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Experimental analysis of the thermal behavior of two cavities kind of living space with and without PCM on envelopes

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Abstract: To highlight the contribution of a phase change material (PCM) in terms of energy storage and thermal inertia in buildings, we conducted a comparative study of active heat balance in two real size cavities, built in the Faculty of Sciences Aïn Chock, Casablanca. The experimental consists of two identical cells: the reference cavity is standard and the other cavity incorporates a PCM with melting temperature of 22 °C. In this experimental and preliminary study, we equipped the cells by a set of thermocouples and equipment for measuring the necessary physical variables (temperatures, solar radiation, wind speed...) for the identification of the thermal efficiency of the cell with PCM. The results show that this material, significantly, contributes to the reduction of energy losses in this type of building.

Keywords: PCM, Building, experimental study, Storage, Thermal inertia, Casablanca

I. INTRODUCTION

As was established in 2007 by the fourth report of the Intergovernmental Panel on Climate Change, 90% of the causes of climate change reside in the emission of greenhouse gases (GHGs). Mitigation of climate change therefore consists in reducing GHG emissions. Since greenhouse gas emissions are, in large part, related to fossil energy consumption, the mitigation of climate change are essentially energy efficiency measures and renewable energy production [1].

The energy used in buildings accounts for about 20.4% of Moroccan's total energy consumption. The demand of the building sector has experienced an upward trend of 47% between 2004 and 2011 [2] (International Energy Agency 2013).

One of the mitigating technologies that have gained increasing attention is energy storage. A promising technology of thermal energy storage is the use of phase change material (PCM).

Phase change material has the ability to store and transfer energy in the form of latent heat at a constant temperature (phase change point) [3]. Therefore, not only it increases the thermal inertia of the walls but used, too, to store energy in latent form to contribute to this internal thermal comfort [4]. PCMs are divided into three types: organic PCM, inorganic PCM and eutectic PCM. Because organic PCMs have various advantages, most researchers have used them in their works [5], [6] and [7].

The PCMs are increasingly used for insulation and heat storage in buildings. It has been a central topic in research for the last 20 years. The PCM can be integrated into walls, ceilings, windows and floors. For integration into the walls, the PCM layer can be sandwiched between the inner and outer walls [8] and [9], absorbed in porous concrete, [10] or impregnated plasterboard [11], [12].

Because of the high thermal mass of PCM walls, they are capable of minimizing the effect of large fluctuations on the inside temperature of a building [13]. They can therefore be very effective in shifting the heating and cooling load to off peak electricity periods (Peak load shifting with energy storage and price-based control system) [14].

The use of PCM in buildings has been studied by many researchers in the last decades. For example, in 2006, Cabeza and al. [15] studied a new innovative concrete with PCM in order to develop a product. They constructed two real size cubicles concrete in Lleida, Spain, to demonstrate the possibility of using microencapsulated PCM in concrete. The experimental results showed that the energy storage in the concrete enhanced walls leads to an improved thermal inertia as well as lower inner temperatures compared with conventional concrete. Chandra and al. [16] concluded that a PCM wall of smaller thickness is more desirable in comparison to an ordinary masonry concrete wall for providing efficient thermal energy storage (TES) as well as better thermal comfort in buildings.

The objective of this study is to evaluate the effect of PCM on heat losses trough the envelope of residential buildings.

Two identical test cavities were constructed at the faculty of sciences Aïn chock, Casablanca, Morocco. The first one has been used as reference cell and the second is equipped with PCM. The PCM was installed on the inner surface of vertical walls. The thermal performance of the walls was compared with the reference cavity by measuring internal walls temperature and ambient cell temperatures. The heat stored in the PCM was evaluate by calculating the convective heat flux along the outer surface of the cell, and conductive thermal flux through the PCM layer, and then we calculate the convective heat transfer coefficients for external building surface.

II. EXPERIMENTAL SET-UP

The experimental set-up consists of two cavities, kind of living rooms, located at the Faculty of Science Ain Chock (FSAC), Hassan II University of Casablanca, Figure.1. The first sample (reference cavity) is made with standard walls, while the inner surfaces of vertical walls, of the second cell, are covered with PCM panels. They are equipped with 75 Thermocouples K-Type (2/10 mm). The assembly is connected to a data acquisition.

