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Heat Exchange Trough a Building Wall with an Air Layer Incorporating a Phase Change Material

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Abstract

The present work consists of a parametric study of a double wall separated by an air layer within PCM panels, exposed to solar radiation. This experimental study was conducted using two real-scale test cavities, located in the Faculty of Science Ain Chock - Casablanca, for active and passive cases. For this purpose, many thermocouples are used for the thermal control of indoor applications, as well as for measuring the temperature field of the air layer within PCM. The evolution of the measured temperatures will make it possible to calculate the heat fluxes densities exchanged through the walls to explore heat transfer inside the air layer with PCM. The results show that the temperature fluctuations are reduced by 1.8 °C for the internal face of the studied wall and by 1 °C for the indoor temperature of the room with PCM compared to the reference room.

Key words: air layer, full scale cavity, solar radiation, PCM, thermal behavior, passive study, active study, heat flux density.

1. INTRODUCTION

In the last decades, the requirements of thermal regulations for buildings have increased in order to reduce energy consumption. Thus, it has become necessary to explore and develop new high-level performance constructions to produce buildings with very low energy consumption. According to the requirements of the Moroccan building energy efficiency code (ADEREE) [1], insulation must be applied to all the walls to ensure thermal comfort with minimal energy consumption. In this context, lies our contribution. Indeed, it involves the use of a phase change material (PCM) to isolate against heat gains in summer and to store any heat losses in winter, and to release it towards the local.

Previous works show that several numerical and experimental studies have focused on the building thermal efficiency. Using optimal polystyrene layer, the wall and the roof insulations lead to an important reduction of heat losses [2, 3, 4, 5, 6]. Elamin [7] has shown that the optimal choice of lake building orientation, the glazing ratio, the air layer thickness, the mass flow rate ventilation for fresh air can contribute significantly in reducing the heating consumption in winter and air conditioning in summer. Gounni et al. [8] studied a textile waste material mainly composed of Acrylic Spinning waste to develop a thermal building insulation, which represents a solution of sustainable development. The thermo-physical parameters of the material were measured, and its thermal performance was tested in reduced scale cavity with controlled boundary conditions. Authors concluded that depending on its cost, the developed insulation based on acrylic spinning waste can be a good challenger for building thermal insulation.

One of the interesting ways to reduce the energy consumption is the use of latent heat thermal storage (LHTES) using phase change materials(PCM) with different melting temperatures in the building envelope [9, 10, 11 and 12]. Two test houses with a classic residential construction showed that the introduction of 1.27 cm of PCM wall panel in the west wall reduced maximum heat flux by 29.7 %, while the optimal location of 2.54 cm of PCM wall panel in the southern wall reduced maximum heat flux by 51.3 %, Lee et al.[13]. Mourid et al. [14, 15, 16]carried out an experimental thermal study using two identical real scale cells: One is equipped with PCM layer installed on the roof and / or in vertical walls. Authors notice a reduction of transmitted flux density from the ceiling to the cavity of 56.8% in the case of a single thickness of PCM layer, and of 88% with double layer of PCM, Compared with a reference cavity.

Phase change materials have the ability to release or store sensitive or latent thermal energy. Several numerical studies have been developed in this context to evaluate the PCM capacity of thermal energy storage. David et al. [17] have conducted a numerical work to evaluate some convective heat transfer correlations. The results show that the convective heat transfer highly influences the storage/release process through PCM walls. Kuznik et al. [18] have carried out an experimental research to enhance the thermal behavior of lightweight building internal partition wall. They realized a differential analysis of walls with and without PCM material, under controlled thermal and radiative effects. The PCM wallboard reduces considerably the air temperature fluctuations in the room. It can be seen that the overheating effect is lower with PCM material and the energy stocked is destocked to heat the air room when the temperature is minimum. Faraji [19] adapted a one-dimensional mathematical model to optimize the latent heat storage wall by integrating two layers of phase change material as sandwich within a concrete wall. He found that, when the PCM layer is placed close to the inner face of the wall, the thermal comfort conditions are considerably improved compared to a concrete wall.

In the present paper, we study the thermal behavior of an air layer within PCM panels in the western wall of a real scale building. For this purpose, two identical cells were constructed: One is within PCM and the other is as a reference cavity. PCM layer inserted inside the air layer of the western wall constitutes the major originality of our work. Results are presented for passive and active studies, and are compared with those of the cavity without PCM.

