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Phase change materials applications to optimize cooling performance of buildings in the Mediterranean area: a parametric analysis

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Abstract

Building integrated thermal energy storage systems cover a wide range of techniques and solutions depending on technology applications and aims. They however all have in common the concept behind: being able to store energy for later use in order to reduce the time mismatch between energy availability and demand. In this context, Phase Change Materials (PCMs) fit the above description, since they would allow for mostly isothermal phase change within normal thermal comfort range. In order to face the typical challenges of the Mediterranean climate, the following concept was elaborated: the idea is to use the phase change mechanics as a substitute to the thermal inertia of massive walls to obtain a similar effect in lightweight structures. A simulated test room was arranged and through parametric analysis the potential of PCM for energy efficiency in connection to natural ventilation strategies was assessed. Simulation results vary according to the configuration analysed but in all cases, cooling consumption reduction reached at least 40% with the use of PCMs. Air Temperature during peak hours in summer can be reduced by more than 7-8°C.

Keywords: Building simulation, Phase change materials, Energy Plus, energy storage

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1. Introduction

The building sector involves over one-third of all final energy and half of global electricity consumed on a global scale. As a result, it is also responsible for approximately one-third of global carbon emissions. With an expected increase of 2.5 billion people by 2050 in the world population and given improvements in economic development and living standards, energy use in the buildings sector is set to rise sharply, placing additional pressure on the energy system.

Energy storage [1] can supply more flexibility and balancing to the grid, providing a back-up to intermittent renewable energy. Locally, it can improve the management of distribution networks, reducing costs and improving efficiency. In this way, it can ease the market introduction of renewables, accelerate the decarbonisation of electricity, improve the security and efficiency of electricity transmission and distribution (reduce unplanned loop flows, grid congestion, voltage and frequency variations), stabilize market prices for electricity, while also ensuring a higher security of energy supply.

The thermal mass of buildings makes possible to store a certain amount of heat. Depending on the amount, distribution, speed of charging/discharging, etc. of the thermal mass it is possible to postpone heating or cooling for a certain period of time without jeopardizing the thermal comfort in the building. If a building is excessively heated/cooled within the comfort band of the room temperature prior to a shutdown of heating/cooling it is possible to prolong the shutdown period. Substituting part of the thermal mass with phase change materials aims to reproduce the peak shaving and delaying for thermal waves typical of massive structure through the phase change mechanism. Multiple PCMs are commercially available that vary in type (salts, paraffins, fatty acids), encapsulation technology (micro and macro encapsulation), and melting temperatures (18-40°C). PCMs represent a potential contribution for reducing peak loads and heating, ventilation, and air conditioning (HVAC) energy consumption in buildings. The use of latent energy storage systems may be one of the solutions to cope with mis-match problems in Net Zero Energy Buildings [1-7] when energy supply and demand are out of phase.

2. Methods

The study aims at assessing the potential for the use of phase change materials as construction material, to be mainly regarded as thermal energy storage. The aim of the analysis is to reduce temperature fluctuations in an indoor environment aiming to obtain a more inert space to enhance the indoor comfort conditions in an energy-efficient way.

The increase in thermal capacitance of the walls would yield much different results as different climates are investigated: the main focus in this study is limited to perform an analysis to the Mediterranean context. The site chosen for the parametric analysis is the city of Palermo in Sicily (Italy), characterized by typical Mediterranean climate, with hot, dry summers and cool, moderately wet winters. An already calibrated model described in [8] is utilized to expand the field of results through parametric analysis in order to obtain a more detailed insight on the thermo-physics of such applications in buildings.

2.1. Modelling

A single thermal zone was created in Energy Plus. The test room is a parallelepiped with dimensions of 2.80m in width, 1.30m depth, 2.44m height. A large square window is on the south oriented façade with a U value of 1.1 W/(m^2 K) (around 50% of the overall south exposed surface). All the opaque surfaces of the test room have around 0.3 W/(m^2 K) U values, while being mainly composed on insulation materials, thus with low thermal capacitance values.

The choice of the construction characteristics aims at exploring the possibility of obtaining indoor temperature within the comfort range also in low-weight structures through the use of PCMs in Mediterranean countries. In order to face the typical challenges of the Mediterranean climate [9], the following concept was elaborated: the idea is to use the phase change mechanics as a substitute to the thermal inertia of massive walls to obtain a similar effect in lightweight structures.

