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NUMERICAL STUDY OF THE INFLUENCE OF THE THICKNESS AND MELTING POINT ON THE EFFECTIVENESS OF PHASE CHANGE MATERIALS: APPLICATION TO THE RENOVATION OF A LOW INERTIA SCHOOL

Joseph Virgone [1, 2], Jean Noël [3], Raymond Reisdorf [4]
[1] Université Lyon 1,
[2] Université de Lyon, Laboratoire DGCB, URA 1652, ENTPE, Vaulx-en-Velin, France
[3] JNLOG, Lyon, France
[4] DuPont de Nemours, Luxembourg

ABSTRACT

The renovation of a building in terms of thermal insulation will improve the level of energy consumption in winter. To improve the summer comfort, we have simulated the introduction of a phase-change material (PCM) in both situations: removed or not removed building. The dynamic building simulation software CoDyBa has been adapted to consider these materials in the calculations. The parametric study is, once the surface material laid down considering the morphology of the premises, about the adjustment of certain characteristics of the material, such as thickness or melting temperature value.

INTRODUCTION

In the framework of the renovation of low inertia buildings, the use of phase change materials (PCM) is an interesting alternative. By their ability to store a large amount of heat, they could present a solution to the problems of summer comfort while allowing energy savings in winter. This work deals with, at the base, the evaluation of the performance of a specific phase change material taking the form of a panel of 5 mm thick. It consists of 60% paraffin encapsulated in a matrix of copolymer (a mixture of polymer-based ethylene). The role of the matrix polymer is to retain the paraffin when it is in its liquid state. The compound has a melting point at 21.7°C, temperature at which it liquefies, and thus absorbs heat from the room. Then, when room temperature falls, it solidifies, and removes the heat.

The modelling was conducted with CoDyBa, thermal simulation software adapted to consider this kind of materials. The results of operative temperature and so thermal comfort can be analysed and the gains provided using phase change materials applied at the internal part of the walls or ceiling can be calculated.

The secretary building of the secondary school, built in 1961, ie before the first French thermal regulation, has a low thermal inertia in addition to thermal insulation of very poor quality. The renovation of the building in terms of thermal insulation will improve the level of energy consumption in winter.

To improve the summer comfort, the establishment of PCM cited previously has been simulated using the software CoDyBa..

A preliminary study was to fit some unknown thermo physical parameters: a monitoring of the on-site temperatures has been made. The weather data of the ENTPE engineering school weather station have also been used for the monitored period. These statements, made in May 2008 have helped to assess the real discomfort in addition to validate the modelling (Pignal, 2008).

Once the material surfaces set, given the morphology of the premises, the parametric study is conducted on the adjustment of certain characteristics of the material, such as thickness, temperature of the phase change or association of other means (such as night ventilation). Several surface possibilities of PCM adjunction have been also considered in order to evaluate the influence of this parameter: façades, ceilings, partitions, or combination of these possibilities.

The modelling of the PCM integration, with different variations, conduct to an improvement of thermal comfort and the results are analyzed to draw conclusions about the best values, for the Lyon climate, of thickness, melting point or PCM area to deploy.

CHARACTERISTICS OF THE SPECIFIC PCM USED

The use of phase change materials in building is a relatively old concept that has never really been exploited because of implementation difficulties inherent in these materials.

The novelty in this case is the encapsulation of a large quantity of active ingredient in a thermoplastic polymer, which, after processing in a relatively thin panel, allows easy installation in all types of building envelope.

This new product (Dupont de Nemours, 2009) consists of 60% of PCM, whose melting temperature is close to 22°C. Figures 1 and 2 show the curve of heat capacity and thermal conductivity measured as a function of temperature. This product is similar to a polymer panel, flexible, 5 mm thick.

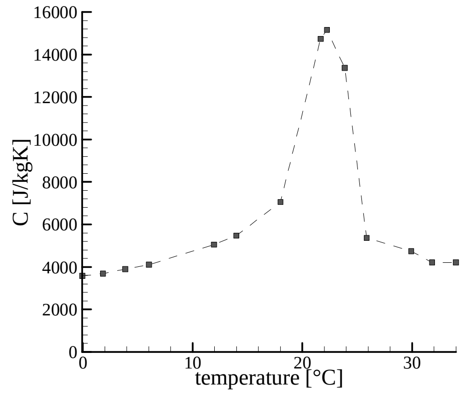

Figure 1. - Experimental PCM material heat capacity measured for several temperatures