Nomenclature

h	Convective heat transfer coefficient (W/m².K)
PCM	Phase Change Material
T_e	External temperature face of Western wall without PCM (°C)
T_{ePCM}	External temperature face of Western wall with PCM (°C)
T_i	internal temperature face of Western wall without PCM (°C)
T_{ePCM}	internal temperature face of Western wall with PCM (°C)
T_{out}	Outdoor Temperature (°C)
T_a	Ambient temperature inside the reference-cavity (°C)
T_{aPCM}	Ambient temperature inside the PCM-cavity (°C)
φ_{cd1}	Conductive heat flux density through the western wall (W/m²)
ϕ_{cd1}	Conductive heat flux through the western wall (W)
φ_{cd2}	Conductive heat flux density through the air layer of the wall with PCM (W/m²)
ϕ_{cd2}	Conductive heat flux through the air layer of the wall with PCM (W)
φ_{cv}	Convective heat flux density through the western wall air Layer with PCM(W/m²)
φ_{cv}	Convective heat flux density through the western wall air Layer with PCM(W/m²)
φ_{ray}	Radiative heat flux density through the air Layer with PCM(W/m²)
ϕ_{tr}	Transmitted heat flux through the air Layer with PCM (W)
ϕ_{Stored}	Heat flux stored in the PCM panels (W)

2. EXPERIMENTAL SETUP

2.1 Test cavities

The experimental setup is located in the Faculty of Sciences Ain Chock in Casablanca (Mediterranean climate Casa foolowing Kopper classification). It is composed of two real scale cavities, Fig.1. The cavities are identical with the same orientations and dimensions of 3 m x 3 m x 3 m. The northern wall is equipped with a simple class window of 1m × 1m and a wood door of 2m × 1m. The vertical walls are identical except for the western wall of the PCM-cavity (Western wall (b)), for which we introduced a 5.25 mm PCM layer in its air layer, Fig.2.The western wall has a thickness of 30 cm and it consists of double bricks separated by anairlayer as indicated in Table 1. This table shows the composition of the western walls with and without PCM. The western wall (a) is studied as a reference wall.

Fig. 1. View of the experimental cells

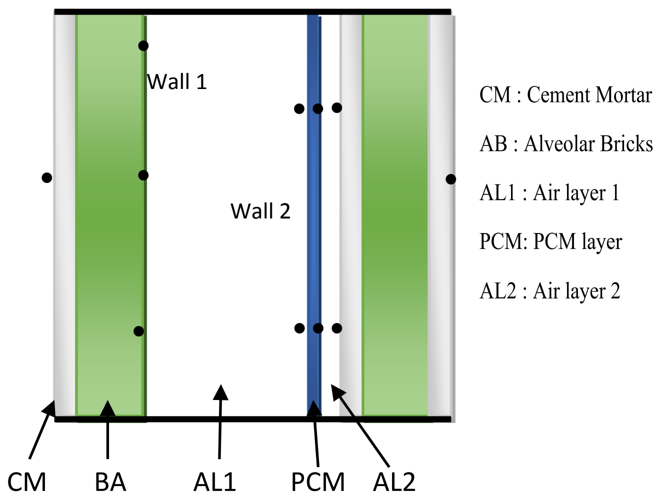

Fig.2. Western walls composition and thermocouples positions

Table 1. Composition of the western walls with and without PCM.

	Wall without PCM	Wall with PCM
Vertical Walls	1 cm concrete mortar 7.2 cm alveolar bricks 12.6 cm, air layer 7.2 cm alveolar bricks 1 cm concrete mortar	1 cm concrete mortar 7.2 cm alveolar bricks 9.8 cm air layer 0.525 cm PCM layer 1.2 cm air layer 1cm concrete mortar 7.2 cm alveolar bricks 1 cm concrete mortar

2.2 Instrumentation and measurements

In order to study their thermal behaviors, the walls were equipped with thermocouples K-type (2/10mm). On the first wall (without PCM) we placed three thermocouples on its inside face, one thermocouple on its outside face, and three thermocouples placed inside the room on the vertical axis passing through the center.