Figure 1. View of the cells

A. *Phase Change Material (PCM)*

The phase change material used is Energain product. It is encapsulated, in panels, by using thin Aluminum coverage (130μm). It is constituted of 60% of paraffin within a copolymer with a melting temperature of about 22°C (thermal comfort temperature).

The panels have dimension of 1 m × 1.2 m × 0.00526 m. The PCM have an enthalpy of 70 kJ/kg. The thermal conductivity is 0.18 $Wm^{-1}.K^{-1}$ in the solid phase and decreases to about 0.14 $Wm^{-1}.K^{-1}$ in liquid phase.

B. *Test cells*

They are apparently identical, but one of them contains about 24 m^2 of PCM: the inside faces of it vertical walls are covered by PCM panels. Cubicle dimensions are 3m×3m× 3m. The north wall is equipped by a window (1m×1m) and a door (2m×1m). As mentioned in Figure 2, the walls of the PCM cavity, are composed by (from inside to outside): PCM Layer (0.526 cm), First air layer (1.2 cm), mortar (1cm), alveolar brick (7 cm), second air layer (13.6 cm), alveolar brick (7cm), mortar (1cm). More details of walls are summarized in Table 1.

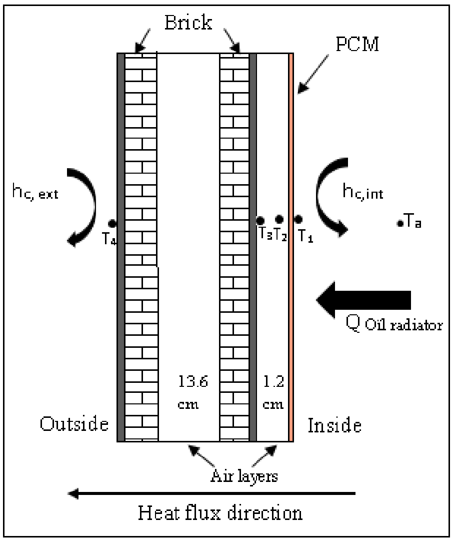

Figure 2. Different layers of the wall with PCM

Table 1. Vertical walls thermal properties without PCM (a), Roof structure and materials properties (b)

	mortar	alveolar	Air	alveolar	mortar
e (cm)	1	7	13.6	7	1
Cp (kJ/kg.K)	0.84	0.79	1.23	0.79	0.84
λ (W/m.K)	1.15	0.47	0.09	0.47	1.15

(a)

	Mortar	Heavy concrete (roof)
e (cm)	20	15
C_p (kJ/kg.K)	0.84	0.92
λ (W/m.K)	1 .15	1.75

(b)

C. *Instrumentation and measurements*

The cells are instrumented with 75 thermocouples K-type (2/10 mm) with an accuracy of ±2% in each wall. They are carefully welded, ensuring that the weld is of the same diameter that the two wires. Then, they are calibrated and the assembly is connected to a data acquisition device. Note that the thermocouples are distributed in order to access to the average temperatures of the walls and the indoor and outdoor temperatures of the cells.

Waiting to finish the installation of the solar heating system, the cells are heated with an electric oil radiator.

D. *Weather data*

The cavities are located in FSAC, Casablanca (33°32’ N latitude, 7°39’ W longitude and altitude 57 m). The weather data used in this study are those relating to 23th to 25th February 2014. Meteorological station, fixed on the roof of the test cells, was used to register the outdoor temperature, solar radiation, wind velocity, wind direction and relative humidity. All data are stored in a desk computer using data logger.

Note that for this period, the outdoor temperature flopped during the first day. It achieves 10°C while for the last two days; it does not come down below 13.8°C as shown in Figure 3. Global heat radiation is, also, presented in Figure 3. It is practically identical for the three days of measurement. It maximum value is around 900W/m². Against, the wind speed has varied considerably between the nights of 23th to 24th February, Figure 4. These fluctuations will act on the outer heat exchange.