Natural ventilation is modeled through the “Zone: Wind and stack object” in EnergyPlus. Such scenarios use empirical formulations to correlate wind angle and speed, fenestration areas and opening factors to calculate the air change rate. The control system chosen has some boundary values outside which ventilation is not provided to improve indoor comfort while neglecting high heating consumption increases in shoulder months: indoor temperature should be higher than 21°C, while outdoor temperature should not be lower than 15°C. Heating and cooling ideal loads setpoints are respectively 20 and 26°C.

Energy Plus allows for modeling of PCM through an implicit finite difference scheme (Crank Nicholson) coupled with an enthalpy-temperature function to account for phase change energy accurately. The PCM wax implemented in the model for the analysis has a non-isothermal phase change behavior, occurring mainly between 23 and 26°C described in Fig.1.

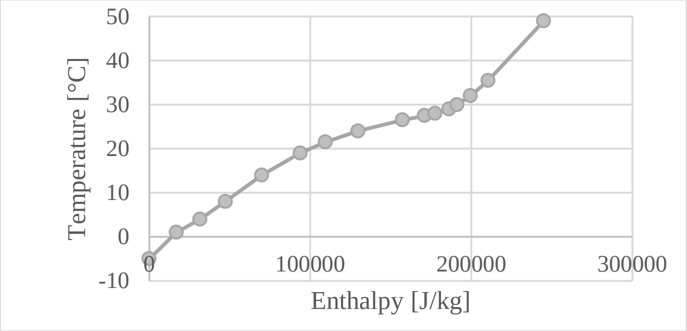

Fig.1 Enthalpy Curve for the modeled PCM

2.2. Concept and Parametric analysis

PCM [2] would cover every internal opaque surface of the building, in order to receive the external thermal wave and use the conductive heat transfer to melt it with a nearly constant temperature environment on the inside of the test room. This solution would however need a careful handling of the heat charge and discharge cycles with use of ventilative cooling during the hottest season at night. Since the main factors playing a role in the thermodynamics of the test room are PCM positioning, solar radiation and ventilation, the proposed parametric analysis explores the influence of the geometrical positioning of the PCM, of the variation of window-to-wall ratios (WWR) for the south oriented facade and of natural ventilation scenarios on the energy performance of the test room.

Table 1 – Scenarios investigated

Scenario	**Description**
S1	Base case, real configuration of the test room (60% WWR), the PCM layers are removed;
S2	PCM placement described in paragraph 2.2;
S3	Design concept of Scenario S2, plus a natural ventilation scenario
S4	PCM placement described in Design concept S2 with a 30% WWR south facade
S5	PCM placement described in Design concept S2 with a 30% WWR south facade, plus a natural ventilation scenario.

The main scenarios explored in the analysis are described in Table 1. Scenario S1 represents the starting “base case”: it is simply the test room, with no application of PCM on the envelope. Scenarios S2-S3 add to scenario S1 two layers of 5mm thick PCM on every opaque wall facing the inside environment. The difference between Scenario S3 and S2 is in the application of natural ventilation only in Scenario S3. S4 and S5 have a reduced WWR if compared to S2 and S3 but keep the differentiation in the natural ventilation use.

3. Results

Results are presented in the form of both overall yearly energy consumption and in the analysis of hourly trends during some selected days taken as example, in both free floating and while calculating thermal ideal loads.

In the following, some of the hottest days from summer will be examined in detail in Fig. 2 and 3 to quantify the potential for improvement in the performance of lightweight envelopes in Mediterranean climates.

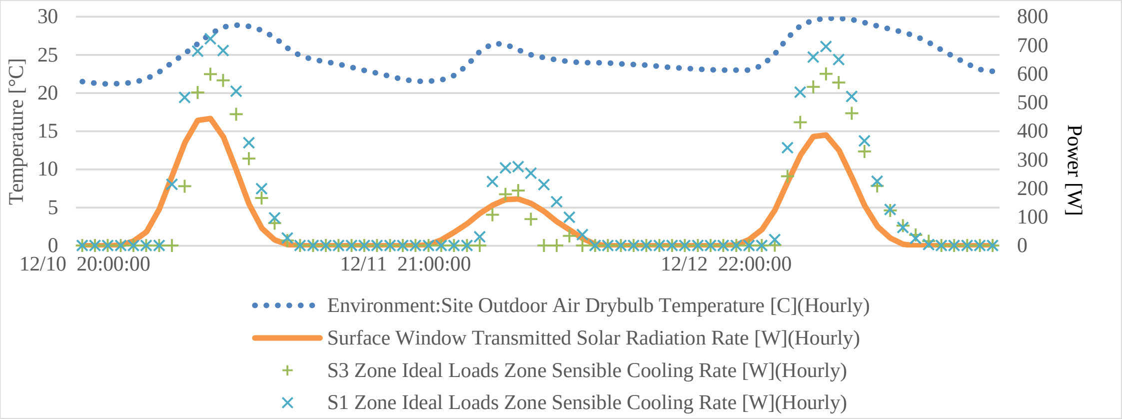

Fig. 2 Ideal loads – August 29th to September 1st

Taking as example scenario S3, it is indeed verified in Fig.2 that the reduction in the cooling peak requirements are reduced by roughly 15% on August 30th and September 1st in comparison to the simple insulated room.