For the second wall with PCM, 10 thermocouples have been installed, Fig.2: 2 thermocouples on each side of the PCM panel, 2 thermocouples fixed on the mortar wall (by the side of the air layer), 3thermocouples on the inside face of the wall and one thermocouple on the outside face of the wall. Three thermocouples are placed inside of each room on the vertical axis passing through the center. The different thermocouples are connected to a data acquisition. The reading time of the temperatures is 10 minutes

2.3 Phase Change Material

The tested PCM is an ENERGAIN® product developed by DuPont de Nemours Company, in the form of a rigid building panel. The mixture is composed of polymer based on ethylene (40%) and paraffin (60%), encapsulated in a panel of dimension 1m × 1.198m × 0.00526m, laminated on each side by two sheets of aluminum of 130 µm. The edges are covered with 75 µm aluminum adhesive tape; the surface mass of the panel is 4.5 kg/m². The PCM panel is characterized by a melting temperature between 20 °C to 35 °C [20]. The PCM thermal conductivity is 0.18 W/m.K, in solid phase and 0.22 W/m.K in the liquid phase, Fig.3.

Fig.3. DuPont ENERGAIN® PCM panels.

2.4 Meteorological data of Casablanca

The meteorological data used are derived from the actual climatic conditions measured by a weather station installed on the roof of the reference cell during two periods: from September 14th to 16th, 2016 for a passive case study and from October 14th to 16th, 2016, for an active case study hereafter detailed.

The measurements were made with a time step of one hour. They are concerning the outside temperature, wind speed, the global solar radiation, and the relative humidity.

The outside temperature variation is given during the three days considered for the first period.Fig.4 shows that the temperature varies between 19.6°C as minimum and a maximum of24.8°C in the first two days. However, on the third day, a decrease to 17°C as a minimum is recorded, with a practically stable maximum, which does not exceed 25 °C. In addition, for the active case, the external temperature fluctuations are practically identical for the three days of measurement, with a difference of 1 °C. The fluctuations range between a minimum of 15.5 °C and a maximum 23.4 °C, Fig.5.

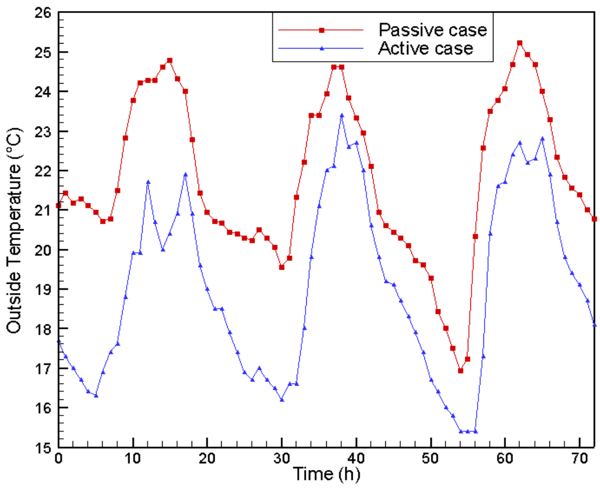

Fig.4. Outside temperature variation, passive and active cases.

In Fig.5, we present the wind speed variation for the studied cases. The curve for passive case shows that the variation is practically identical for the first two days, between 0 and 8 m/s. Unlike for the 3rd day, from 7:00 a.m. to 10:00 p.m., there is a wind speed variation between 0 and 7 m/s and it becomes calm (around zero) outside this period. Also, the curve of the active case varies from 9:30 a.m. until 7:00 p.m. to attend a maximum value of 5 m/s, Fig.5. This figure shows also that it becomes calm (wind speed around zero) over the night.

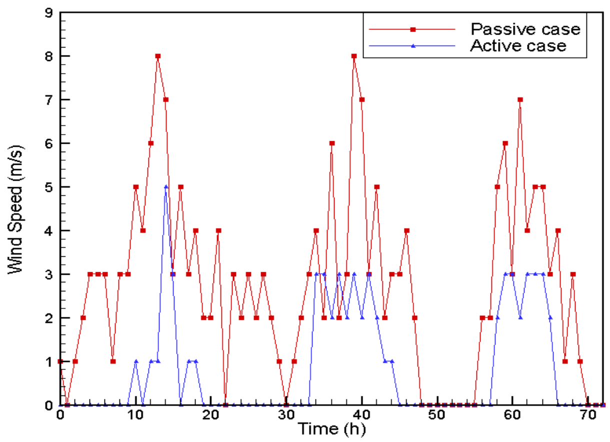

Fig.5. Wind speed variation, passive and active cases.