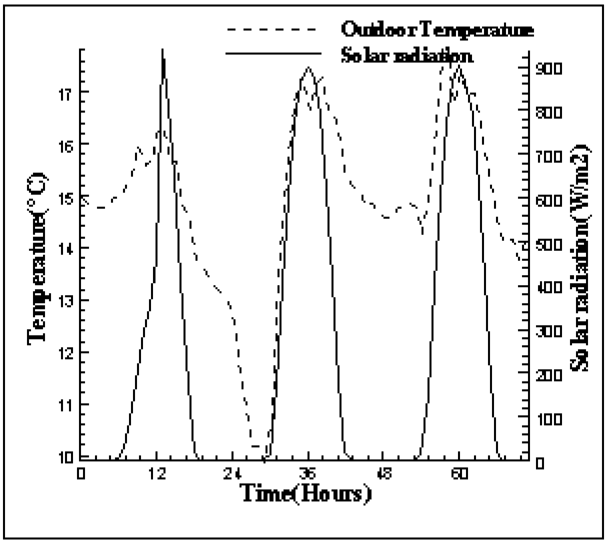

Figure 3. Time wise variations of the outdoor temperature and solar radiation

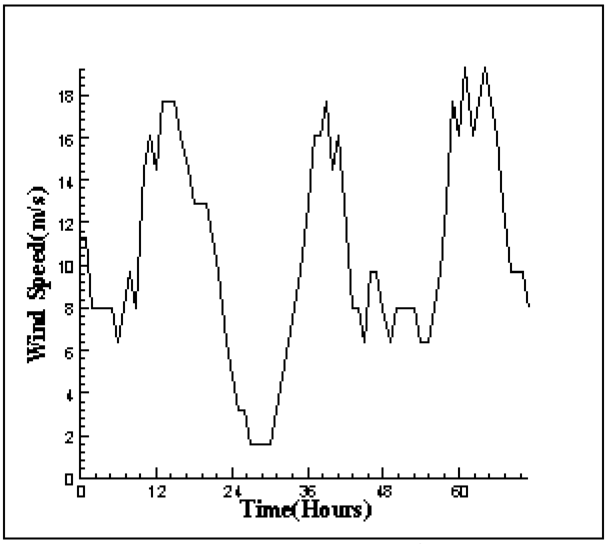

Figure 4. Time wise variations of wind speed

E. Data exploitation

The measured temperatures are used to determine the conductive heat flux in the first air layer (width=1.2cm) for each wall (west, east, south and north) equation (1).

We have equipped each wall with four temperature sensors (T_1, T_2, T_3 and T_4, Figure 2) inserted in the different layer at the same height.

Only measurements made at night are used and, so, the effect of solar radiation can be eliminated.

We neglected the convective flux in this layer and radiation heat exchange between air and walls.

The calculated flux will be used to evaluate the convective heat transfer coefficient on the outside walls.

Referring to Figure 2, the conductive heat flux through the first air layer is:

$$Q_{Cond} = \frac{\lambda_{air}}{e_{air}}\left(T_2 - T_3\right) \tag{1}$$

Where Q_{Cond} is the conduction heat flux, trough air layer, λ_{air} thermal conductivity of air e_{air} thickness of the first air layer. Heat transfer coefficient can be defined as:

$$h_{c,ext} = \frac{Q_{cond}}{T_4 - T_e} \tag{2}$$

A comparison with literature results [18, 19, 20 and 21] will be given for this parameter.

Heat flux stored in the PCM, is the difference between the flux exchanged by convection between the wall and the ambient air inside de cell (warmer than the wall), on the one hand, and that which passes outwardly by conduction (losses), assessed at the level of the air layer using equation (1) on the other hand. We use equation (3).

$$Q_{stored} = Q_{conv,in} - Q_{Cond} \tag{3}$$

$$Q_{Conv,in} = h_{c,\text{int}}\left(T_a - T_1\right) \tag{4}$$

$h_{c,\text{int}}$: is the convective heat transfer coefficient along the internal faces of the building. It is a fundamental unknown, in this work. We found some previous works suggesting definitions of this coefficient. We selected those proposed by ARSHRAE [17] giving $h_{c,\text{int}}$ =9.1W/m².K for configurations similar to ours. It will be a subject of our future experimental works.

