Experimental energetic evaluation of changeable thermal inertia PCM containing walls

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ABSTRACT

The insertion of Phase Change Materials (PCM) inside light dry assembled building envelopes seems to be the right way to solve overheating problems usually caused by the low thermal inertia of such walls. An experimental campaign was held during the summer of 2004 at the “Renewable Energies Outdoor Laboratory” of the Polytechnic University of Marche (Ancona, Italy), where three experimental boxes were built: two of them were built with the south-facing walls containing PCM characterized by different stratifications, whereas the third box was built using a light multi-layered south facing wall without the insertion of PCM (hereon referred to as “reference box”). The use of the PCM provided three main positive results when compared to the reference box:

- lowering of the radiant surface wall temperatures, even if not provided with a thick insulation layer;
- strong reduction of incoming heat flux in the presence of a PCM layer, whose peaks are halved compared to the reference wall;
- shift in time of the highest incoming heat flux value occurrence which, for south-facing PCM containing walls, moves to a number of hours later than the reference box’s wall.

1. INTRODUCTION

As of the 1980s, a certain interest regarding the use of “Phase Change Materials” (PCM) for the accumulation of latent heat in built elements or in the technical plants of buildings has been registered, and recently many more experiments (Khudhair et al., 2004) have been carried out principally regarding:

- the combined use of PCM and systems for storing heat during lower energy cost hours in order to discharge it during the subsequent hours (Kunping et al., 2003) and for the exploitation of renewable sources such as solar energy;
- embedding plasterboard panels with PCM in order to increase latent heat and thereby increase the global thermal inertia of buildings (Neeper, 2000).

The advantage points provided by both these applications lie overall in PCM’s high latent heat of fusion and in the fact that its fusion temperatures are close to those of the comfort temperatures of inhabited environments.

A research group of the Polytechnic University of Marche, is carrying out studies aimed at testing the suitability of using PCM to solve problems tied to the overheating of light, dry assembled walls and roofing, already object of a three-year experimentation within the framework of an European Commission CRAFT project entitled “C-Tide” (Changeable Thermal Inertia Dry Enclosures). In fact, using low thermal inertia structures in climatic contexts characterized by intense solar radiation, would result in high thermal loads – whose course would be in phase as compared to the external climatic conditions – and the increase of the average temperature of such stratifications.

The aim, in this contribution, is to demonstrate that such problems can be solved by inserting a homogeneous layer of PCM between the insulating layer and the external finish in order to make it function as a shield in relation to solar radiation and to contribute to improving the comfort level.

During the experimental campaign held at the “Renewable Energies Outdoor Laboratory” of the Department of “Energetica” (Polytechnic University of Marche) in Ancona during the summer of 2004, two PCM containing walls were analyzed in experiments aimed at comparing their behavior with a reference wall which had the same characteristics with the only difference being that the reference wall did not contain PCM. The results demonstrated that the maximum thermal flux in the PCM containing walls is reduced by more than 50%, thus contributing to a reduction of the energetic consumption for air conditioning purposes.

2. EXPERIMENTAL APPARATUS

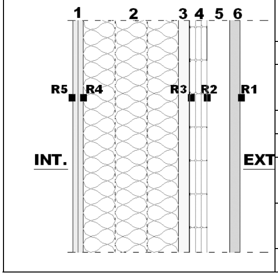
Eight small parallelepiped buildings measuring 3 m per side (experimental boxes) make up the “Renewable Energies Outdoor Laboratory”, three of these were used to experiment PCM walls. Their reciprocal positioning was chosen so that the shadow cast by each box would not interfere with any other box and all the boxes faced the same direction: each box had one of its walls facing south. They were all placed on rectangular concrete platforms. The walls which are not facing south and the roof where all built in the same manner using sandwich panels made up of two aluminum sheets and an internal 0.12 m thick insulating mineral wool layer. Another 0.1 m thick polystyrene layer was added and then covered by a reflecting sheet: the total transmittance of such walls is equal to 0.176 W/(m^2·K) (considering an external heat transfer coefficient of 25 W/(m^2·K) and an internal one of 7.7 W/(m^2·K)) according to the Italian UNI 10344[1] standard and its absorbance is approximately $\alpha = 0.4$. A 0.1 m thick polystyrene panel (density 15 kg/m^3) was placed above the flooring in order to decrease dispersion towards the ground and keep its superficial temperature even with that of the other walls. The south facing walls were built with the stratifications under investigation borne by a metal structure: in box n. 3 was assembled a wall (Fig. 1) equipped with 32 °C melting temperature PCM and a ventilated air layer, which is not present in the wall of box n. 2 (Fig. 2).