The global solar flux density is presented in Fig.6. The heat flux density profile is almost identical for the three days for the passive case. It attends 820 W/m² as a maximum value. Except that, there are slight disturbances because of the cloudy passages on the first and second days. In addition, for the active case, the maximum solar radiation reaches 513 W/m², 711 W/m² and 553 W/m² respectively for the first, second and third days. These fluctuations will act on the thermal resistance of the walls.

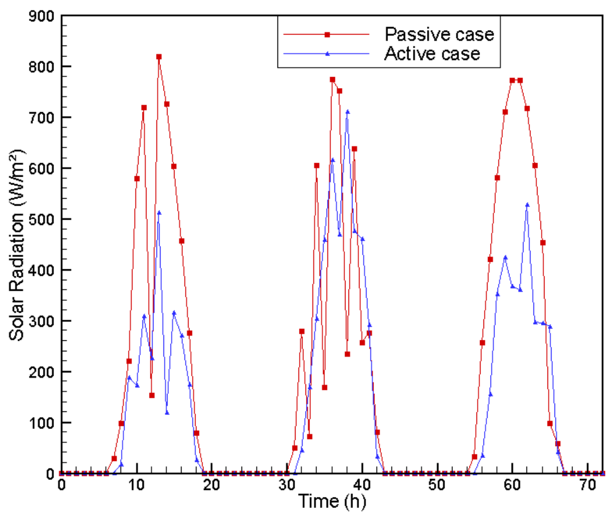

Fig.6. Solar radiation variation, passive and active cases.

3. RESULTS AND DISCUSSIONS

First we proceed to the comparison of the internal and external temperatures of the Western wall as well as the ambient temperatures of the two studied cells in the passive case from September 14th to 16th 2016 and then in the active case from October 14th to 16th 2016. Subsequently we focus on the thermal behavior of the air layer with PCM for the two studied cases. The third part of the results is dedicated to the PCM energy storage.

3.1 Thermal profiles of the Western wall

3.1.1 Passive case study

In order to quantify the impact of PCM on the thermal profiles of the cell envelopes, we illustrate inFigs.7, the thermal variations on the internal and external faces of the western walls of the two cavities, respectively. The western wall, which is subjected to solar radiation, reaches its maximum temperature at 4:00 p.m. The external face temperatures are the same for the both cases, and they vary between 17°C and 36°C. The temperature of the internal face of the western wall without PCM varies between 22 °C and 28 °C, whereas, for that with PCM, it varies between 22.1 °C and 26.3 °C, Fig.7. The presence of the two phases of PCM (liquid and solid) reduces the inside face temperature fluctuations of 1.8°C compared to that of the wall without PCM. This figure shows, also, a time shift between the outside and inside face temperatures. The wall with PCM has a good thermal inertia compared to the wall of the reference-cavity.

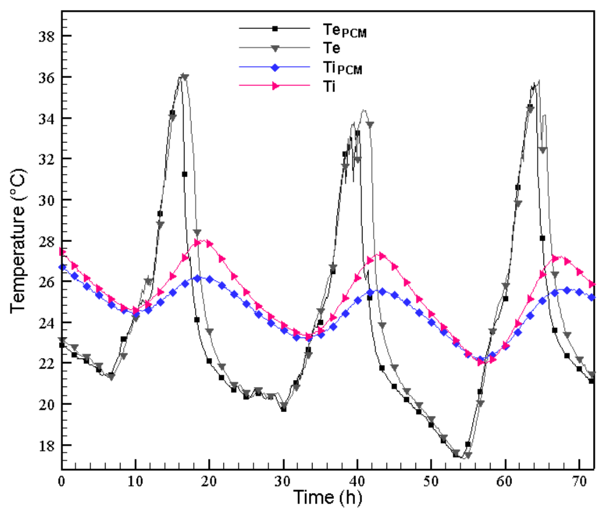

Fig.7. Temperature variation on internal and external faces of the western walls with and without PCM, September 14th to 16th, 2016.