III. RESULTS AND DISCUSSION

A. Thermal profiles

The experiments aimed at determining the thermal behavior of heated samples with and without phase change materials (PCM) and estimating the external convective heat transfert coefficient. To highlight this process, we will compare the internal temperatures of the walls and the ambient temperature of the PCM cavity to those of the reference cell and evaluate heat quantity stored in PCM.

Temperatures were monitored, collected and analysed during three mounth, January, February and March. Only the results of three specific days are presented in this paper.

Fiqure 5 shows the air temperature profiles inside the two samples. We notice that there is always a temperature difference in the cells. The maximum gap is obtained in the afternoon and reached 2.47°C, as indicated in Table 2. These temperature profiles are varing between a miminum of

29.53°C and a maximun of 33.41°C during the two last days and fell to 26.72°C during the first day, in the PCM sample, due to external conditions. In the reference cavity, it fluctued from 25.39°C to 30.99°C. Fluctuations at the curve related to the reference cell, in the afternoon of the third day, are due to external pertubarbation (door opening). This temperature difference can be explained by the thermal inertia of PCM.

In Fig.ure 6, we show the temperature curves on the inner faces of the south walls (with and without PCM). The two curves have substantially the same manners as those of the ambient air, apart from the variation ranges of the two temperatures that are 23.5 °C to 29 °C, for the cell with PCM and 22 °C to 27.5 °C, for the reference cell.

Time variations of the two temperatures on the inner faces of the ceilings are shown in Figure 7. The behavior of these functions is different from those in Figures 5 and 6. In fact, the gap is growing in the days to reach 4.44 °C. By cons, overnight, the two curves are practically identical and the difference between the two temperatures drops to 0.56 °C. Note also that the thermal maxima, in the case of the cell with PCM, increase from day to day. This is due to heat accumulation in the wall with PCM.

Except for the thermal profiles of the ceiling and especially on the first day, all temperatures do not come down more than the PCM melting temperature which is 22 °C. It means that there is always a liquid party of PCM in spite of the reduction in the night-temperature of Casablanca.

Finally, we conclude there is a considerable contribution of the PCM, regarding thermal insulation in the building.

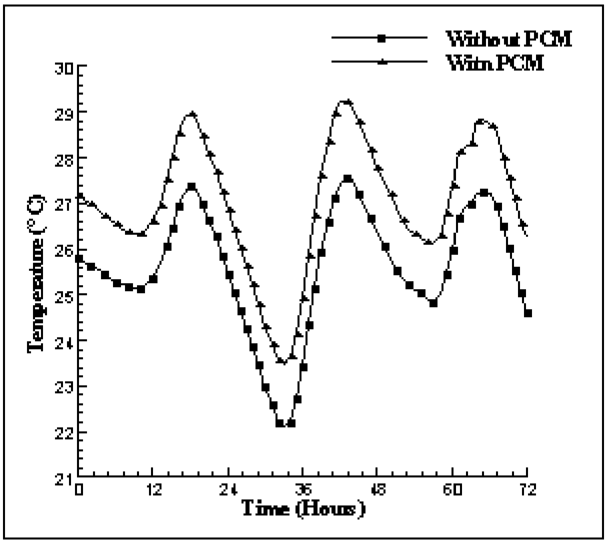

Figure 5. Time evolution of the indoor temperatures of the cells

Table 2. Maximum and minimum temperature deviations of the walls

	Ceiling	South	East	West	Indoor
ΔT_{max}	4.44	1.69	2.41	0.80	2.37
ΔT_{min}	0.56	1.39	2.17	0.97	1.68

