Monitoring system for the evaluation of the energetic behaviour of PCM containing walls

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ABSTRACT

As dry assembled multi-layered walls very often suffer overheating in hot climates because of their low thermal inertia, the appropriate use of Phase Change Materials (PCM) inside the same walls can increase their thermal mass before they reach high temperatures (which they tend to do when irradiated by the sun) avoiding overheating.

Two main experimental campaigns were carried out at the "Renewable Energies Outdoor Laboratory" of the Polytechnic University of Marche (Ancona, Italy): the first outdoor experimental campaign (2003) was aimed at testing and comparing the behaviour of seven different PCM containing stratifications to a reference dry assembled wall, while the second campaign (2004) focused on the behaviour of the two PCM containing walls which gave the best results during the previous test. In the second experimental campaign, the installation of a complicated air temperature control system allowed the task of maintaining internal air temperatures at a fixed value, in this way the differences relative to the energetic behaviour between the PCM containing walls and the reference one were evaluated.

1. INTRODUCTION

Light dry assembled walls (having low thermal inertia) exposed to solar radiation and temperature differences between the outdoor environment (T_e) and the interior (T_i), with $T_e > T_i$, are the transference site of the incoming heat towards the interior and the environmental thermal load which ensues results in phase with the external climate variations.

Since three years a technological system which foresees the use of a "Phase Change Materials" (PCM) within light stratifications in order to convey adequate thermal inertia and improve their energetic behaviour is being studied in the framework of the European Commission CRAFT project entitled "C-Tide" (Changeable Thermal Inertia Dry Enclosures). In fact at the Polytechnic University of Marche theoretical and experimental studies were carried out on the thermal behaviour of PCM as eutectic salts. During the transfer of thermal energy from the exterior to the interior in light walls, the heat which penetrates the PCM layer determines its fusion and therefore the quantity of heat entering the environment is lessened. A temporal shifting of the thermal load as compared to the external climatic conditions also ensues as well. By designing the stratifications adequately, the absorbed heat can be removed using natural or forced ventilation and released almost totally towards the exterior during a subsequent phase, when the temperature differences allow it.

For intermediate latitudes, the presence of PCM in external partitions is useful during the winter season as well, due to the capacity to absorb radiation which reaches the building's external surfaces during the daytime. It can be released later towards the interior, during the hours when, because of the absence of other passive heating contributions, it is more necessary (as during the late afternoon and night-times), contributing to the heating system own function. Thanks to the thermal inertia increase it is also possible to lower the internal temperature's dependence from the continuous external air temperature and solar radiation shifts.

Furthermore, PCM has the peculiar quality that it has a high ratio between latent heat of fusion and specific weight, and this allows maintaining an excellent manoeuvrability of the dry assembled light panels, while guaranteeing them high thermal properties, similar to those of walls with high thermal capacity. The bibliography (Khudhair et al., 2004) shows that a lot of experiments have been carried out on internal elements of buildings, like PCM waxes inserted inside wallboards or PCM layers in the floors. But experiments on dry assembled light walls containing a homogeneous layer of PCM between the external finish and the insulating layer are ongoing at the "Renewable Energies Outdoor Laboratory" of the Department of "Energetica" (Polytechnic University of Marche). Two campaigns have been carried out to date: the first outdoor experimental campaign (2003 summer season) was aimed at testing and comparing the behaviour of seven different PCM containing walls to a reference dry assembled wall; after the verification of the seven experimental hypotheses, during the second outdoor experimental campaign (2004 summer season) it was opted to verify the hypotheses where the PCM demonstrated better performances (De Grassi et al., 2004). During both campaigns and for each wall, air temperatures and the ones at the interfaces of PCM containing walls were monitored; but in 2003 experimental campaign high air temperature oscillations inside boxes were monitored, caused by the use of standard split systems for air conditioning purposes, preventing a reliable comparison with the reference box because the internal boundary conditions were not the same for each of them. In the 2004 experimental campaign that problem was solved with the installation of an air temperature control system, with the task of maintaining internal air temperatures at a fixed value of about 25°C, with an oscillation range lower than 0.2°C and a thermal gradient inferior to 1°C, that guaranteed the creation of the same internal environmental condition for each box. In this way the comparison between PCM containing walls and a reference wall without PCM was evaluated.

