DOI: 10.1051/e3sconf/20172200057

Influence of PCMs on thermal behavior of building walls: experimental study using the walls of a reduced scale room

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Abstract. Using Phase-Change Materials (PCM) for lightweight building applications can increase equivalent thermal mass and provide energy savings. In the present experimental work, the heat transfer performance testing of some building walls, with or without PCM, is carried out using a reduced-scale cubic room (the test-cell). The cubic cell is heated by an incandescent bulb placed on its centre, and it is housed in an air-conditioned large-scale room that allows to control the ambient air temperature. The effect of the double PCM layer and of its location relatively to the outside surface of the wall is tested and discussed in terms of overall transmitted heat flux and in terms of reduction of the inside and outside surface temperatures. Findings shows that the additional inertia introduced by the PCM leads to a reduced overall heat flux transmission by the wall and to a lesser daily temperature amplitude on the surface of the wall that enhances the thermal comfort inside the building. In the next step of this work, the case of sandwich walls with air gap, and with wood and PCM layers will be considered.

1 Introduction

Building envelopes significantly impact the human thermal comfort. Improving the thermal performance of these envelopes can help achieve the desired thermal comfort. This can be obtained by enhancing the thermal resistance and inertia of the walls [1]. However, design limitation of the thickness and the weight of the wall implies that the enhancement of the thermal resistance and inertia cannot be easily set on the desired values. An alternative solution to improve the thermal performance of these envelopes is to enhance its thermal inertia and storage capacity by integrating Phase Change Materials (PCMs).

Recently, the integration of the PCM in building envelopes have been successfully validated for reducing heating and cooling energy demand and increasing the thermal comfort [2, 3]. The most previous research papers showed a reduction in peak heat flux across the PCM enhanced walls, a time delay related to the peak cooling-heating load and a reduction of the fluctuation of the indoor air temperature [4].

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However, there are some design challenge still pending: the most critical one is the integration method of the PCM into building envelop i.e. the optimal thickness and location in the building wall. In a recent review, Konuklu et al. [5] highlighted the technique of the PCM integration into building. There is a class of technics that are easy to implement, among which direct incorporation, immersion and macro-encapsulation. But those techniques faces the serious problem of the leakage of the PCM. The second class of PCM integration technics is the micro-encapsulation of the PCM. This last method, proposed as a solution to overcome the problem of the leakage of the PCM seems to be the most suitable for the PCMs integration in the layers of the building sandwich wall.

In this paper, the used PCM layer is laminated within two aluminium sheets and constitute a part of the sandwich wall. This integration method is referred as the thermal shield [6, 7]. The aim of this research paper is to experimentally investigate the effectiveness of the PCM layer in reducing the surface temperature and the heat flux across the wall. The used test-cell simulates in reduced scale and under laboratory conditions a room of a building with sandwich walls. The effect of the PCM layer and of its location relatively to the outside surface of the wall is presented and discussed in terms of overall transmitted heat flux and in terms of reduction of the inside and outside surface temperatures.

2 Experimental device

2.1 The used PCM

The used PCM in the present study consists of a panel, with two aluminium sheets 130 microns thick that contains a solid copolymer (ethylene, 40%) and paraffin (60%) with properties shown in the Table 1. The panel edges are sealed with an aluminium tape 75 microns thick. The final form of the composite PCM is a flexible panel, 0.5 cm thick, as shown in the Fig. 1. It can be integrated directly into the structure during the construction of the building or added during the building renovation.

Table 1. Thermal properties of PCM.

Fusion temperature	21.7°C–31 °C
Latent heat of fusion (0°C–30°C)	> 70 kJ/kg
Total heat storage capacity (Temperature range 0°C to 30°C)	~ 140 kJ/kg
Thermal conductivity (solid phase)	0.18 W/(m·K)
Thermal conductivity (liquid phase)	0.14 W/(m·K)

Fig. 1. PCM used in this study.