The wall of box n. 1 (Fig. 3) was instead used as benchmark, given that it was built using a light, dry assembled structure where the first three layers facing the interior coincide with those of the other two walls, but there is no PCM between them and the external finish.

2.1 Packaging on the PCM layer

Glauber salts with a melting temperature of 32°C, density 1450 kg/m^3, latent heat of fusion

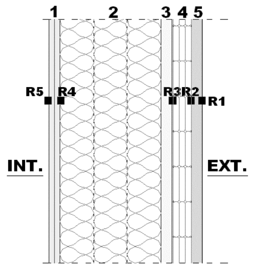
Box n° 3 (With ventilated ai layer)



N	*Layer*	*Thick (m)*
1	Plaster	0.025
2	Mineral wool	0.225
3	Chipboard	0.02
4	*PCM*	*0.03*
5	Ventilated air layer	0.05
6	Cement aggregate	0.025

Figure 1: South stratification of box n. 3 with the position of the temperature sensors.

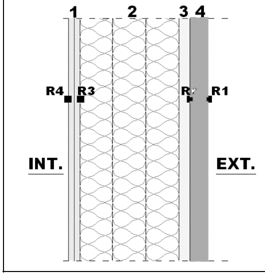
Box n° 2 (Without ventilated ir layer)



N	*Layer*	*Thick (m)*
1	Plaster	0.025
2	Mineral wool	0.225
3	Chipboard	0.02
4	*PCM*	*0.03*
5	Cement aggregate	0.025

Figure 2: South stratification of box n. 2 with the position of the temperature sensors.

Box n° 1 (Benchmark



N	*Layer*	*Thick. (m)*
1	Plaster	0.025
2	Mineral wool	0.225
3	Chipboard	0.02
4	Cement aggregate	0.025

Figure 3: South stratification of box n.1 -reference box – with the positioning of the temperature sensors.

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[1] At point 10.1 it suggests those values for the external and internal adduction coefficient. The use of such values is provided for by the actual governing standard EN 832 (May 2000).

$1.9 \cdot 10^5$ J/kg, specific heat in the liquid and solid state equal to $3.6 \cdot 10^3$ J/(kg·K), was used in order to form an even 0.03 m thick PCM layer. The advantage provided by the use of such salts can be found mainly in the ease with which they can be worked at the solid state (they are available as powders) and in their fire resistant qualities. The salt was packaged in rectangular aluminum envelopes measuring (0.2x0.08) m and 0.01 m thick. The results of previous experiments (Lemma et al. 2004) demonstrated that such envelopes loose their shape during the passage from the solid to the liquid state passing from a rectangular shape to a drop one and changing the thermal characteristics of the wall within which they are inserted. In order to solve these stability problems, they were stiffened between two sheets of aluminum measuring (0.62x0.25) m (Fig. 4), made not deformable by binding the sheets using a high resistance tape applied along the borders; in order to obtain a 0.03 m thickness, three envelop layers were placed within each tile.

In order to assemble such tiles in the boxes (Fig. 5), aluminum “C” shaped profiles (40x40x2) mm were fixed to the wooden panels and coupled using expansion bolts on “L” shaped (40x40x2) mm profiles, both measuring 3 m in length (that is, the same height as the walls). Vertical tracks were obtained by anchoring such profiles, capable of supporting the tiles which lie one against the other.

2.2 Monitoring system

The need to compare the energetic behavior of the south facing wall of the reference box (n. 1) and that of the two PCM containing boxes (n. 2 and n. 3) implied that the boundary conditions of each had to be identical; to ensure this a system for controlling the interior temperatures was conceived (Principi et al., 2005) which guaranteed its preservation at a constant value. The boxes are divided into two volumes: a technical one containing 23.5°C air temperature and a control one at 25°C using a plasterboard partition assembled with the interposition of a thermal insulation layer. Eight fans were installed to be used for supplying or extracting air as needed, with the aim of keeping the air temperature at 25°C in the control volume. The monitoring system consists in a series of “Rt 100” type resistance thermal detectors (RTDs) used to measure the temperature in relation to time on the internal and external surfaces of all the walls and the interfaces between the layers of the materials making up the south facing walls (Figs. 1, 2 and 3). Furthermore, nine constantan-copper thermocouples were installed in order to record the air temperature values in all the control volume (Fig. 6). In order to monitor the atmospheric conditions, a meteorological station for measuring outdoor environmental parameters equipped with the following sensors was put in place:

- pyranometer (for measuring irradiance);
- a rain gauge;
- anemometer (that combines the sensors for measuring both wind speed and direction);
- thermo-hygrometer (for measuring air temperature and air humidity).