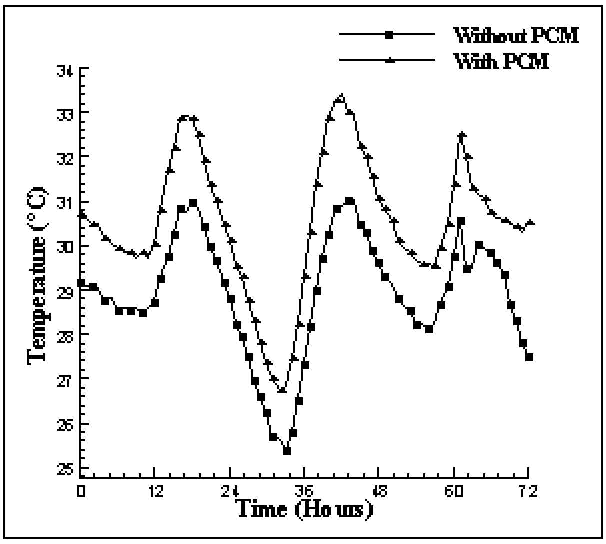

Figure 6. Time evolution of the south wall internal face temperatures

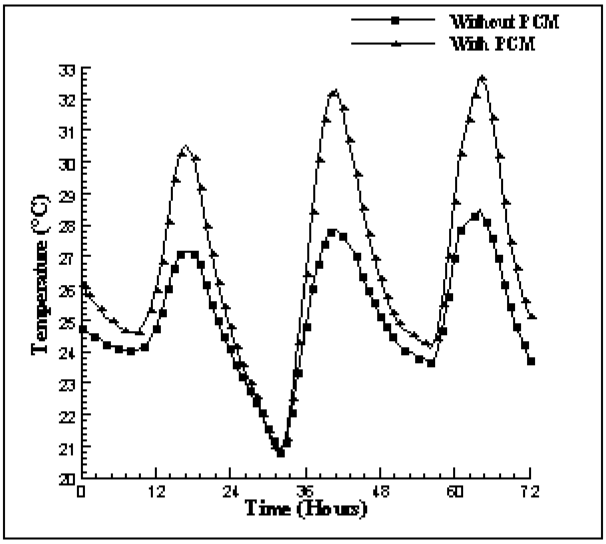

Figure 7. Time evolution of the ceiling internal face temperatures

B. heat transfer

1) External convective heat transfer coefficient

Generally, this coefficient is influenced by several factors, such as the geometry of the building, the position at the building envelope, the building surface roughness, wind speed, wind direction, air flow patterns and surface to air temperature differences [22]. In urban areas, local air flow patterns around a building strongly depend on the arrangement and geometry of neighboring buildings which strongly influence $h_{c,ext}$. Ground type influences the mean wind speed and turbulence intensity profiles [23,24] which also influence $h_{c,ext}$.

In this work, the external heat transfer coefficients are calculated using measured temperatures of both inner and outer faces of the cell walls (west, east, south and north). Their variations with time are shown in figure 8 for the south wall, knowing that the calculation period is between 0 AM and 5 AM (First day). We can see that the maximum of wind speed coincides with the increased of convective heat transfer coefficient for each wall.

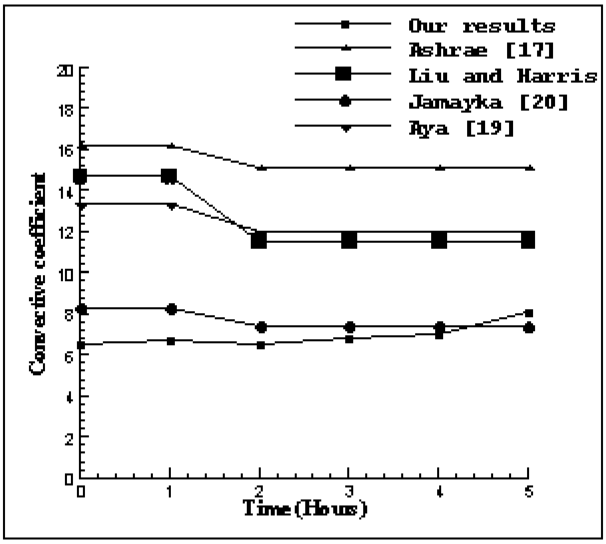

Figure 8. Time evolution of the external convective heat transfer coefficient of the south wall

Small differences between the experimental average convective heat transfer coefficient (our results) and the models (Jayamaha & Al), as shown in Table 3 and Figure 8. These deviations are, certainly, due to the location of the cavity and the type of ground that surrounds this latter, which are different from the conditions, suited to each model. Most of the model is based only on the wind speed without taking into consideration different temperature gradients.