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2.2 Test-cell

The heat transfer performance testing of the walls is carried out using a cubic room built with reduced scale, here termed as test-cell. The vertical walls of this test cell are removable and exchangeable in order to discuss the thermal insulation and inertia with or without PCM of several configurations. The test cell dimensions are 0.4 m x 0.4 m x 0.4 m. The heating of the test cell is provided by an incandescent bulb placed at the centre of the cubic cell. The test-cell is housed in an air conditioned large-scale room. The used air conditioning system permits the control of the temperature of the ambient air, Fig. 2. The four vertical wall of the test-cell are: a glazed wall (wall 1), a wooden wall (Wall 4) and two PCM walls (Wall 2 and Wall 3). The successive layers with their respective thickness are given from indoor toward outdoor as shown in the Fig. 3. At real scale, the thicknesses would be 15 cm and 5 cm, respectively, for the wood (or equivalent) layer and the PCM layer.

Notice that the inside surfaces of the three walls Wall 1, Wall 2 and Wall 3 are the same (wood surfaces) and hence they have the same radiation properties, i.e. they have the same radiative absorptivity and emissivity.

Fig. 2. Test cell placed in a room with controlled temperature.

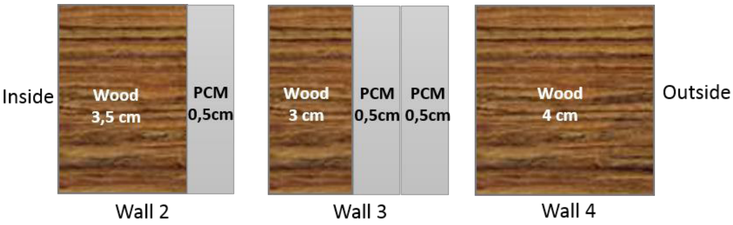

Fig. 3. Composition of test cell walls.

2.3 Measurement devices

Using k-type thermocouples (2/10 mm), with 0.1°C as error, the temperature measurements at the indoor and at the outdoor of the test-cell and the parietal temperatures of the walls (i.e. interior and exterior surfaces) are performed. The heat flux density through each wall is measured using a 2.54 cm diameter heat flux meters, with an accuracy of ±3% and a 0.3 s response time. The flux meters are placed on the inside of the surface of the walls. All the temperature and flux measurements was carried out with time intervals of 5 minutes.

3 Results and discussion

3.1 Operatives conditions

The experimental test-cell is sets up in such a way that its interior and its exterior sides can simulates the interior or the exterior condition of a real room. The experimental data analysed concern two cycles of heating with different time period. In the first cycle, the heat source inside the test cell is switched "on" for a successive time duration of 11.6 h, and then switched "off" for 3.75 h. In the second cycle, the heat source is switched "on" for 4 h and then switched "off" for 2 h. The test-cell indoor maximum temperature set-point is 37°C. Furthermore, in order to maintain a sufficient temperature difference between the outdoor and indoor of the test-cell, the outdoor air temperature of the test-cell, i.e. the laboratory room temperature is kept constant (Fig. 4) at 19°C thanks to the aforementioned air conditioning system. Under these conditions, the interior of the test cell simulates the exterior of a building at real scale in the summer season.

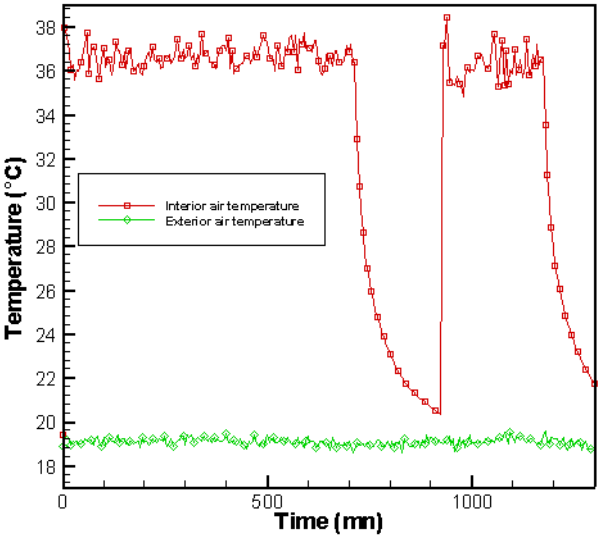

Fig. 4. The exterior and interior air temperature.