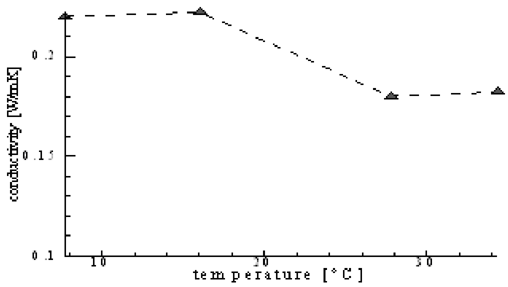

Figure 2 - Experimental PCM material thermal conductivity measured for several temperatures

THE SOFTWARE CODYBA

The software

Software CoDyBa (Jnlog, 2009, Judkoff et al, 1995) is devoted for teaching and research but also for engineering designer offices. This is a tool for forecasting the dynamic thermal behaviour of a building, to establish an energy balance or to analyze the influence of certain parameters (such as controllers, windows, solar protection or the orientation of a building, etc.).

CoDyBa has been performed to consider the walls containing PCM. This version has been tested with the results of measurements on simple cases and the comparison is satisfactory (Virgone et al, 2008), this validation work was conducted as a benchmark for the French project PREBAT "IMCPBAT".

Modelling of PCM

One dimension treatment of the temperature in the wall is defined by the Fourier equation. The enthalpy h exchanged by the PCM is considered from the heat capacity *C(T)* of the material, depending on the temperature. The relationship between the two quantities is given by:

$$C(T) = \frac{dh}{dT} \qquad (1)$$

Thus, we get:

$$\rho.C(T).\frac{dT}{dt} = \mathrm{div}(-\vec{q}) \qquad (2)$$

In CoDyBa, the heat capacity is modelled by "exponential" form:

$$\begin{cases} C = C_0 + (C_M - C_0).e^{-\left(\left(T_R - T\right)/\Delta_1\right)^2} & T \leq T_R \\ C = C_\infty + (C_M - C_\infty).e^{-\left(\left(T_R - T\right)/\Delta_2\right)^2} & T \geq T_R \end{cases} \qquad (3)$$

T_R corresponds to the temperature of the peak of the curve. We calculate, then, the latent heat L with the relation:

$$L = \frac{\sqrt{\pi}}{2}.[\Delta_1.(C_M - C_0) + \Delta_2.(C_M - C_\infty)] \qquad (4)$$

We consider the thermal conductivity as:

$$\begin{cases} \lambda = \lambda_0 & \text{if } T \leq T_R \\ \lambda = \lambda_\infty & \text{if } T \geq T_R \end{cases} \qquad (5)$$

Then the values to provide are T_R, C_0, C_{00}, C_M, Δ_0, Δ_{00} for the capacity calculation and λ_0, λ_∞ for the conductivity one.

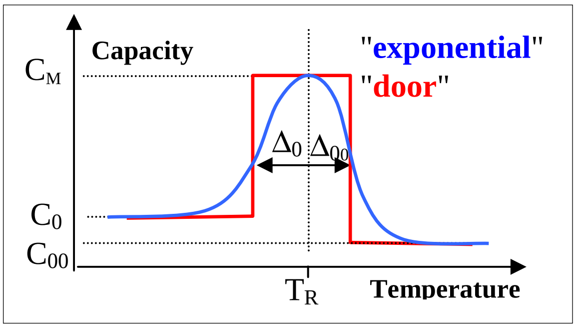

Figure 3 - Modelling of the heat capacity of a PCM in CoDyBa software

The “door” form is another possibility to describe the heat capacity, as presented in Figure 3. Anyway, extensive tests have shown few differences in results in terms of resultant room temperature. The most important factor is the latent heat, which depends on the integral and not on the form. Furthermore, the “exponential” form presents the advantage to a better match with the experimental capacity measurements.

In CoDyBa, a wall is represented by a “R2C” model: 2 surface “capacities” (2 variables) linked by a “resistance”. In the development of the PCM version, this analogical model has been preserved. It is based on the subjacent assumption of a linear temperature in each wall layer. This model is less accurate than a volume or finite element method, but led to a good equilibrium between calculation speed and result precision (see a benchmark in Virgone, J. et al, 2008).