A datalogger (Datataker DT 500 series 3) with 10 analogical type inputs and 4 digital input- outputs equipped with two channel expansion modules (CEM type) which increase the analogical inputs to 30, 44 for the digital ones

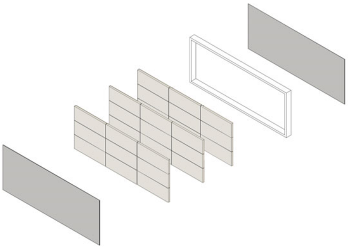


Figure 4: Prototype of the tile for the formation of the PCM layer.

Figure 5: The experiments boxes in their final layout (from left to right) n. 1, 2, 3.

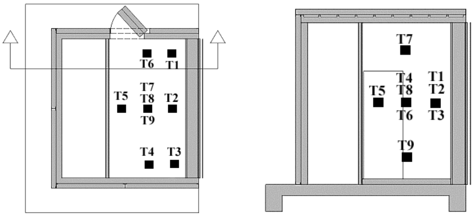


Figure 6: Thermocouples positioning within each box; plan (left) and section (right).

and to 10 the relay and digital “open collector” type outputs. All the temperature sensors have 0.1 °C sensitivity.

3. RESULTS OF THE 2004 EXPERIMENTAL CAMPAIGN

The strong thermal insulation of the previously described boxes was aimed at reaching the adiabatic conditions, in order to make the energetic behavior of the boxes sensitive to the sole influence of the south wall. By imposing an internal well-being temperature of 25 °C, thanks to the use of a split system air conditioning system, the temperature course of the south walls stratifications was monitored.

The experimental campaign was carried out between July 9th and September 11th 2004. The air temperature values (thermocouples) and the wall temperatures (RTDs) were recorded every 5 minutes using the data logger. Data regarding the following points will be analyzed below:

- the south wall of box n. 1, without PCM, used as a reference and whose sensors (identified using the letter “R” followed by a number) are placed as in Figure 1;
- the south wall of box n. 2, without a ventilated inner air layer with external finish 0.025 m thick cement aggregate over the 0.03 m thick PCM layer (whose sensors, identified using the letter “R” followed by number, were placed as in Figure 2);
- the south wall of box n. 3, equipped with a 0.05 m thick ventilated inner layer between the 0.03 m thick PCM layer and the 0.002 m thick external finish made up of a metal sheet (whose sensors, identified using the letter “R” followed by a number, were placed as in Figure 3).

3.1 Data analysis

The data pertinent to the temperatures regarding each interface and the extreme surfaces of the south walls were analyzed. Considering that the internal air temperature was fixed at 25°C, and that all the other walls were monitored with the same boundary conditions in all the boxes, it was possible to carry out a comparison between the internal superficial temperatures of the south walls. As illustrated in Figure 7, the boxes containing the PCM have temperatures which are sensibly lower than those without PCM. The temperature of the three boxes follows the forecasted course, that is, during daytime the reference always remains at a higher temperature as compared to those containing PCM (where the box without a ventilated layer behaves more favorably than the one with) and especially these last ones present lower temperature ranges than the reference one.

