and release of a new component with PCM for integration in floors for thermal management of buildings, *Energy and Buildings*, 63, 2013, pp 29–35.

[20] L. Karim, F. Barberon, P. Gegout, A. Bontemps, L. Royon, New pcm components for thermal management of light envelope of buildings, *Energy & Buildings*, 68, 2014, 703 – 706.

[21] European Project ThermCo., Thermal Comfort in Buildings with Low-Energy Cooling Contract No. EIE/07/026/SI2.466692, May 2009, submitted by Technical University of Denmark.

[22] J.F. Nicol, Characterising occupant behaviour in buildings: Towards a stochastic model of occupant use of windows, lights, blind heaters and fans, *Seventh International IBPSA Conference*, Rio de Janeiro, Brazil, August 13-15, 2001.

[23] Comsol Multiphysics® software, version 3.5a, www.comsol.com.

[24] A. Bejan, in Convection Heat Transfer, John Wiley & Sons, Inc., N.Y., USA.