Modelling of blinds

It is possible in the CoDyBa to associate a shading device to each window of a building. This can be

constituted of Venetian blinds or screens, inside or outside. It is characterized by the "g" value including also the glassed window. This factor g includes the primary and secondary heat transmission of the whole apparatus, and solar calculation are made at each time step.
The numerical determination of g value is done in two steps. First, an optical analysis determines the amount of incoming solar radiation that is absorbed in the crossing of each layer and how the windows transfer the radiation inside. Secondly, an analysis of heat transfer determines the incoming energy from the heat balance made on each sheet. This assessment takes into account the direct and the diffuse radiation, the characteristics of the windows and blinds, shading and the angle between the direction of the sun and the normal of the glazing.

4. DESCRIPTION OF THE BUILDING STUDIED

This one is the secretary building of the college of the city school Claude Bernard located in Villefranche-sur-Saône in the Rhône. It dates of the'60s and has never been renovated. So, thermal comfort problems are many, as in summer or in winter.

Figure 4 - Exterior view of the building studied

The building, with its main facade facing south, measures 79 m long and has a width of 9 m. In this building we can found at ground floor, meeting room, offices of stewardship, the headmaster, a reprography space and the guard lodge. The floor is constituted with different housings.
The facades are very poor insulated (4 cm of insulation in a sandwich panel), windows with single glazing, have a little airtight joinery, roofing steel trays are poorly insulated (5 cm of insulation) and have no thermal inertia, as the façades. The building is on crawlspace and slab beams are made from slabs. The interior walls are made of hollow bricks coated with plaster, the whole being of 5 cm thickness.

The planned renovation is to make a lining inside 5cm polystyrene and one cm plasterboard. The roof will receive an addition of 8 cm of glass wool in the tray of the steel floor. Finally, the windows will be replaced by efficient windows.

Figure 5 - Interior view of the building studied

For the simulation of the building, we have cut a 4 m wide current part of the building. (see Figure 6) and divided it in 4 zones: the crawl space, the ground floor (or first floor), the ceiling of the ground floor and the second floor.

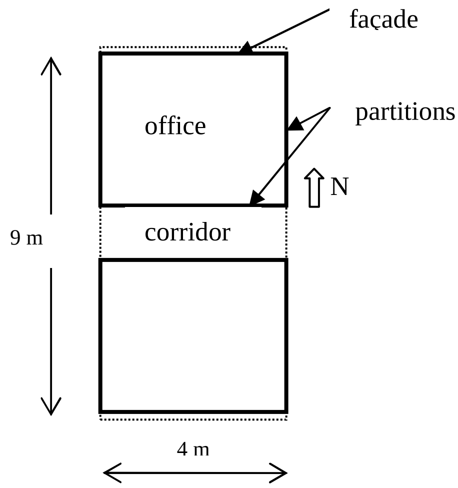

Figure 6 - Simplified diagram of the model studied

Different simulations were carried out to evaluate the performance of PCM in summer conditions in the both situations: without reinforcement of the insulation and in the case after thermal renovation. The ventilation rate was considered constant over the summer period and equal to 4 air change per hour, given the supposed opening of the windows. No air-conditioning system is considered nor heating and the internal loads are neglected, considering the low occupation of this building. The external blinds have been considered permanently closed on the south facade. We have not placed blinds in the north. The positioning of PCM is between the insulation and plasterboard when it exists. Surfaces treated with PCM are given in Table 1 via a ratio versus the building internal volume. The 12 simulations carried out with the weather data of the Macon station, a town quite close to the college, are grouped in Table 2.

Table1

Surfaces covered with PCM

Surfaces covered	Ratio Surface PCM/Internal Volume
àFaçades + ceiling	0.56
Façades + plafonds + cloisons (2 faces)	1.23

Table 1

Simulations performed

Case	Name	Renoved	PCM		S/V
			T_R (°C)	e (mm)	
1	R_withoutPCM	Yes	-	0	0
2	R_PCM22_5	Yes	22	5	0.56
3	R_PCM22_10	Yes	22	10	0.56
4	R_PCM22_20	Yes	22	20	0.56
5	R_PCM27_10	Yes	27	10	0.56
6	R_cloisonsPCM	Yes	22	5	1.23
7	NR_withoutPCM	No	-	0	0
8	NR_PCM22_5	No	22	5	0.56
9	NR_PCM22_10	No	22	10	0.56
10	NR_PCM22_20	No	22	20	0.56
11	NR_PCM27_10	No	27	10	0.56
12	NR_cloisonsPCM	No	22	5	1.23

