

Improving energy efficiency through artificial inertia: the use of Phase Change Materials in light, internal components

Marco Imperadori¹, Gabriele Masera², Giuliana Iannaccone³, Davide Dell'Oro⁴

¹ Professor, Engineer, Dipartimento BEST, Politecnico di Milano, Milano, Italia

² Senior Researcher, Engineer, Dipartimento BEST, Politecnico di Milano, Milano, Italia

³ PhD, Architect, Dipartimento BEST, Politecnico di Milano, Milano, Italia

⁴ PhD Student, Engineer, Dipartimento BEST, Politecnico di Milano, Milano, Italia

ABSTRACT: Phase Change Materials (PCM's) are characterised by a large thermal capacity and by melting temperatures close to those associated with human comfort. Thanks to the "artificial inertia" they can give a building, they can be used in components such as wallboards, floors, etc. in order to:

- store free heat gains during winter days and release energy during the night;
- reduce overheating risks in summer, especially in well-insulated Structure / Envelope constructions (Str/En) with poor thermal capacity (lightweight construction), thanks to the peak-shaving effect;
- store off-peak energy – both in winter and summer – in order to have, during the day, a warm / cool surface that contributes to irradiative comfort in winter / summer.

An extensive experimental campaign was set up in Ancona (I) and Gävle (S) during the EU-FP5-funded research called C-TIDE (Changeable Thermal Inertia Dry Enclosures), involving Politecnico di Milano, Università Politecnica delle Marche, BMG and three SME. Different configurations were studied and tested on site, allowing to understand the potential for integration of hydrated salt PCM's in lightweight floors and internal partitions. The experimental campaign included:

- prototyping a specific packaging system based on aluminium pouches (the "PCM blanket");
- testing the blanket – both in wall and floors – in experimental boxes with controlled temperature conditions;
- testing the implication of sandwiching the blanket in a traditional plasterboard wall from the point of view of assembly procedures, time, everyday use, etc.

The results, which were supported by mathematical modelling using the FDM method, show a good potential for integration of PCM's in light plasterboard components. PCM's work as a thermal flywheel, reducing the peak loads (for heating and / or cooling) and energy consumption.

Keywords: high energy-efficient buildings, comfort, artificial thermal inertia, phase change materials, technology transfer, structure-envelope techniques.

1. INTRODUCTION

In the last years, the building sector has been undergoing significant changes as concerns both building techniques and energetic strategies. This trend is confirmed by EU directives; in particular, the 93/76 one regarding the emission of CO₂, estimates that over 40% of the global energy consumption can be attributed to the Building Construction sector. Moreover, the sector contributes heavily to GHG emissions. The positive aspect is that there is wide scope for improving its energetic performances, simply using technologies that are already available on the market, such as thermal insulation, efficient glazing, ventilation systems with heat recovery, and so on. Through the exploitation of renewable sources and the optimization of the buildings' thermal behavior the same Directive maintains that it is possible to reduce this consumption level to 22%.

On the other hand, performance requirements are growing higher because of both more stringent

regulations and higher comfort requirements by the users – the spreading use of air conditioning systems, also in houses, is just an example of this trend.

These two issues mean that a deep reconsideration of how buildings are designed and built is required, in order to provide high performance levels with a limited environmental impact – which is simply the definition of *sustainable development* applied to buildings.

As energy consumption decreases, the solutions adopted need to be more climate-specific, in order to capitalise the on-site conditions of temperature, sun radiation, prevailing winds, shading and so on. In Italy, cold winters are followed by mild mid-seasons and by quite hot summers, with limited temperature excursion between day and night. Here low-energy buildings, on these bases, need to be both "conservative" in winter, "protective" in summer and "neutral" during the mid-seasons, when comfort can be obtained by simply opening the windows: a clear

example of what can be called a *climate sensitive approach*.

2. THE C-TIDE RESEARCH

2.1 The issue of summer cooling

A basic strategy required to save energy for cooling is the reduction of overheating inside the building – and this should be considered *before* deciding what kind of system to adopt for cooling. Apart from efficient shading of the glazed areas, the use of thermal mass is critical in order to control temperature peaks and the cycle of temperature during the day, so reducing the load on the cooling system.

It is possible to identify two very distinct ways of using thermal mass:

- the first is when the envelope of the building is not extremely insulated: in this case, a thermal mass in the wall can help delay and smooth out the incoming heat flow by solar radiation – this is what happens in thick wall constructions;
- the second is that of an internal thermal mass that contributes to the storage of energy during the day (also in winter) and releases it during the night, when the air temperatures are supposed to be lower. In well-insulated buildings, this is the most important issue about thermal inertia as the wall is almost adiabatic and the heat flow through it is practically eliminated. The required storage capacity is low, as energetic inputs are relatively small.