In Fig.8, we present the ambient temperatures of the cavities. For the cavity without PCM, the thermal curve fluctuates from 23°C to 27.6°C, while, in the case with PCM it varies from 22.2 °C to 26.8 °C. The outdoor temperature varies between 17°C and 25.5°C. The same figure shows also, that the indoor temperatures are higher than the outdoor due to the cells orientation that promotes solar radiation gains. The thermal fluctuations of PCM wall are lower than those of the reference wall. It turns out that the integration of PCM reduces the temperature fluctuations of 1°C during our tests. Emphasize that the temperature evolution curves with and without PCM have a time shift of 2 hours, this is explained by the good thermal inertia exhibited by the Phase Change Material. Obviously, thermal fluctuations in the cases with and without PCM are more organized that those of the outdoor temperature, Fig.8.

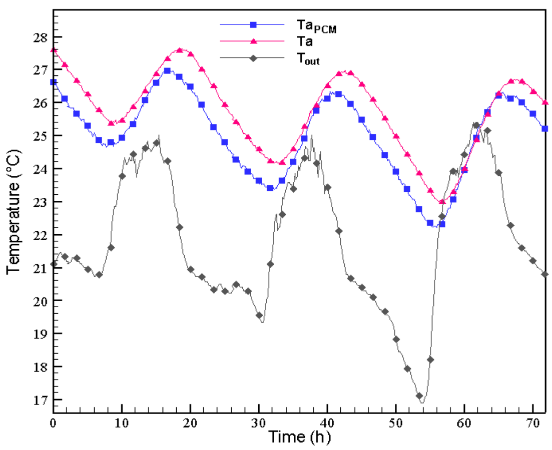

Fig.8. Variations of the ambient temperatures of the cavities with and without PCM, September 14th to 16th, 2016.

3.1.2 Active case

In Fig.9, we present the temperature variations on the inner and outer sides of the western walls for both cases with and without PCM. We observe that the temperature fluctuations of the external face of the walls vary between a minimum of 15 °C and a maximum of 30 °C. The curves show that external temperatures are almost identical during the diurnal period. At night, there is a small difference of 0.5 °C, which proves that the presence of the PCM does not influence considerably the temperature of the external faces of the wall. It should be noted that the internal face temperatures for the two studied cases oscillate around 17.5 °C, due to the regulation of the indoor temperature around 18 °C within the two cells, in order to ensure their thermal comfort. It should be noted that the difference between the curves related to the internal faces of the walls and the temperature of the external faces on reaches 10 °C, along the first day, and 12.5 °C for the second and third days.

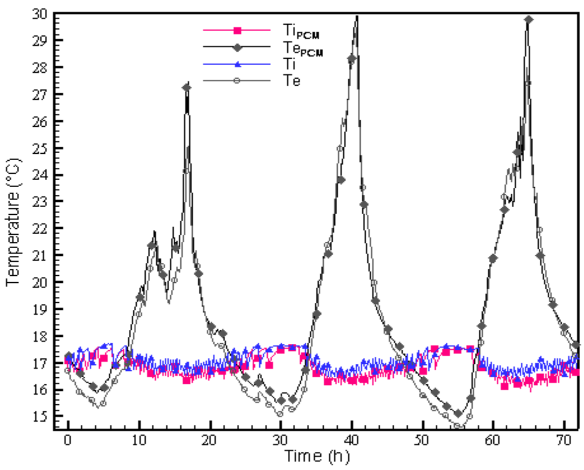

Fig.9. Temperature Variations of the inside and outside faces of the western walls with and without PCM, October 14th to 16th, 2016.

We notice that the introduction of a PCM panel of 5.25mm on the outer side of the western wall air layer has a significant effect on the temperature of ambient air. The thermal study has allowed us to quantify in detail the heat flux densities within the air layer incorporating PCM.

3.2 Heat Transfer through the walls with and without PCM

The effect of the PCM energy storage can be discussed efficiently by studying the difference between thein coming and the leaving flux densities from the PCM layer, as well as the convective flux density inside the air layer. Conductive, convective and radiative flux densities were calculated using the measured temperatures (T_1, T_2, T_3, T_4…) as mentioned if Fig.10.The empirical correlation of convective heat transfer coefficient in a rectangular cavity was employed using the measured temperatures values as boundary conditions.

