Optimal design of PCM in internal walls for nZEB buildings

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Abstract— **The implementation of phase change materials PCMs in the building sector has been recently regarded as a valuable strategy in order to achieve nearly Zero Energy Buildings. If properly employed in the internal partition, the PCM layer can increase the thermal storage capacity of the building with consequent reductions of air-conditioning energy requirement. Furthermore, an adequate thermal mass of internal walls can help in attenuating the indoor air temperature drop consequent to the shutdown of the air-conditioning system in winter condition as well as attenuating a temperature rise in summer. These aspects are amplified in highly-glazed buildings, where owing to the solar radiation entering through the glazed surfaces, the surface temperatures of the internal walls are highly variable and it is thus possible to exploit the phase change.**

In this study, the energy performances of highly-glazed buildings with PCM integrated in the internal walls were evaluated by a parametric analysis conducted by means of dynamic numerical simulations. A modular two-story reference building, with a highly glazed external envelope, located in Rome was investigated considering three different typologies of external opaque walls, different volumes of PCM integrated in the internal walls and several values of melting temperature in the summer and winter seasons. The simulations were conducted with the aim to assess the thermal energy requested for heating and cooling and to determine a temperature deviation index to quantify the ability of PCM to maintain the indoor air temperature at acceptable levels, when the system is not operating.

The results of the analysis showed, both in insulated and non-insulated buildings, in which conditions in a warm Mediterranean climate, the phase change materials can mitigate the energy demand associated with the building air conditioning and temperature deviation in the environments when the system is switched off.

Keywords— PCM, nZEB, parametric simulation, energy saving, indoor temperature deviation

I. Introduction

The European Directives lead toward the objective of achieving nearly Zero Energy Building (nZEB). In this context, the building envelope plays a fundamental role in the design phase and, therefore, recently numerous passive solutions have been investigated in order to improve the thermal building performances. For this purpose, the presence of a phase change material (PCM) in the building walls has been considered as a new interesting solution particularly suitable for the energy requalification of existing buildings with low inertia, to reduce maximum loads and energy needs in the winter and summer. In particular, when employed in the internal partition, the PCM layer increases the thermal storage capacity with consequent reduction of the surface temperature fluctuations and energy requirements for indoor air-conditioning [1].

The thermal performances of a PCM are determined by several parameters and, moreover, the attainment of melting and solidification cycles in the layer, with consequent storage and release of energy, depends on the extent of the heat flux through the wall containing the phase change layer. In the literature, the studies with the aim to evaluate the dynamic and energy performances of PCM in the building envelope can be divided into three main groups according to their focus: on the PCM layer level, wall level and building level. For the first category, in Ref. [2-4] the authors have addressed the problem of the definition of the dynamic and energy behavior of a layer subject to phase change. Considering the entire wall, the study of the optimal location of the PCM layer in the wall stratigraphy in relation to the thickness and the thermal properties of the different layers and PCM is fundamental to increase the thermal mass and reduce the heat flux peaks through the wall [5]. Considering the whole building, in a single-story residential building with PCM-enhanced roof construction, in the weather conditions of Melbourne and Sydney, the minimum heating and cooling loads of the air-conditioned building, were obtained for an optimum melting temperature of 23 °C [6]. By integrating PCM in partition walls of a lightweight office building, owing to the high dependency of the PCM performance on the climatic conditions, the type and the quantity of PCM to install should also be evaluated according to the diurnal temperature swings, and the preferred season [7]. In a similar study, the possibility of refurbishing a building with PCM plaster on the inner side of the building envelope, focusing on energy savings and indoor thermal comfort in the cooling season, was investigated [8]. The results were obtained varying the phase change temperature, wallboard thickness and the location of the PCM layer, in five Mediterranean climates: Ankara (Turkey), Athens (Greece), Naples (Italy), Marseille (France), and Seville (Spain). The results suggested that the PCM does not provide the same benefits throughout all the months of the cooling season and that the refurbishment by means of PCM wallboards seemed more appropriate for a semi-arid climate (Ankara) rather than hot/subtropical Mediterranean climates. The experiments conducted also highlighted that the optimal phase change temperature has a seasonal characteristic, and complete discharge or complete heat storage is difficult to obtain for a single PCM. A recent study, both on the wall and building level, with the use of PCM layers on either the external or internal side of the walls, has established the optimal layer position by considering the energy needs and costs [9]. In the aforementioned researches, the influence of many factors on the PCM thermal behavior were investigated. However, the

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case studies considered regarded specific building envelopes, while the charge and discharge phenomena also strongly depend on the insulation level of the building envelope.