Table 3. Mean heat transfer coefficient (West and South walls)

	Ashrae	*Jamayka*	*Aya*	*Harris*	*Our results*
South	15.93	8.05	13.06	13.97	7.95
west	15.93	8.05	13.06	13.97	8.06

2) Heat flux stored in PCM

To quantify heat flux stored in the PCM, we performed a specific heat balance on each wall of the cavity. Indeed, we evaluated the convective flux exchanged between the inside air and the wall (using the internal coefficient $h_{c,\text{int}}$ given by [5]), as well as the flux passing outwards (energy losses), based on the characteristics of the air layer (1.2 cm) we fitted in each wall. Stored heat flux Q_{stored} for all the surfaces may be expressed by equation (3).

Figure 9 shows the three curves for the total flux received by the south wall (by convection), flux stored in the PCM, and lost flux to the outside (by conduction). Note that the average values of these heat fluxes are:

$$\overline{Q}_{conv} = 29.84 \text{W/m}^2$$

$$\overline{Q}_{stored} = 19.23 \text{ W/m}^2$$

$$\overline{Q}_{cond} = 10.61 \text{W/m}^2$$

With $\overline{Q}_{conv}$, $\overline{Q}_{stored}$ and $\overline{Q}_{cond}$ are, respectively, the average convective, stored and lost heat fluxes of the south wall.

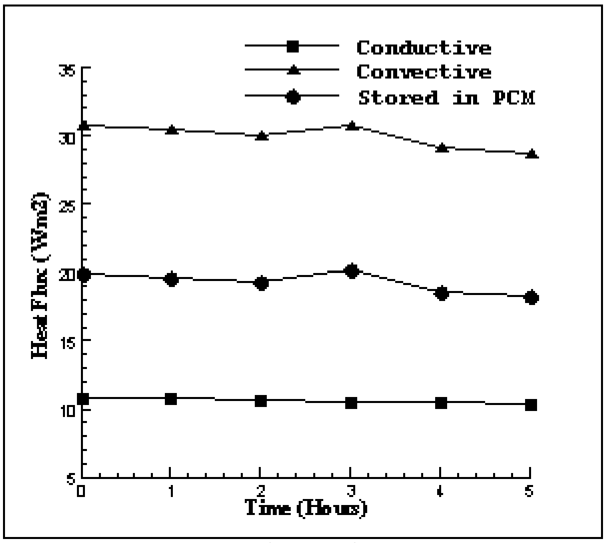

Figure 9. Time evolution of the heat fluxes (Conductive, convective and stored in PCM) of the south wall

IV. CONCLUSION

This study intends to support the application of phase change materials (PCM) in building as passive alternative to maintain the thermal comfort with a significant reduction of energy losses to the outside and as a result of a significant savings in heating energy.

The experimental results presented in this study showed the ability of PCM to increase the thermal inertia of the walls. A significant reduction of heat flux through the wall with PCM, due to absorption of heat flux in this latter. It can, therefore, be concluded that PCM is effective for storage of heating losses, and improvement of thermal comfort.

The heat stored by phase change material can reduce the heating time, and by the way, reduce the consumption of electrical energy. We find that Q_{stored} reaches 64% of thermal losses through the south wall without PCM.

Results show, also, that thermal losses through the ceiling are important, and so, we plan to incorporate a layer of PCM in the ceiling, in our future works.

The application of such materials for construction makes it possible to improve thermal comfort and reduce the load of Heating, Ventilation and Air-Conditioning (HVAC) systems for save electric energy.

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NOMENCLATURE

$h_{c,ext}$: External convective coefficient

$h_{c,in}$: Internal convective coefficient

$\overline{Q}_{conv}$: Average value of convective heat flux

$\overline{Q}_{stored}$: Average value of stored heat flux

$\overline{Q}_{cond}$: Average value of convective heat flux

Q_{stored} : Stored heat flux

$Q_{conv,in}$: Convective heat flux of interior

Q_{Cond} : Conductive heat flux

ΔT_{max}: The maximum difference of temperature

ΔT_{min}: The minimum difference of temperature

PCM: phase change materials

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