RESULTS

Evolution of temperatures in summer for the different cases

Figure 7 shows the evolution of operative temperatures on a day in June. The second floor is, as might be expected, the more uncomfortable as temperatures can reach that day the 29°C against 27°C at the ground floor. There is the significant reduction on the maximal temperatures with PCM. In particular, a peak temperature lowered by almost 4°C in the best case. The amplitude of temperature is significantly lower and the temperature drops down less than 2°C at night with PCM, what is also favourable to thermal comfort. The most favourable case observed from the figure is a 20 mm thickness of PCM with a melting point at 22°C, in the case renovated. Given the temperature levels of materials on this day, the melting point of 27°C is less efficient. It can also be seen that renovating the building brings certain freshness to the building by reducing the heat gains through the insulated surfaces. It would be different if we had less protected windows (without blinds) or if we took into account internal loads. The storage of latent heat of PCM plays an important role in inertial changing temperatures.

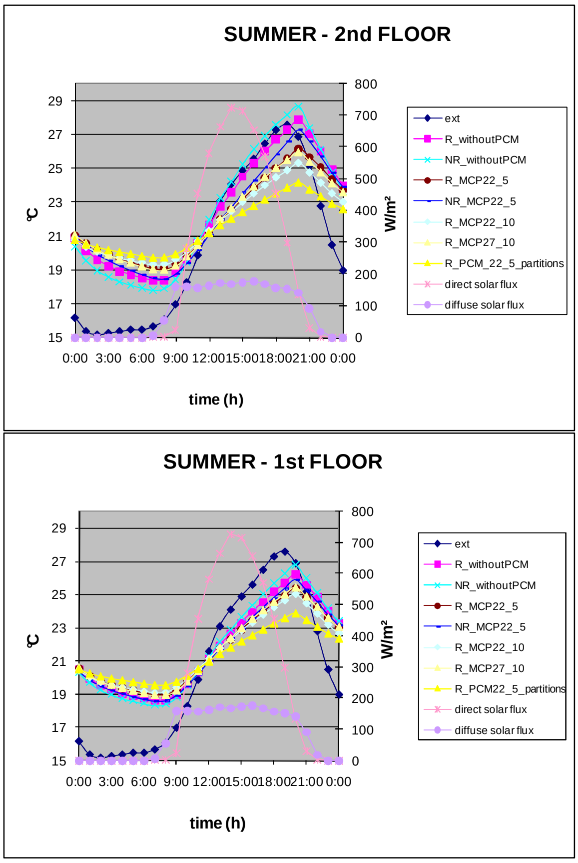

Figure 7 - Evolution of the temperature at ground floor (first floor) and the second floor one day in June in different conditions

Figure 8 shows, on a full summer, the percentage of time for which a certain temperature is exceeded. This one is greatly reduced by the addition of PCM, especially if the thickness is important. The general shape of these curves shows the effect of reducing to zero the amplitudes of temperature differences around 22°C, melting point of most of the solutions envisaged with PCM. The curves confirm that the case of melting point 27°C is less efficient in the sense that we have already taken some dispositions (opening windows and setting up stores in the south) to reduce global temperatures. There is also improved efficiency by increasing the surface of PCM: the best case presented in this figure is the addition of PCM (5 mm) on the two sides of the partitions, in complement to the ceiling and façade PCM installation.

The curves concern the internal operative temperatures. They can be a good representation of the thermal comfort of a person placed in these rooms, although this concept does not take the air speed into account, nor the moisture.

We considered 26°C temperature as a quite acceptable result. Moreover, the French legislation prohibits cooling below this value. Beyond 26°C, if we consider that there is thermal discomfort, it is interesting to compare the percentages of time (compared to the total duration of the summer), exceeding this value (Figure 9).