The objective of this study is to evaluate the influence of the insulation level of the external envelope on the energy needs and indoor temperature deviation, compared to that of set-point, of a generic highly-glazed office building with PCM integrated in the internal partitions. For this purpose, the effect of the melting temperature and PCM amount was analyzed for three different types of opaque external walls with different steady and dynamic thermal properties. The external climatic conditions are typical of a Mediterranean locality and the air conditioning system is supposed to operate in intermittent mode. The parametric analysis is carried out by means of dynamic simulations and aims to evaluate the influence of the introduction of PCM in the layers of the internal walls on the energy performance of the building, comparing the results with that of the reference configuration without the presence of PCM. Furthermore, the study aims to evaluate the ability of the PCM to attenuate the temperature deviation maintaining the indoor air temperature close to that of set-point when the air-conditioning system is not working. In other words, the attenuation of the indoor air temperature, when the air-conditioning system is not operating, is compared in the cases of presence and absence of PCM material in the internal walls.

II. METHODOLOGY

A. *Simulation software*

In this paper the energy performances of a building with PCM layers in the inner walls were evaluated by means of numerical simulations performed in the simulation environment TRNSYS [10]. The building thermal behavior was modeled by Type 56, whereas the thermal behavior of the walls containing PCM was implemented through the Type 1270 [11], designed to interact with the building model. The Type 1270, validated in recent researches [6], requires as input the density, specific heat capacity, melting temperature and latent heat of the PCM layer. The mathematical model hypotheses that the specific heat capacity cp of the PCM is not temperature-dependent when fully solid or liquid and the phase change process occurs at constant temperature. When the PCM material with mass mpcm is in liquid or solid phase, the temperature at the end of a time step Tf, as a function of the temperature at the start of a time step Ti, is given by:

$$T_f = T_i + (q_1+q_2)/m_{pcm}\, c_p \qquad (1)$$

Where, q_1 and q_2 are the conductive heat fluxes coming from the adjacent layers.

When the PCM temperature equals the melting temperature Tm, the phase change occurs at a constant temperature, and Type1270 records the amount of energy stored or released. If the energy absorbed by the PCM during a particular time step exceeds the latent storage capacity, the Type1270 computes the energy required for the complete phase change and then attributes the remaining energy to the sensible temperature change in the liquid phase using Eq. (1). Likewise, when the PCM releases to the surrounding wall layers, more energy than has been stored in a particular time step, the Type1270 computes the amount of energy required to solidify the PCM fully and applies the remaining energy to a temperature change in the solid phase using Eq. (1).

B. *Case study*

Simulations were performed based on a modular two-story reference building (10 m x 10 m x 6 m), as reported in Fig. 1.