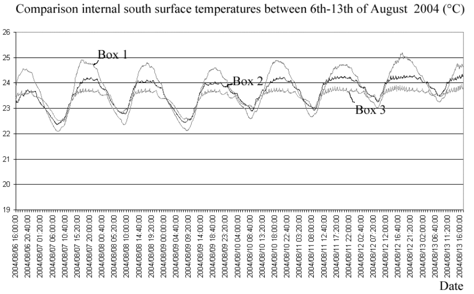
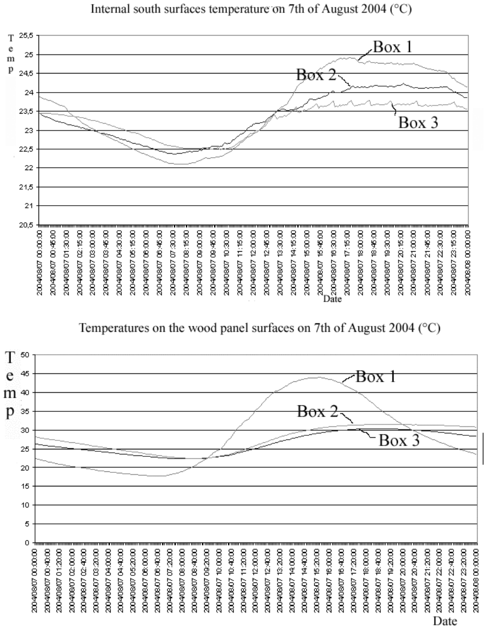


Figure 7: Comparison between the radiant temperatures of the three boxes during the period between August 6th and 13th.

For example, if we focus our attention on the data which regards August 7th in Figure 8-a, we notice that during night time the reference wall



a)

b)

Figure 8: Comparison between the internal radiant temperatures and those outside the wooden panel on August 7th.

drops to 22°C and then arises to 25°C during the day, whereas the one containing PCM keeps a temperature of approximately half a degree higher and during the daytime drops by 1 and 0.7°C respectively for box n. 2 and n. 3. The improvement cannot be attributed but to the presence of PCM. It is sufficient to analyze Figure 8-b where the temperature of the interface between the wooden panel and the PCM for box n. 2 and n. 3 (sensor R3 of Figs. 2, 3) and the interface between the wooden panel and the external finish of box n. 1 (sensor R2 of Fig. 1) to convince ourselves that this is the case. It can be noted how, for the reference box, the temperature is in the range of 11-13°C above that of the other two (which remains inferior to 32°C, which is the PCM melting temperature) and therefore a greater gradient is determined in the wall of box n. 1 with the ensuing greater heat flux towards the interior.

The course of the south internal superficial temperature (Fig. 7) is inferior to those imposed at 25°C for the air temperature. Explanation can be found in the fact that the south wall faces the partition which divides the volumes in two. This is why heat loss by irradiation between the dividing partition and the internal surface of the south wall causes of the temperature to drop below 25°C, but this does not invalidate the experimental results given that the same phenomenon is identically repeated for the three boxes.

The fluxes were analytically calculated given the availability of the temperature gradient data formed within each south wall of the boxes and measured every five minutes. Knowing the gradient between the interface out of the wooden panel layer and the internal surface of the south wall, on the basis of the characteristics of the materials which make up these wall portions furnishing a thermal resistance of 5.29 $(m^2 \cdot K)/W$, the specific thermal fluxes were calculated.

In this case also the comparison between the fluxes for the period between August 6th and August 13th 2004 (Figure 9-a) demonstrates the delay effect and the reduction of heat transfer due to the presence of PCM inserted in the light stratifications, as compared to those of the reference box n. 1. Similarly, in the previous case, focusing our attention on August 7th 2004 in Figure 9-b, it is possible to quantify the reduction of the maximum flux from 3.5 W/m^2 for the reference wall up to 1 W/m^2 for the wall without ventilation and approximately 1.3 W/m^2 for the wall with ventilation. The particularity that the ventilated layer apparently does not foster improvement, should be attributed to the presence of hot air in the inner ventilated layer which, in any case, contributes to the thermal gain.

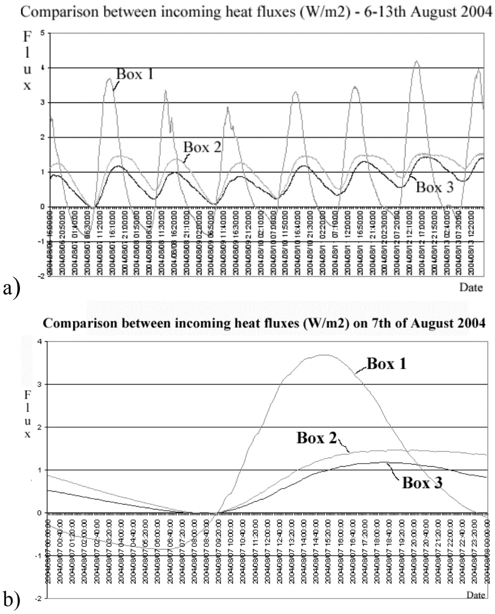


Figure 9: Comparison between the thermal fluxes of the three boxes in the period between August 6th and August 13th (a) and for August 7th 2004 (b).