The heat flux density transmitted by conduction from the outside to the PCM panel is calculated as fellow:

$$\varphi_{Cd1} = \frac{(T_1 - T_{23})}{\frac{e_{brique}}{\lambda_{Brique}} + 2 * \frac{e_{mortier\ de\ ciment}}{\lambda_{mortier\ de\ cimet}}} \; ; \qquad \text{(eq.1)}$$

$$T_{23} = \frac{T_2 + T_3}{2} \; ; \; \phi_{Cd1} = \varphi_{Cd1} \times S$$

Inside the air gap, the heat transfer between the surface of the PCM panel and the air space is composed of convective and radiative heat flux densities:

- Convective heat flux density between the surface of the PCM and air layer is:

$$\varphi_{CV} = h * (T_{67} - T_{a2}) \; ; \; \phi_{CV} = \varphi_{CV} \times S \; ;$$

$$T_{67} = \frac{T_6 - T_7}{2}; \qquad \text{(eq.2)}$$

T_{a2} is measured using a thermocouple placed in de center of air layer.

The thermocouple T_{a2} is placed at 6.5 cm from the PCM panel.

The convective coefficient h is given by a correlation [21] and is kept equal to h=1.25 W/m².K

- Conductive heat flux density between PCM and the air layer is evaluated using a thermocouple T_{a1}. T_{a1} is placed close the PCM panel (e_{a1} = 2 mm). In this zone the thermal profile is practically linear and heat transfer is essentially made by conduction.

$$\varphi_{Cd2} = \frac{(T_{67} - T_{a1})}{\frac{e_{a1}}{\lambda_{air}}}; T_{67} = \frac{T_6 + T_7}{2}; \phi_{Cd2} = \varphi_{Cd2} \times S \qquad \text{(eq.3)}$$

- Radiative heat flux density between the two sides of the air layer (PCM aluminum panel and cement mortar),

$$\phi_{ray} = \sigma * S * (\varepsilon_{AL} T_{67}^4 - \varepsilon_{CM} T_{89}^4); \qquad \text{(eq.4)}$$

$$T_{89} = \frac{T_8 + T_9}{2}$$

The heat flux density transmitted to the cavity through the wall 1 is:

$$\phi_{tr} = (\phi_{Cd2} + \phi_{CV} + \phi_{ray}) \qquad \text{(eq.5)}$$

The heat flux density stored by PCM layer is calculated by:

$$\phi_{Stored} = \phi_{Cd1} - \phi_{tr} \qquad \text{(eq.6)}$$

λ_{air}: Air thermal conductivity coefficient (W/m.K),

h: convection coefficient (W/m².K),

ε_{AL}: Thermal emissivity of the Aluminum

(ε_{AL} =0.55),

ε_{CM}: Thermal emissivity of Cement mortar

(ε_{CM} =0.9),

σ:Stefan-Boltzmann parameter ($W.m^{-2}.K^{-4}$),

S : Surface of the wall (m²).

3.2.1Passive case: 14th to 16th September 2016

In Fig 12, we present the heat fluxes transferred from the PCM panels to the air layer. We first observe that the convective flux oscillates around Zero and is negligible compared to the fluxes exchanged by radiation and by conduction. It can be emphasized that convection is not developed in the air space. The conductive fluxϕ_{cd2} is negative and reaches values of up to 80 W (in absolute value) evolving from inside the cell to the air layer. On the other hand the flux exchanged by radiation oscillates between -30 W and +30 W, thus indicating that the face of the PCM is colder the day than that of the cement mortar (wall 1). At night the opposite happens: the PCM evacuates some of the stored heat and keeps these faces warmer than the environment.

As can be seen in Figs 4 and 7, the cavity studied is almost always warmer than the outside environment. This explains why the conductive flux ϕ_{cd2} through the wall (wall 1) is always negative, Fig.12: the cavity warmer, because of contributions through the ceiling, evacuates heat through the vertical envelope. In this case, the thermal boundary conditions are not controlled on both sides. The notion of thermal resistance is practically obsolete because, on the one hand, the flow can change direction from time to time and on the other hand there is a part of the heat flux stored in the PCM. This remark is also valid for the conductive flow ϕ_{cd1} (through wall 2) which oscillates between -350 W and + 950 W, Fig.13. Note also that the stored flux ϕ_{stored} varies as ϕ_{cd1} with a slightly weak intensity. Indeed, it is the conductive fluxϕ_{cd1} that influences the amount of energy stored in the MCP, since the transmitted fluxϕ_{tr} remains very low as shown in Fig.13.