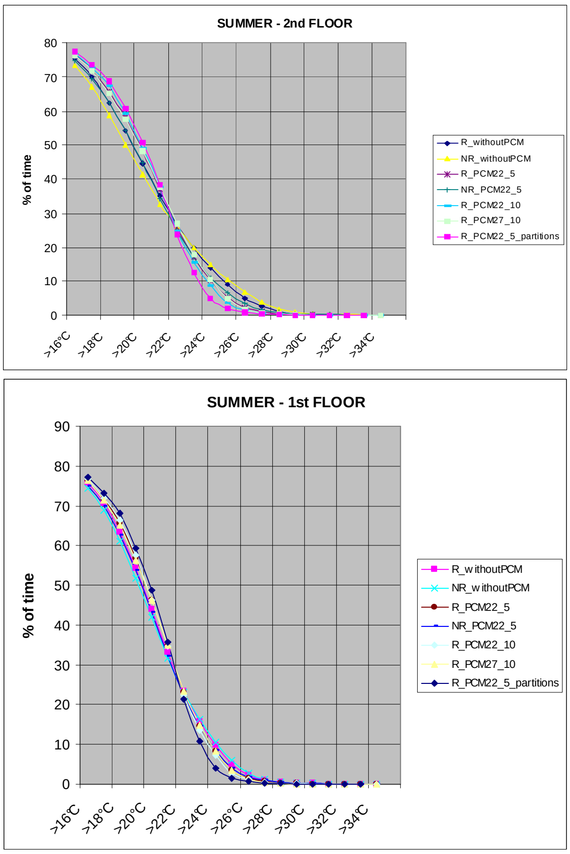

Figure 8 - Percentage of time for which a given temperature is exceeded on the full summer (1 May to 30 September)

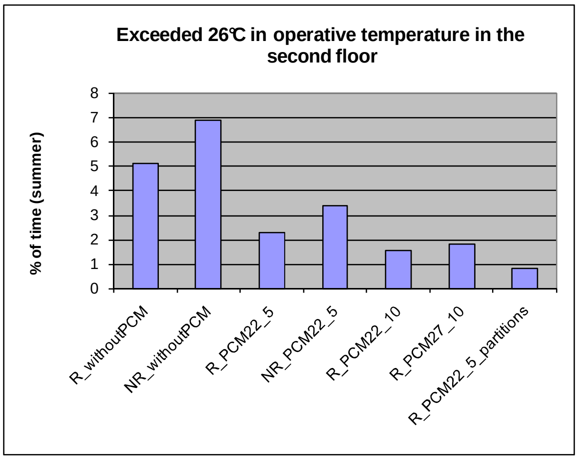

Figure 9 - Statistics on the percentage of time for which 26°C are exceeded in the second floor

This period may be less than 1% (which represents 31 hours per year, see figure 10) for the best solution while discomfort, for the same operating conditions of the building was originally, without renovation, nearly 7% time, approximately 260 hours.

Figure 11 indicates that the maximal temperature in the best solution do not exceed 30°C. It was higher than 33°C without any solution.

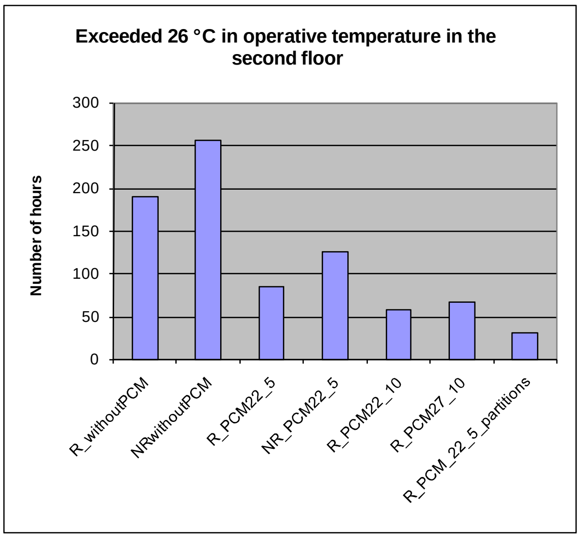

Figure 10 - Statistics on the number of hours for which 26°C are exceeded in the second floor during the whole summer

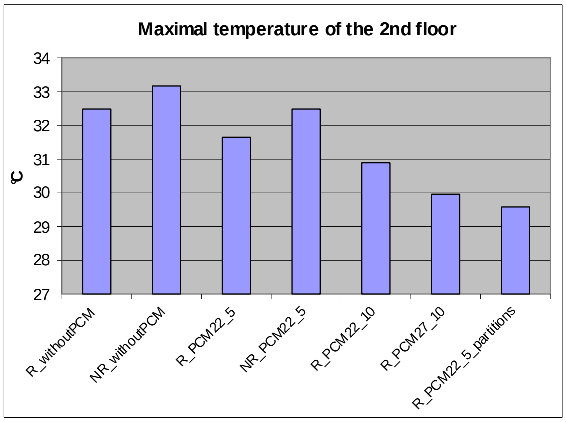

Figure 11 – Maximal temperature in the second floor during the whole summer

Correlation between the gains in the maximal operative temperature and PCM thickness or surface deployed