2.2 Phase Change Materials for light constructions

The use of mass in summer cooling strategies, anyway, needs to be considered against recent trends in construction technologies, particularly hyper-insulation. A very clear trend is the one towards so-called Structure / Envelope construction, that is dry-assembled, light, layered solutions assembled on steel or wood sub-structures independent from the load-bearing structure. This construction method, very much removed from traditional, massive techniques, allows for high performance levels with a reduced use of materials, the possibility of selective dismantling and recycling of components, low embodied energy processes, and so on, and is spreading widely in Central European areas.

The EU-funded CRAFT research called C-TIDE (*Changeable Thermal Inertia Dry Envelopes*) moved in 2002 from the consideration of the opposite requirements deriving from the advantages of thermal mass (which is obtained, in general, through heavy elements) and from those of light Str/En construction.

The basic idea was the integration in light buildings of *Phase Change Materials* (PCM), that are salts or paraffins that undergo a phase change process (that is, a reordering of the microstructure) involving the storage, or release, of latent heat.

PCM's could then be used in order to obtain thermal storage elements that do not add unnecessary weight to the construction and that – what is more – can be *tuned* to have a melting temperature coherent with the human comfort necessities. If the PCM is made to store heat at a

useful temperature (both from the sun or from a vector fluid, such as hot water), this means that it will maintain *that temperature level* until the whole phase change process has taken place, so reducing overheating (in summer) or cooling (in winter) of the interior environment. A sort of “programmable inertia” can thus be obtained by regulating the melting temperature and the quantity of PCM's in the building. C-TIDE research was two years long (November 2002 to November 2004) and involved some building component and PCM manufacturers (Vanoncini S.p.A. and Impresa Pietro Poggi from Italy, Climator S.A. from Sweden) and, as academic partners, Politecnico di Milano and Polytechnic University of Marche from Italy and BMG Gävle from Sweden.

A great deal of work – among other research themes – went in the study of a technical solution that would be suitable for the inclusion of a PCM layer in the stratification of a light building element, such as an internal plasterboard wall or a floor. The main problems concerned:

- the durability of the packaging element: PCM's should be in an air-tight container to maintain their physical properties, otherwise in time the melting process does not take place anymore;
- the morphological compatibility of the packaging elements with the other components of the technical element (wall, floor, etc.);
- the easiness of installation of the PCM element, which should not require particular expertise by the workers in order to fit smoothly in the assembly process of the building element;
- the limitation of damages to the solution in case one of the packaging elements fails.

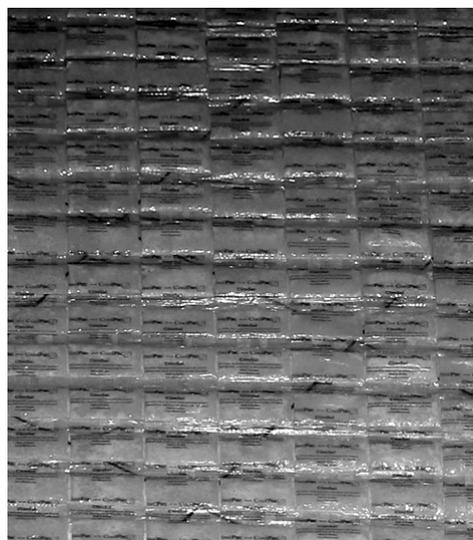


Figure 1: The PCM blanket

The output of this process was what is called a "PCM blanket", that is a series of pouches containing PCM, of limited thickness to improve heat exchange with nearby elements, welded in series in order to obtain a continuous element (figure 1). Each pouch is some 8 x 4 cm wide, while the blanket is to be produced in a modular size of about 100 x 50 cm. The main advantage of using small-size pouches, besides *limiting the effects* of a damaged element, is that the blanket can be *easily cut* to the required dimensions following the welding lines, without the use of any special tools – apart from a cutter.

2.3 The PCM blanket in a radiant floor

One of the possible uses that was imagined for the PCM blanket is an underfloor application, integrated to a radiant heating or cooling system (figure 2). In this sense, the blanket would replace the thermal mass traditionally obtained through concrete elements, giving the added benefit of being able to design both the operating temperature of the system and its thermal capacity according to the specific situation.