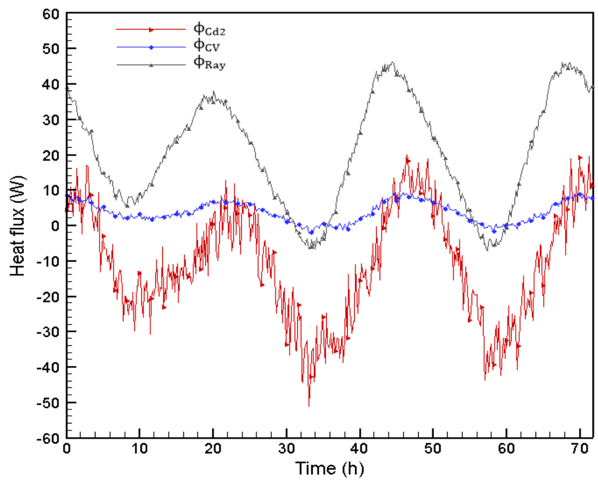

Fig.12. Heat fluxes transmitted from PCM to the air layer, passive study

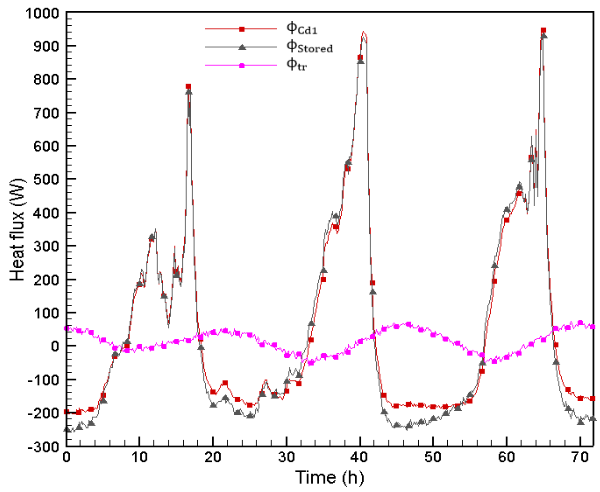

Fig 13. Heat fluxes, transmitted through the wall 2, stored in PCM and transmitted to the cavity, passive study.

3.2.2 Active case: 14th to 16th October 2016

In this case, we imposed an almost constant value of the ambient temperature T_{in} = 18 °C in order to impose a heat flux entering from the outside to the inside of the cavity during the day.

In Fig.14, we present, as for the passive case, the heat fluxes transmitted by convection, conduction and radiation, through the air layer object of this study. Firstly, it can be emphasized that the convective flux and the radiative fluxes are almost always positive. Note also the low value of the convective flux through the air layer despite the fact that there is a slight development of boundary layer flow close to the MCP face (not shown here). On the other hand, the conductive flux is negative during the three days of tests. Evolutions two types of heat transfer prove that the PCM side of the air space is hotter than the one on the left (Wall 1). On the other hand, it is possible to draw the opposite of the variation of the conductive flux. Indeed, we can question the method used to calculate the conductive flux (eq.3). This is only valid when natural convection flows of separate boundary layer type are available, El Alami et al. [22]. It should also be noted that we have neglected the involvement of thermal bridges in heat exchange with the air space.

Fig.15 shows that conductive and stored heat fluxes vary in the same manner of those of passive case (Fig.13) during the day. By night, their behavior changes slightly. The stored heat flux is greater than conductive one (absolute values) because of the PCM solidification. PCM is releases stored energy towards the air layer and the outside.

The air layer problem is usually complicated especially when the studied room is connected directly to the ground and exposed to real weather conditions, as is the case here. Indeed the thermal bridges are manifested in a considerable way between the local, on the one hand and the ground and the external environment on the other hand. In addition, the outside temperature variation with time and the incident solar flux on the envelope realize a transient heat transfer regime. In this work we neglected the contribution of the thermal bridges and worked in pseudo stationary mode.