2. EXPERIMENTAL DEVICES

In order to simulate buildings, eight parallelepiped shaped identical boxes were built at the "Renewable Energies Outdoor Laboratory" (Fig. 1) with 3 m sides and identical building characteristics. The only exception is the south facing wall as the one built with the different stratifications containing PCM; the boxes' positioning was chosen so that the shadow cast by each would not cause interference with the others; they were positioned on rectangular plan concrete platforms in order to isolate them from the ground.

The south facing walls were built with variable stratifications borne by a metal structure: in order to lower the number of parameters to keep under check, the first three wall layers facing the interior were built with the same geometric and physical characteristics for each box (Fig. 2):

- 0.025 m thick plasterboard panel;
- 0.225 m thick mineral wool insulation;
- 0.02 m thick wooden panel covered by an outside vapour barrier.

The other exterior facing layers were instead differentiated according to the box, with a

Figure 1: The "Renewable Energies Outdoor Laboratory".

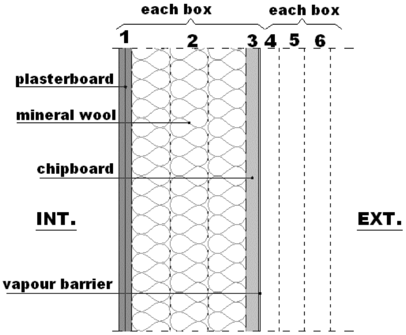

Figure 2: Portion of south walls common to all the boxes (first three layers facing the interior).

Table 1: 4°, 5° e 6° layering of the south walls of the eight boxes.

N° of box	N° of layer	Layer	Thick (m)
1	4	Cement aggregate panel	0.025
	5	Absent	-
	6	Absent	-
2	4	Ventilated air layer	0.05
	5	PCM 48°C melting layer	0.03
	6	Cement aggregate panel	0.025
3	4	PCM 48°C melting layer	0.03
	5	Cement aggregate panel	0.025
	6	Absent	-
4	4	PCM 32°C melting layer	0.03
	5	Cement aggregate panel	0.025
	6	Absent	-
5	4	Ventilated air layer	0.05
	5	PCM 32°C melting layer	0.03
	6	Cement aggregate panel	0.025
6	4	PCM 32°C melting layer	0.03
	5	Ventilated air layer	0.05
	6	Cement aggregate panel	0.025
7	4	PCM 36°C melting layer	0.03
	5	Steel sheet layer	0.002
	6	Absent	-
8	4	PCM 36°C melting layer	0.03
	5	Not ventilated air layer.	0.08
	6	Plexiglas layer.	0.005

maximum of three; Table 1 lists the layers making up the portions of the external stratifications: it should be noted that only the south wall of box n. 1 does not contain PCM (as this is the reference box). The other walls and the roofs were all built using sandwich panels made with 2 aluminium sheets and a 0.12 m internal layer of mineral wool.

3. MONITORING SYSTEM

The air within the boxes was monitored using ten “T” type constantan-copper thermocouples with shielded finish and connected to the analogical inputs of the datalogger (Datataker DT 500 series 3) having 10 analogical inputs, and 4 digital input-outputs installed within the boxes. The dataloggers were equipped with a “memory card” capable of obtaining up to $3.5 \cdot 10^5$ data units in a 1 Mb card. The data were memorized in a PC using Delogger software for elaboration aims. The datalogger can be programmed and it can manage digital signals which can be used to turn on the alarms. Each datalogger was connected in series to two channel expansion modules (CEM series 3) in order to have up to 30 analogical inputs, 44 digital inputs and 10 relay outputs (Fig. 3). Nine “Pt 100” resistance thermal detectors (RTDs), with 0.1°C sensitivity, were installed for measuring internal surface temperatures of all the walls, the roofing, pavement and the external surface of the south wall. As previously specified, a split system for stabilizing air temperature was installed in each box. The atmospheric conditions were monitored by a specific meteorological station equipped with:

Figure 3: The datalogger and the channel expansion modules inside a box.