The proper design of surfaces and thicknesses can be estimated by analyzing how these parameters affect the maximal temperature in the second floor: does it is better more surface of thin material or thick one concentrate on a smaller area ? Even if we already expect to the answer when we know how the mass distribution influence generally the improvement of inertia, it is interesting to consider the issue in the case of material with a more complex behaviour than the conventional inert one. These results have been got from the Pignal (2008) work, on the same building, but with more results summarised. We carried on figures 12 and 13 the curves of variation of the gain on the maximal temperature during the summer depending on the thickness of the PCM parameters (considered the melting point of 22°C) and the influence of the surface of materials deployed. In fact, larger gains can be achieved in mid-season but they are not considered here. Indeed, they are sensitive to fluctuations (speed of temperature changing) and the radiation entering the premises that may be more important in mid-season due to the more normal incidence of the sun.

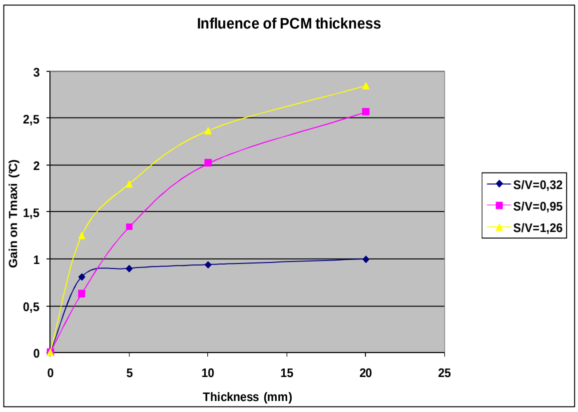

Figure 12: influence of the PCM thickness of PCM for 3 S/V ratios

It may be noted that the trend is for a sluggish performance when the PCM thickness increases. Indeed, it is the first millimetres that count. Beyond 20 mm we can attend to a relatively little gain.

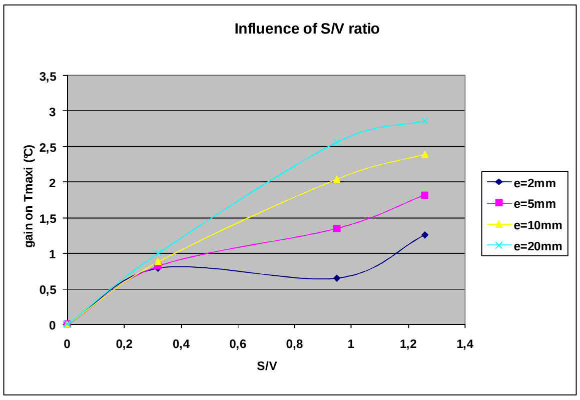

Figure 13: influence of the surface of PCM deployed, for different PCM thicknesses

It is almost the same tendency when increasing the PCM surface for thicknesses of 10 or 20 mm: we cannot attend to large gains for values higher than 1 for the S/V ratio. For lower thicknesses, the behaviour is somewhat different: it seems that there are very low or not at all gains between S/V equal 0.3 and 1. This is probably because the PCM is completely in liquid state and the activation of the latent heat is not allowed.

It may be noted that the same efficiency is obtained if we consider a S/V ratio of 0.5 with 2 cm of PCM and a S/V of 1.0 with 5 mm of PCM thickness: a division by 2 of the PCM mass can be implemented for the same result.

CONCLUSION

We used a numerical simulation tool to model a building completely, with its ventilation, its shading devices and in presence of PCM. The application to the case study of a building of low inertia that needs renovation has enabled us to see that insulating the building does not automatically lead to increased summer discomfort. That would be not true in presence of more important internal loads. A study of the influence of various parameters on the effectiveness of the solution tends to confirm that it is better to allocate a large area of material of low thickness (5 mm thickness seems interesting) than to large thicknesses, if we want limit the quantities to be implemented. The improvement of the inertia of an old building is now made possible by the use of PCM, associated with external insulation, solar protection and major ventilation, which is efficient especially during night.

NOMENCLATURE

C	heat capacity, $J / kg.K$
T	temperature, K
e	thickness, m
T_R	melting temperature of PCM, K
q	heat flux, W
S	surface of PCM, m^2
V	internal volume of the building, m^3
t	time, s t time, s
λ	thermal conductivity, $W / m.K$
h	enthalpy, J / kg
ρ	density, kg/m^3

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