In the following parts, a qualitative study based on the parietal temperature profiles will be performed in the first section. A quantitative study will be performed in the second part of the paper in which the heat flux densities across the four vertical walls are quantified.

3.2 Thermal profiles

Fig. 5 and 6 show the inside surfaces temperatures of the four walls during the two heating-cooling cycles. As shown in those figures, the inside surface temperature of the Wall 1 (glass) is the lowest. This behavior indicates a less thermal resistance and also a less thermal inertia. Because of those two facts, it releases a huge heat flux to the other side. In the three other walls, the massive and resistive layers of wood and PCM decrease the heat flux that crosses the wall and hence, as shown in Fig. 5, reduce the outside surface temperature of those walls, i.e. Wall 2, Wall 3 and Wall 4.

During the heating phase, it is noticed from Fig. 5 that the outside surface temperature of the glazed wall (Wall 1) is the higher. This confirms the fact that the glass had the higher thermal conductivity.

On the other hand, it can be clearly seen that PCM walls (Wall 2 and Wall 3) can reduce significantly the outside surface temperature compared to the wooden wall (i.e. Wall 4). This occurs because PCM layer reaches its interval melting temperature and then would melt as a function of temperature, which translate to a reduction on the surface temperature. Recalling that in these operative conditions, the outside surface of the walls simulates the inside surface temperature of a real room in summer conditions, the lower is this surface, the lower is the heat flux rate transmitted and the best is the thermal comfort in the room. This is the reason why the comparison between the walls is made only on the wall surface temperature.

The outside surface temperature of the walls with PCM layer (i.e. Wall 2 and Wall 3) is the same with few more reduction for the wall with double PCM layer (i.e. Wall 3). This is because the second PCM layer of Wall 3 don't occur a fully melting which translate to a very few reduction on the outside surface temperature compared to Wall 2. Actually, the first PCM layer of the Wall 3 stores the majority of heat coming from heat source, which prevent the second PCM layer to occur a fully melting.

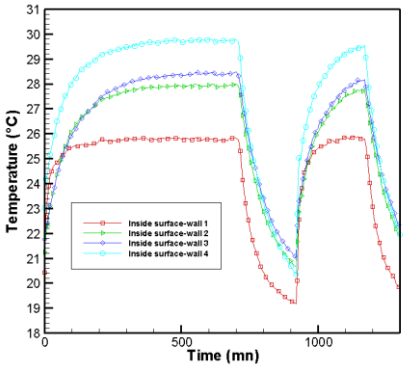

Fig. 5. Inside surface temperature.

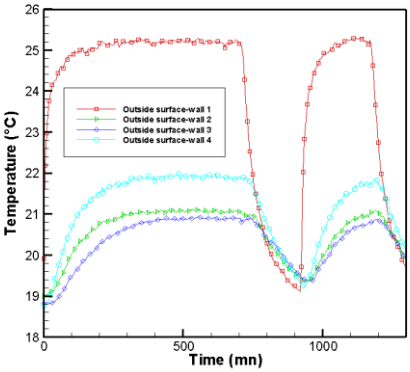

Fig. 6. Outside surface temperature.

Based on this finding, it is concluded that, the PCM layer reduces significantly the inner surface temperature of a real room that experiences summer conditions. The double PCM layer (Wall 3) seems to achieve a less reduction of the surface temperature (Fig. 6) than the single PCM layer (Wall 4) but, in the same time its surface temperature (Fig. 5) is higher than the one of Wall 4. To have a comprehensive understanding about the effect of PCM layer on the thermal Inertia of the wall, a quantitative study is done on the following section.

3.3 Heat flux densities through the walls

The fluxmeters sensors are placed at the inside walls surfaces in order to compare the absorbed flux for the four walls. Fig. 7 shows the heat flux across the four walls at this location. Firstly, it can be seen that the flux density related to the glass wall (Wall 1) is greater than the ones of the other walls. However, the walls that contains the massive layers (i.e. wood and PCM) has the lowest absorbed heat flux. This measure results confirm the results about heat flux that one can deduct from the thermal profiles of Fig. 5.