The technical solution is composed by two layers of the PCM blanket with the water pipes embedded between them in order to enhance heat exchange between the surface of the pipes and the PCM contained in the pouches. The upper surface is then made smooth through a thin self-levelling screed, where the floor material can be laid.

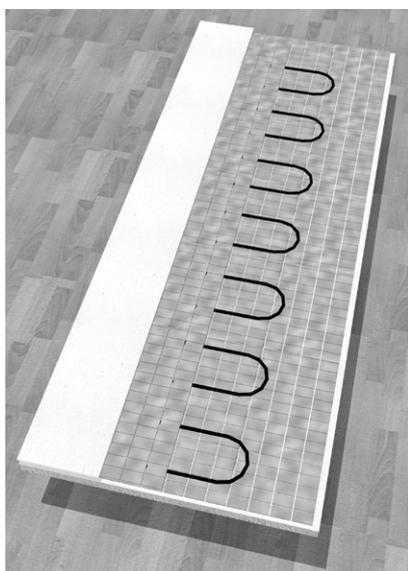


Figure 2: The underfloor radiant system

The basic idea was to maintain the floor at a more or less *constant temperature*: that of the melting point of PCM contained in the blanket. In summer, the floor heats up, because of the radiation from the sun entering the windows, but when it reaches the melting temperature the phase change process begins. Then, the energy gained from the sun is used in latent form, while the temperature of the PCM layer remains constant.

If the melting temperature is accurately chosen, during the phase change process the floor *works as a*

radiant surface at a comfortable temperature for the users of the building. Most of the energy coming from the sun is thus used for PCM melting instead of increasing the air temperature inside the building. When PCM's are completely melted, or night has fallen, cool water circulating in the floor is used to activate the inverse process of solidification (discharging of the PCM layer by taking latent heat away). In this way, the PCM element is ready for another storage cycle, be it the same day or the next morning.

If the melting temperature is well chosen, a similar strategy can be used also in winter, with hot water used to warm up PCM's, which then release heat to the internal environment. In both seasons, anyway, it is clear that the idea is to integrate closely the PCM element and the heating / cooling system, in order to reduce its peak load and the time it needs to work: *the PCM blanket helps the radiant system work less.*

The hypotheses at the base of the C-TIDE product development were tested at real scale, during the summers of 2003 and 2004, in some experimental boxes built for this purpose at the "Renewable Energies Outdoor Laboratory" of the Department of "Energetica" of the Polytechnic University of Marche, Ancona, Italy. The boxes are cubes, approximately 3 m wide, built in insulated sandwich panels and very well insulated in order to reduce heat gain through the walls. Two of these boxes were specifically devoted to the experimentation of the underfloor PCM system, and included a large south-facing window simulating heat gain in a current house. The reference box was "neutral", in the sense that it did not include neither PCM's nor the radiant system, while the experimental box included the underfloor system as described above. Cooling water was extracted directly from the water distribution system of the city, so it entered the floor at a temperature of around 14°C.

The monitoring campaign showed that the presence of PCM inside the floor can reduce overheating, thanks to the floor surface that absorbs solar radiation entering the south-facing glass. Results show a significant temperature difference in the peak temperatures between the test box and the one with underfloor PCM. After 4 pm of each day, when PCM were completely melted, cool water was circulated in the floor in order to obtain the inverse process of solidification. This allowed to have the PCM elements ready for the next storage cycle the day after.

2.4 The PCM internal wall blanket

Another use for PCM blanket is a wallboard application, integrated between two plasterboard layers fixed to a metal sub-structure.

The integrated wallboard could be simply assembled by ordinary workers, without changing the assembly process of a normal plasterboard wall.

The installation sequence could be identified as follows:

1. Assembly of partition wall sub-structure
2. Boarding (inner layer)
3. Application of PCM blanket
4. Boarding (outer layer)
5. Finishing of outer faces



Figure 3: The installation of the blanket.

Installation of the metal sub-structure and boarding do not present any specificity when compared to traditional plasterboard construction.



Figures 4-5: Assembly of metal substructure and inner layer.

As concerns the PCM blanket module, this should be hung from the top of the board. One side of the upper reinforcing tape (600 mm wide) should be positioned in coincidence with a side of the mounted board. The dimension of the blanket is designed in order to use two modules for one plasterboard. Hanging of the board should be performed by drilling screws in the upper reinforcing tape strip. In particular situations (edges, openings, particular geometries, crossing elements, etc.), the blanket should be adapted by removing strips of pouches, or single pouches, by a cutter knife along the welding lines. Care should be taken in order to avoid breaking the remaining pouches. The blanket modules are designed so that the screwing lines corresponding to the vertical studs behind remain visible after their installation, in order to ease application of the external board. The difference in thickness should be compensated by strips of pressed mineral wool glued to the board.