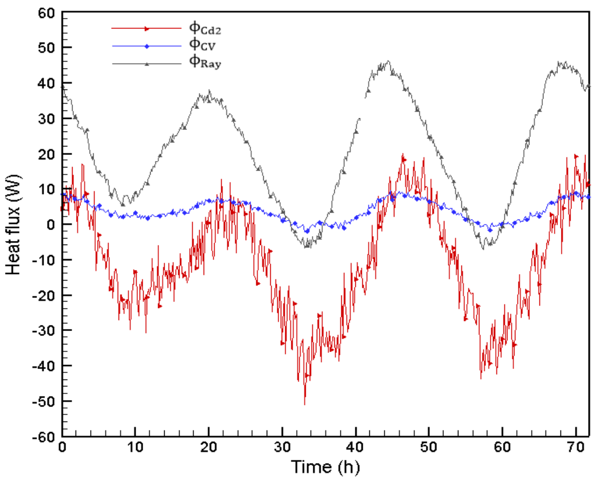

Fig.14. Heat fluxes transmitted from PCM to the air layer, case of active study

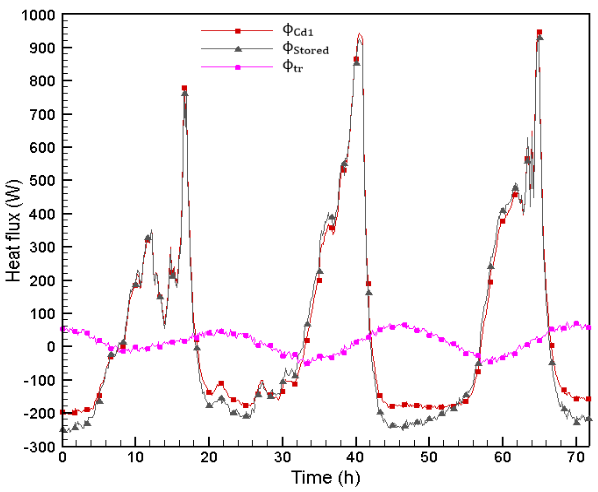

Fig.15. Heat fluxes, transmitted through the wall 2, stored in PCM and transmitted to the cavity, case of active study.

4. CONCLUSION

Thermal improvements in buildings caused by the PCM integration depend on the type and melting temperature of PCMs, the components, conception and orientation of the building, and meteorological conditions. In this way, an experimental study of the thermal behavior of an air layer within PCM layer in a western wall of real scale building is conducted.

The experimental setup is composed of two cavities, located within the Faculty of Science Ain Chock, Casablanca. One is within PCM panels in the west wall and the other has ordinary walls, during the periods: September 14^{th} to 16^{th} 2016, for the passive study and October 14^{th} to 16^{th} 2016, for another study with air-conditioning of 18°C as indoor temperature.

This study showed that the integration of PCM in the air layer of the western wall reduces the temperature oscillations of the internal face of about 2 °C during September. It turns out, also, that the ambient temperature fluctuations are reduced by 1°C during our tests. Emphasize that the temperature evolution curves with and without PCM have a time shift of two hours, this is explained by the good thermal inertia exhibited by the Phase Change Material.

Inside the western wall air layer, in passive study, the temperature variations with time show that thermal behavior of the air layer evolves as a function of the solar flux received by the western wall (containing the PCM). The air layer heats up when the global solar radiation reaches the western wall, and reaches its maximum value of the heating around 06:00 pm. Next to the PCM panel face (wall 2), there is appearance of a weak natural convection flow quantified by a negligible convective flux compared with those transmitted by conduction and radiation. In this study, the temperature of the face of the wall containing PCM varies around the PCM melting temperature; when this latter exist in the two phases. On the other hand, in active study, PCM panels remain solid and play the role of a simple insulator, because of the ambient temperature of the cavity set at 18 °C, while de PCM melting temperature is between 21°C and 31 °C [21].

The stored and released energy by the PCM layer is clearly remarkable as indicated above. It is interesting to note that the curves of the stored flux in PCM and the flux transmitted by conduction with and without air conditioning are practically identical. This is explained by the higher thermal capacity and the higher specific latent heat of the used PCM.

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