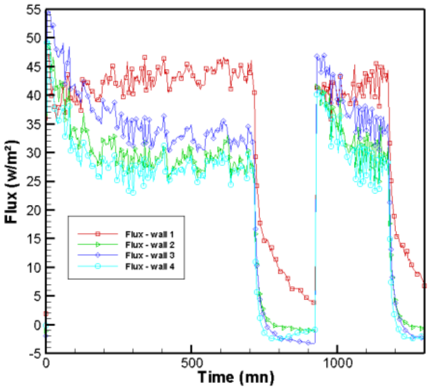

Fig. 7. heat flux across the four walls at the inside surface.

3.4 Stored heat flux

In this section, the stored amount of heat in the PCM layer contained in the two PCM walls (i.e. wall 2 and wall 3) is presented and discussed. To achieve this objective, the conductive heat flux, which crosses the wood layer of PCM walls, is calculated based on the following equations:

$$q_{cd} = \frac{\lambda}{e} \Delta T \qquad (1)$$

with

λ: Thermal conductivity of the wood layer which is 0.14 W/(m.K);

e: Thickness of the wood layer which is 3.5cm and 3cm, respectively, related to the Wall 2 and Wall 3.

ΔT: is the measured temperature difference between the inside and outside wood surface (°C).

Then, the heat flux stored into PCM layer is quantified as following:

$$q_{st} = q_{in,meas} - q_{cd} \qquad (2)$$

where

$q_{in,meas}$: Measured inlet heat flux related to the Wall 2 and Wall 3 (W/m²).

First of all, it should be emphasized that the contact between the wall layers is assumed to be perfect. This means that the thermal resistance between the wall layers is zero. The stored heat flux related to the Wall 3 is quantified between the two PCM layers. This means that the temperature difference ΔT is calculated between the two PCM layers. Fig. 8 shows the stored and released heat flux in the PCM layer of the PCM walls. Based on the comparison between the figures 7 and 8, during the heating period, the PCM layer stores the major part of the inlet heat flux. We notice that the double PCM layer stores more heat flux. This can be obviously explained by the thickness of the double PCM compared to the single PCM. Therefore, we can conclude that, under these conditions, the walls outfitted with single and double PCM behave in the same way. During the heating off period, the PCM layer releases (negative flux rate in Fig. 8) the absorbed heat flux, its value reaches 12 and 16 W/m², respectively, for the single and double PCM layer and then decreases until 0 W/m². The time period of the heating off was not sufficient to estimate the time needed to release the entire heat, i.e. to have a value of 0 W/m².

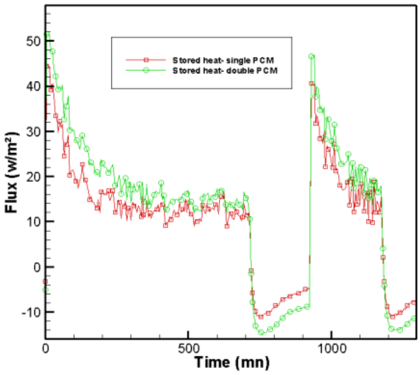

Fig. 8. Stored heat flux in the single and double PCM layer.

4 Conclusion

In this experimental work, the thermal performance of a building wall that contains a single or two PCM layers is evaluated, in term of the surface temperature and of the stored heat flux. A test-cell cavity at reduced scale placed in a thermally controlled room was used. The results shows that: The PCM layer reduces the surface temperature by storing a large amount of absorbed heat flux and then increases the thermal Inertia of the wall because the inside surface temperature of the walls outfitted with PCM layers is reduced due to its important latent heat of fusion. The thermal comfort is thus enhanced by walls with PCM layers.

- The time needed to release the stored heat flux is over 4 hours.
- Under the experimental condition, the wall with double PCM layer behaves like the wall with single PCM. This happens because in the second PCM layer of the wall with double PCM layer occur only a partial melting.
- Further tests are recommended with large heating off period in order to estimate more accurately exactly the time needed to release the entire stored heat. Indeed, a higher heat source set-point temperature is recommended to reach more quickly the interval melting temperature of the second PCM layer of the wall with double PCM layer.

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