Installation of these strips is mandatory to avoid loss of planarity in the finished surface.



Figures 6-7: Application of PCM blanket.

Final boarding of the outer face allows to finish the surface and prevents melted PCM to fall towards the bottom of the pouches. This has to be avoided in order to allow a homogeneous behaviour of the wall and to prevent segregation of the salt.



Figures 7-8: Outer layer boarding and finishing.

2.5 Installation test of the internal wallboard

During the experimental campaign of the C-Tide research, a sample of internal wall board was tested applying layers packaged in blankets containing PCM to provide artificial thermal inertia.

The internal wallboard was 120 cm wide, following the modularity of the metal substructure (studs at 600 mm centres) and 310 cm high, according to the height of the test room.

All the tests showed the good performances of the internal wall blanket allowing its installation.

At the end of test campaign, a part of the plasterboard, close to the floor, was removed in order to evaluate possible straining of melted salts. Test showed that PCM inside the wallboard were perfectly placed inside the pouches and perforations on these induced a light halo confined to the damaged.

During the test with expansion plug, a part of the wallboard was milled at the opposite side of the fixture to assess if Climsel pouches could interfere or impede the anchor.

The test showed the complete absence of interference of PCM and the success of the system. Coring on the wallboard was made to allow the placing of boxes of the electrical equipment. This operation pointed out an occlusion of the auger machine because of the deposit of salts, but it wasn't a problem.



Figures 9-10: Coring of the wallboard.

Several load tests was carried out to verify the performance of the internal wall blanket compared to a normal one.



Figures 11-12: Load and breaking tests.

3. THEORICAL SIMULATION ON THE PASSIVHAUS IN CHIGNOLO D'ISOLA (BG)

The first Italian Passivhaus (space heating less than 15 kWh/m² /year) was built in 2003 in Chignolo d'Isola, close to Bergamo.

Low energy consumption was achieved through efficient enclosures (hyper-insulated envelopes and low-emissivity windows) and ensured a high standard of thermal comfort in winter. Conversely, a HVAC system was required to maintain desired summer time indoor environmental conditions.

In order to study the effects of the PCM-based enclosures and partitions on the indoor climate, a dynamic numerical simulation was performed on this building.

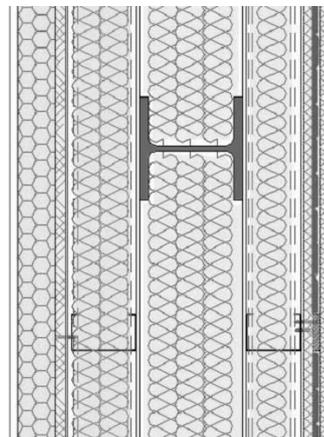


Figure 13: An example wall PCM layer on the right hand side.

An explicit finite difference method was used for the simulation. The building was divided into elements of finite dimensions. The heat balance for each element was calculated by hypothesizing that the thermal capacity of the element is condensed into one point and the heat transfer with the adjacent element is linearly dependent on the temperature difference between the two nodes. The building model is therefore composed by a network of resistances and capacitances.

In order to accurately determine the transition phase the specific heat capacity of the phase change material node was expressed as function of the temperature. Still the shape of the curve was manually determined as there is no $c_p(T)$ curve available at the moment. The thermal conductivity, instead, was supposed to be constant over the temperature interval. A carefully determined time step was used to ensure the stability of the simulation.

Calculations showed that PCM walls allow for energy savings through reducing HVAC operational time. However if used in a passive way, PCM only facilitates desirable thermal comfort conditions for short periods of time.

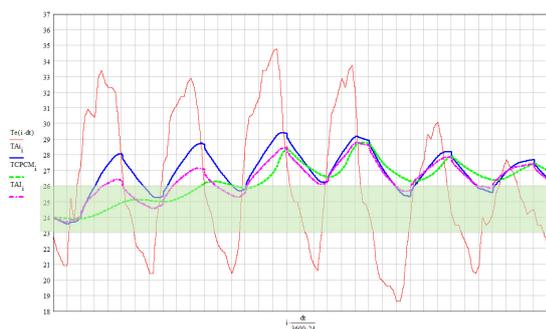


Figure 14: The range of comfort temperature levels during 6 days in summer time – PCM walls used in a passive way. From the 3rd day on, discharging does not happen anymore.