Figure 3 is instead well representative of the relevance of natural ventilation in such applications. The free floating S1 scenario zone air temperature reached nearly 50°C inside the room immediately after the solar radiation peak. The application of PCM layers all over the opaque walls in the simulated room gains a net reduction of the temperature peak of 8-10°C during sunny days. The potential for ventilation, although limited by the high external air temperature also during the night, is still relevant during the evening of the first and second day depicted in the figure.

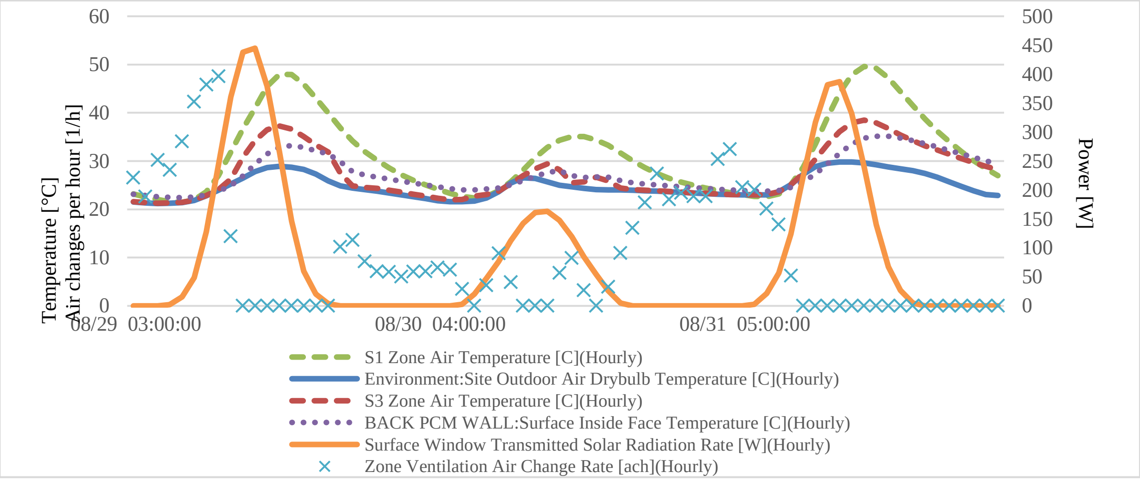

Fig. 3 Free-floating analysis – August 29th to September 1st

Fig. 4 describes the monthly share of the cooling ideal loads for all the scenarios described.

It is clear that the natural ventilation ones perform better under cooling conditions (S3-S5).They all show energy loads lower than S1 by more than 50% in some cases. The trade-off between heating increase and cooling reduction looks in favor of the reduction of the windowed area performed for S4 and S5 scenarios that prove to be the best performing ones in Mediterranean locations. The solution "as it is" (S2) proves mostly efficient in the shoulder and milder months where the indoor temperature would be driven easily in the PCM melting range. Thus scenario S2 reduces to zero all the cooling loads during most of the year and significantly reduces thermal loads in October and May, but provides only moderate energy loads reduction during summer.

During the hottest months, it is needed to improve the design and control of the indoor environment: coupling a proper bioclimatic design by reducing the window to wall ratio, implementing natural ventilation strategies and performing charging and discharging of the thermal storage, grants a reduction of the cooling ideal loads of S5 to roughly one third if compared to the initial design.