- 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).

The experience gained during the 2003 experimental campaign highlighted the need to improve the stability and uniformity of the temperature inside the boxes, in fact, the analysis of the data demonstrated an oscillation of the air temperature around the 25°C position up to 3°C, with differentiations among the different boxes. Tests were carried out even with the split system deactivated and it was demonstrated that on the average the PCM improves the comfort conditions in the internal environment of the experimental boxes, carrying out both a qualitative (Lemma et al., 2004) and statistical (De Grassi et al., 2004) comparison between the data relative to the reference box and those with PCM. In particular it became evident that the presence of PCM lowers the internal superficial temperature of the walls and the thermal load peak, besides delaying the heat wave as compared to the reference wall. In order to improve the stability of the temperature an air temperature control system was installed during the 2004 experimental campaign; the experiments were repeated on models of the walls n. 4 and n. 6, which in 2003 were the ones which demonstrated to be the most energy efficient.

Improvements applied to the 2004 experimental set up

On the basis of the 2003 experiences the following changes were applied to the boxes:

- the walls which were not facing south were ceiled using 0.1 m thick polystyrene panels and then covered with a reflecting sheet (absorbance α = 0.4) in order respectively to make those walls approximately adiabatic and to reduce the effect of solar radiation to a minimum;
- the thermal insulation of the floor was increased in order to make its superficial temperature even to that of the other walls;
- an internal air temperature control system was set up in order to make internal temperature constant and even, as described below.

A control system capable of keeping indoor temperature stable around a constant 25°C value was designed. Therefore, the *controlled variable* is the average temperature of the internal air, calculated by the recordings of the nine thermocouples dislocated within the boxes at three different heights and distributed in order to monitor all the boxes’ control volume. In order to avoid the formation of temperature gradients, it was opted to use a suitable actuating device, which instead of using the air jet of the split system directly, was realized through the interposition of eight fans installed on a partition between the control volume and the technical one (containing the split system with a refrigerating power 3010 frig/h = 3500 W); the fan lay out at three different heights guaranteed an uniform distributed air flow (Fig. 4). The wall between the two rooms is made up of a double plasterboard panel on a metal structure with 0.05 m thick polystyrene layer interposed in order to minimize the heat transfer between the technical volume and the control volume when the fans off. The fan power was designed using Visual-DOE 3.1 software, which allowed forecasting that under the least favourable climatic conditions, occurred at 5:00 p.m. of August 6th 2004, the thermal load can be discharged by introducing, via 4 fans, 700 mc/h of air at a temperature of 1.5°C lower than that of the control volume.

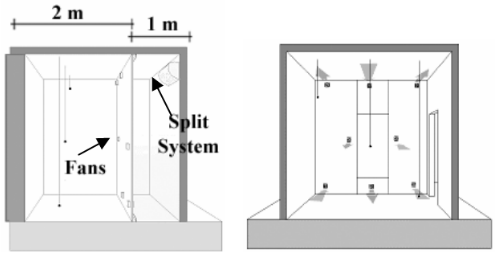

Figure 4: Internal layout of the boxes, with the partition and the position of the fans.

A *feedback* control system can be made up of two chambers containing hot and cold air to be inserted in an environment according to whether we wish to raise or lower its temperature; a measuring device for the controlled variable; a comparator and compensator; an amplifier for transmitting the signals and an actuating signal device for turning on the fans. As the measurements obtained during the 2003 campaign demonstrated that the internal air never fell below 25°C, and wishing to keep the air temperature at this value, it was decided that only the cold air chamber would be used. The cold air is kept constant at the temperature of 23.5°C in a technical volume containing the split system, to then be supplied to the control volume when needed. Two main advantages can thus be obtained:

- the activation of the split system does not interfere with the south wall given that it does not set off convective motion in the control volume;
- as the air temperature in the two rooms is almost the same, activating the fans does not determine any relevant drops in temperature.