3.2 Statistical analysis on the data

In order to draw quantitative conclusions, having a wide observation sample available, a comparison was carried out between the maximum thermal fluxes out of the reference box and the boxes containing PCM, estimating their difference with a 5% error level. In short, we ask ourselves what percentage decrease of the mean of the maximum fluxes can be determined by the use of PCM in a conventional wall (with or without ventilation) at a 95% confidence level. Having three data samples available, one for each wall type, containing the maximum thermal fluxes registered for each day, after having converted the flux samples from continuous to discrete, having obtained the first and second moments and after having carried out the Jarque-Bera test, it was inferred that we were in presence of normal distributions. Using the standardized Gaussian (Wonnacott et al., 1990) it is therefore possible to carry out classical hypothesis tests on the difference between the mean of the fluxes, and with a confidence level of 95%, it can be stated that the difference between the mean value of the maximum thermal flux values entering the reference box and that of the two boxes containing PCM is at least equal to the following values (only the inferior quantile is reported):

$$Q_{max1}\text{-}Q_{max2} = 2.36\ \mathrm{W/m^2}$$

$$Q_{max1}\text{-}Q_{max3} = 2.15\ \mathrm{W/m^2}$$

This, in the first case, means an average reduction of the maximum fluxes of 63% and, in the second case, of 58% at a 95 percent confidence level. Similar tests were carried out on the maximum internal superficial temperatures:

$$T_{max1}\text{-}T_{max2} = 0{,}43°\mathrm{C}$$

$$T_{max1}\text{-}T_{max3} = 0{,}51°\mathrm{C}$$

And on the time lags of the thermal peak load:

$$Q_{load1}\text{-}Q_{load2} = 3.03\ \mathrm{ore}$$

$$Q_{load1}\text{-}Q_{load3} = 2.93\ \mathrm{ore}$$

It can be noted that the three hour shift in both cases means recording the thermal peak at 5:30 p.m. instead of about 2:30 p.m., with considerable advantages in comfort. The thermal properties of light walls with PCM are similar to the ones that characterize high thermal inertia walls, e.g. masonry.

4. CONCLUSIONS

Thanks to the complex experimental apparatus it was possible to demonstrate that PCM can be the solution to the overheating problems of low thermal inertial dry assembled walls. The fact that a reduction of the maximum fluxes greater than 50 percent can be hypothesized at a 95 percent confidence level, indicates how the use of PCM can determine a drastic consumption decrease for air conditioning, making the behavior of dry assembled walls close to those of highly thermal inertia ones built using mortar, for instance. By making a comparison between the two PCM and the reference walls (32°C melting point), the first of which does not have an inner ventilated air layer and the second with a ventilated inner layer towards the exterior, we can conclude that the potential of PCM is so high that it does not necessarily require an air ventilated layer (which might however be useful for the roof) and that if we wish to improve performance the ventilation could be placed on vertical walls with PCM at a melting temperature lower than 32°C, increasing the potential for energy savings.

REFERENCES

Khudhair, A.M. and M. Mohammed 2004. A review on Energy conservation in building applications with thermal storage by latent heat using phase change materials. Energy conversion and management – An International Journal, v 45, n 2, pp. 263-275.

Kunping, L. and Z. Yinping, 2003. Modeling and simulation of thermal performance of under-floor electric heating system with shaped-stabilized PCM thermal energy storage plate. Energy and the Environment-Proceedings of the International Conference on Energy and the Environment, v 2, pp. 1069-1074.

Neeper, D.A., 2000. Thermal dynamics of wallboard with latent heat storage. Solar Energy, v 68 n 5, pp 393-403.

Principi, P., C. Di Perna, G. Borrelli and A. Carbonari, 2005. Monitoring system for the evaluation of the energetic behavior of PCM containing walls. Palenc meeting, Santorini, Greece, 19- 21 May.

Wonnacott, T.H. and R.J. Wonnacott, 1990. Introductory Statistics – fifth edition. New York-Chichester-Brisbane-Toronto-Singapore, John Wiley and sons ed.