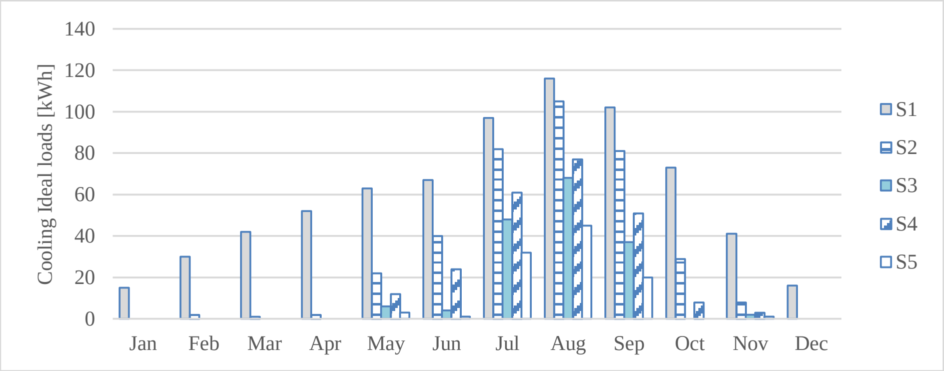

Fig. 4 Cooling monthly ideal loads for the case-study

Fig. 5 shows instead heating ideal loads for the same scenarios: all the scenarios mark small reductions in energy loads as well in the heating phase, due to the capability of the storage system to store solar gains and deliver them later when needed. This is especially clear when checking that the S1 system is the only one showing cooling needs during winter in Fig. 4.

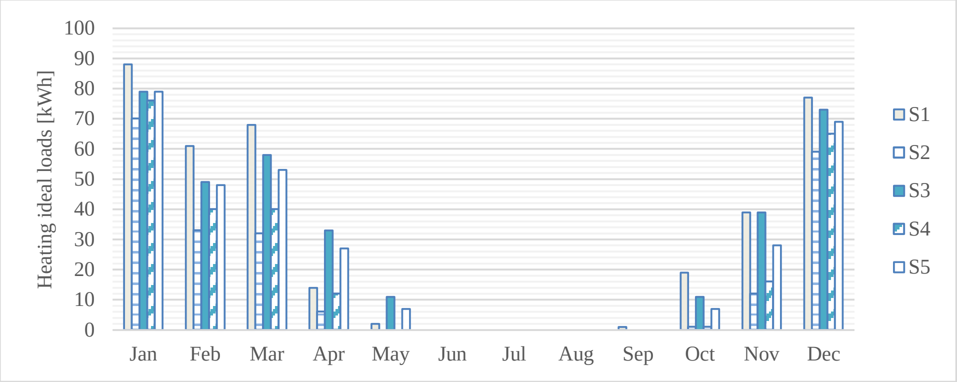

Fig.5 Heating monthly ideal loads for the case-study

As Fig.6 suggests, the best performing scenario is the S5 one, implementing PCMs on all the opaque structures, a lower window to wall ratio and natural ventilation. It reaches a reduction of more than 62% of the overall energy loads during a year.

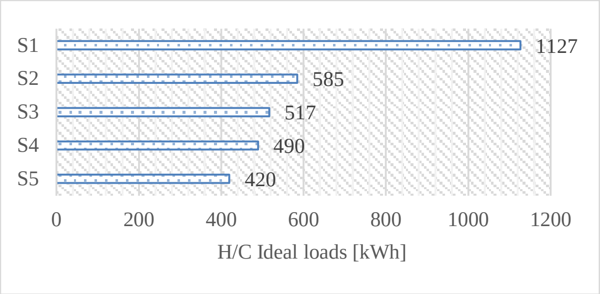

Fig. 6 Overall thermal ideal loads for the five scenarios analyzed

4. Discussion and conclusions

The results have shown that the proposed solutions are viable to improve with relevant results the thermo-physical performance of lightweight structures located in the Mediterranean area. The proposed scenarios were simulated and proved to be able to make the test room much more “inert” and less reactive to outdoor variation of conditions when needed, or greatly benefit from natural ventilation to improve the efficiency of the storage system. Energy savings close to the 65% (S5) of the original results for the test room without PCM are obtained during the analysis. Sunlight plays a major role as in the Mediterranean, as average high solar radiation mean that during winter PCMs are effective in storing excess solar gains and releasing them when needed, thus reducing also heating energy needs. During summer, instead, the combination of PCM, ventilation and a lower window to wall ratio value prove the best performing solution. The no-natural ventilation scenarios look as the best performing scenarios for heating (S2-S4), while the natural ventilation ones perform better under cooling conditions (S3-S5).They all perform anyway better than S1 by more than 50% of the total energy loads in most cases. The trade-off between heating energy increase and cooling energy needs reduction looks in favor of the reduction of the windowed area performed for S4 and S5 scenarios, proved to be the best performing ones in Mediterranean locations. Cooling energy needs are further reduced by the high energy density the modeled PCM shows in the temperatures comfort range (22-26°C): the correct choice of the PCM melting/solidification temperature range may further improve the performance of such systems. The potential application for such solutions are widespread e.g. existing buildings retrofit. From the point of view of modern research, these concepts would be useful to reduce the need for interaction between energy grids and net zero energy buildings and may play a relevant role in the decarbonization of the energy sector.

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