In order to simplify the control system from multivariable to single-variable discrete-time one, it was decided that the mean air temperature of the control volume should be monitored at pre-established time intervals, instead of for every single thermocouple, given that the diffusion of the air supplied by the fans guaranteed the annulment of the thermal gradient. The final control system is thus made up of (Fig. 5):

- *measuring device* of the data relative to the controlled variable, given by the combined system of nine “T” type thermocouples +

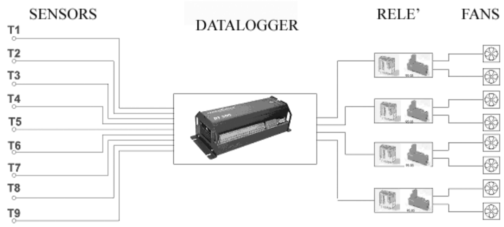

Figure 5: Structure of the control system.

channel expansion modules + datalogger, capable of converting the tension recorded by the thermocouples into temperature;

- *comparator* which compares the recorded temperatures with the reference one (25°C), to possibly turn on the fans (datalogger);
- *compensator*, also made up by the datalogger which, following the instructions of an algorithm, chooses the type of corrective action to be followed (it can also be null);
- *signal amplifier*, a series of “relay finder 40.50”, which transformers the steady state current sent by the datalogger through the “open collector” type (12V with a maximum current of 8 A) into the current needed for supplying the fans’ functioning apparatus;
- *actuating signal device*, made up of the whole of the “mod. 12321 M120/5 A” fans with progressive self-locking device, capable of supplying cold air and discharging hot air from the control volume.

The control systems’ algorithm (Fig. 6) was conceived with two factors in mind: the delay between the temperature recording and the air temperatures’ trend inversion; the considerable entity of the thermal loads during the hours of maximum exposure to sunlight.

Both the first and second factor require that the first fans be activated at a temperature inferior to the one to be kept in the environment (24.8°C as compared to 25°C), to then increase the effect in case the trend inversion has not occurred. Setting off the apparatus (each apparatus is a pair of fans, one of which supplies air in the control volume and the other discharges it) takes place progressively activating a pair of fans at a time when the registration of the temperature at time-step “t” encounters a 0.2°C increase as compared to the previous recording and if this same temperature is higher than 24.8°C. Over sizing the system mainly favoured the use of a low number of fans, which were simultaneously activated only during the major thermal load hours.

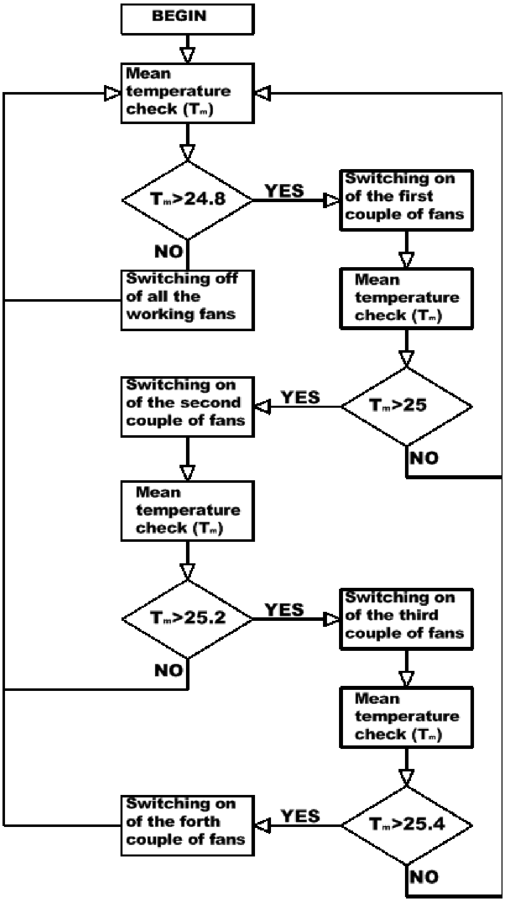

Figure 6: Control system functioning algorithm.