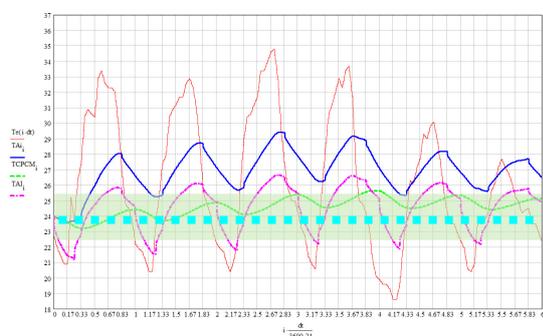


Figure 15: The range of comfort temperature levels during 6 days in summer time – PCM walls used with HVAC system. The indoor environmental conditions are completely satisfied.

4. CONCLUSIONS

From the technical point of view, the project involving the design, manufacture and preliminary testing of an innovative PCM floor system may be judged as satisfactory. The performance of the system has been confirmed by an experimentation campaign lasting a full summer season. The PCM blanket is now under production from one of the partners of the C-TIDE research, while further studies are under way to assess the possible use of PCM in low-energy buildings for warm climates.

REFERENCES

[1] Hed. G.; Bellander R. – *Mathematical modelling of PCM air heat exchanger*, in «Energy and Building», n. 39, 2006, pag. 82-89.
 [2] Imperadori, M.; Masera, G.; Lemma, M. – *Super-efficient energy buildings*, Proceedings of XXXI IAHS World Congress on Housing, Montreal, Canada, 2003.
 [3] Jóhannesson G. – *Active Heat Capacity, models and parameters for the thermal performance of buildings*, Lund Institute of Technology, Lund, 1981.
 [4] Jóhannesson G. – *Lectures on Building Physics, Heat and Moisture Transfer*, Kungliga Tekniska Högskolan, Stockholm, 2004.

[5] Lemma, M.; Torcianti, N.; Imperadori, M.; Masera, G. – *Gli involucri sensibili: progetto e costruzione di pareti ventilate ad inerzia variabile (Sensible envelopes: design and construction of ventilated façades with variable inertia)*, Proceedings of international symposium “Involucri quali messaggi di architettura” (“Building envelopes as architecture messages”), Naples, Italy, 2003.

[6] Lemma, M.; Imperadori, M. – *Phase Change Materials in concrete building elements: performance characterisation*, Proceedings of XXX IAHS World Congress on Housing, Coimbra, Portugal, 2002.

[7] Principi, P.; Di Perna C.; Carbonari, A.; Borrelli, G. – *Experimental energetic evaluation of changeable thermal inertia PCM containing walls*, Passive and Low Energy Cooling for the Built Environment, (PALENC 2005), Santorini Island, Greece, 2005.

[8] Principi, P.; Di Perna C. – *First theoretical and experimental data referred to the energetic behaviour of building component utilising Phase Change Materials*, Proceedings of 5th International Congress Energy, Environment and Technological Innovation (EETI 2004), Rio de Janeiro, Brazil, 2004.

[9] Principi, P.; Di Perna C.; Carbonari, A.; Borrelli, G. – *Monitoring system for the evaluation of the energetic behaviour of PCM containing walls*, Passive and Low Energy Cooling for the Built Environment, (PALENC 2005), Santorini Island, Greece, 2005.

[10] Principi, P.; Di Perna C.; Carbonari, A.; Ferrini, M. – *Validation of Numeric finite Element Calculation Model Through the Laboratory experimentation of Artificial Programmable Inertia Walls*, Proceedings of XXXII IAHS World Congress on Housing, Trento, Italy, 2004.

[11] Principi, P.; Di Perna C.; Carbonari, A.; Masera, G. – *Experimental analyses of the thermal behaviour of an underfloor latent heat storage system*, Proceedings of XXXIII IAHS World Congress on Housing, Pretoria, South Africa, 2005.

[12] Re Depaolini, C., *Materiali a cambiamento di fase applicati all'edilizia*, tesi di laurea, Relatore prof. Giuseppe Turchini, Correlatore Prof. Marco Imperadori, Politecnico di Milano-Polo Regionale di Lecco, a.a. 2004-2005.

[13] Zambelli, E.; Imperadori, M.; Masera, G. – *Artificial programmable inertia for low-energy buildings: integrating Phase Change Materials in building components*, Proceedings of XXXII IAHS World Congress on Housing, Trento, Italy, 2004

[14] Zambelli, E.; Imperadori, M.; Masera, G.; Lemma, M. – *High energy-efficiency buildings*, Proceedings of the 4th international symposium on Heating, Ventilating and Air-conditioning ISHVAC 2003, Beijing, China, 2003.