4. EXPERIMENTAL RESULTS

The diagram of the internal temperatures recorded every 300 seconds (Fig. 7), illustrates that the air temperature oscillations are reduced to a minimum and never topped 0.2° C around the 25 °C value.

Furthermore, the gradient within the monitored control volume never topped the degree unit (Fig. 8). This experimental apparatus allowed recording the superficial temperatures of the wall without oscillations around the equilibrium position (Fig. 9).

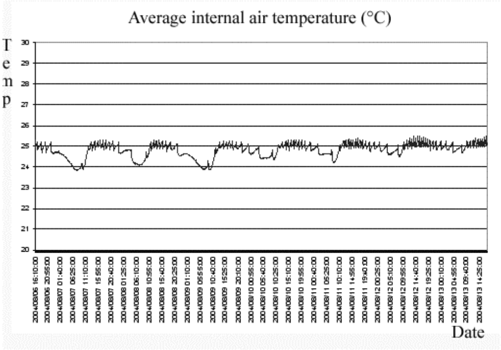

Figure 7: Average air temperature inside Box 4 between August 3rd and 8th 2004.

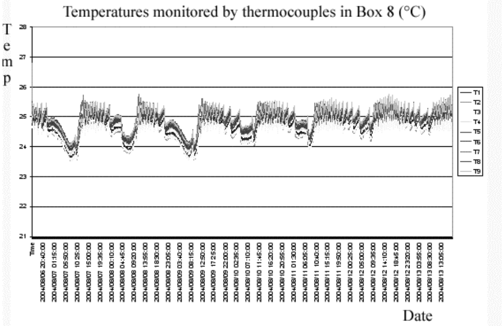

Figure 8: Temperature course recorded by the 9 thermocouples in Box 4 between August 6th and 13th 2004.

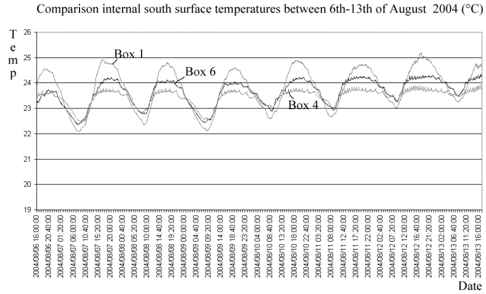

Figure 9: Internal superficial temperatures of the south walls of the three experimental Boxes between August 6^{th} and 13^{th} 2004.

5. CONCLUSIONS

The control system adopted for the conditioning of the indoor air seems to be particularly suitable for small sized experimental environments inserted in summer climates. Thanks to its use it was possible to carry out a comparison between a wall without PCM and other two with (but with different stratifications) at same internal boundary conditions (and obviously external ones as well). It guaranteed the possibility to estimate the considerable advantages in terms of the reduction of the maximum incoming fluxes (Principi et al., 2005), whose estimate was possible thanks to the stabilization of the walls’ internal surface temperature. In this manner the comparison between the energetic behaviour of the different walls was carried out at identical conditions and therefore avoiding the distortion of the evaluation which could have caused by the concurrence of different uncontrolled phenomenon.

REFERENCES

De Grassi, M., A. Carbonari and G. Palomba, 2004. A statistical approach for the analysis of thermal contribution of artificial programmable inertia walls, XXXII IAHS World Congress, Trento, Italy.

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.

Lemma, M., F. Mori and N. Torcianti, 2004. Experimental evaluation of planned thermal inertia walls. XXXII IAHS World Congress, Trento, Italy.

Principi, P., C. Di Perna, G. Borrelli and A. Carbonari, 2005. Experimental energetic evaluation of PCM containing walls with changeable thermal inertia. Palenc meeting, Santorini, Greece, 19- 21 May.