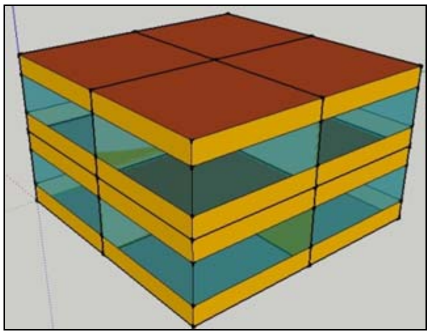

Fig. 1. 3D Representation of the building thermal zones and envelope

Each floor is made of four squared thermal zones (Zones 1 – 4 in the first floor and zones 5 – 8 in the second floor) divided by internal partition walls in which the PCM is integrated. The amount of glazed surfaces in the external building envelope is supposed to be 50 % of the total surface and the typology of windows is 4/12/4 double glass with low emission treatment, with a thermal transmittance of 2.83 $W/m^2 K$ and a solar factor of 0.755. The frame percentage is 40 % of the overall surface area. The building is supposed to be used for office activities and provided with an air-conditioning system to maintain the indoor set point temperature of 20 °C in winter and 26 °C in summer. The heating/cooling system operates from 08:00 to 18:00 from Monday to Friday and it is not operating during weekends. The presence of people and internal gains are defined though a proper schedule where, in zone 2 and zone 6 (with the two external walls exposed to south and east) the total amount of internal gain (sensible, latent, equipment and lighting) is equal to 450 W, whereas in zone 4 and zone 8 (with the two external walls exposed to north and west) they are respectively 230 W and 220 W. The hourly simulations were conducted for the locality of Rome, Italy (Latitude L=49°54') for which the climatic conditions are taken from the national standard UNI 10349-1 [12]. The PCM used in the simulations is a hydrate salt [13] with a latent heat of fusion of 254 kJ/kg, melting temperature of 32 °C, thermal conductivity of 0.554 W/(m K), specific heat capacity in the solid and liquid phase of 1.76 kJ/(kg K) and 3.31 kJ/(kg K), and density of 1485 kg/m^3.

C. *Parametric analysis*

To evaluate the influence of PCM integration in the internal walls on the overall building thermal performance, a parametric and optimization analysis was developed. Three building envelopes with different insulation levels were considered. The stratigraphy, with the steady and dynamic thermal characteristics of the three walls (W1, W2 and W3) are reported in Table I.

W1 represents a non-insulated wall, whereas W2 and W3 have an insulation layer placed on the external side of 2 cm and 4 cm respectively.

In addition, for each opaque building envelope, the PCM melting temperature and the volume of PCM installed in the internal walls were varied. The melting temperatures adopted in the study are in the range 16 °C – 30 °C with a variation step of 1 °C, and were chosen in accordance with the indoor comfort temperatures requested in both the heating and cooling seasons.

TABLE I. THERMOPHYSICAL PROPERTIES OF THE INTERNAL AND EXTERNAL WALLS FROM THE INNER TO OUTER LAYER

W1	Thickness [m]	Thermal resistance [m²K/W]
plaster	0.010	0.014
brick	0.240	0.267
plaster	0.010	0.014
Periodic thermal Transmittance (Y_{ie}) [W/m²K]	0.826	
Steady thermal Transmittance (U) [W/m²K]	2.149	
W2	**Thickness [m]**	**Thermal resistance [m²K/W]**
plaster	0.010	0.014
brick	0.220	0.244
insulating	0.020	0.500
plaster	0.010	0.143
Periodic thermal Transmittance (Y_{ie}) [W/m²K]	0.216	
Steady thermal Transmittance (U) [W/m²K]	1.060	
W3	**Thickness [m]**	**Thermal resistance [m²K/W]**
plaster	0.010	0.014
brick	0.200	0.222
insulating	0.040	1.000
plaster	0.010	0.014
Periodic thermal Transmittance (Y_{ie}) [W/m²K]	0.142	
Steady thermal Transmittance (U) [W/m²K]	0.704	
Internal walls	**Thickness [m]**	**Thermal resistance [m²K/ W]**
plaster	0.020	0.029
brick	0.060	0.130
plaster	0.020	0.029
Steady thermal Transmittance (U) [W/m²K]	2.796	

The simulated amount of PCM material installed in the whole building was of 2 m³, 4 m³ and 6 m³, distributing it with a constant thickness in all internal partitions..

D. *Perfomance indexes*

In the evaluations of the thermal performances of a retrofitted building through the use of PCM in the internal partitions, important conclusions can be drawn from the amount of thermal energy requested for heating (Q_w) and cooling (Q_s) to maintain the corresponding set-point temperature in the two seasons when the air-conditioning system in activated. These values allow to determine the configuration that maximize the energy saving, either in one season or at a yearly level. Further interesting results can be obtained considering the capacity of the PCM to maintain the indoor air temperature, when the system is not operating, to acceptable levels close to the corresponding set-point temperature for a longer period compared to the configuration without PCM. In order to assess this condition an hourly indoor temperature deviation index (DI) was evaluated for each i-th zone of the building. The index was defined as:

$$DI_{h,i} = 20\ °C - T_i \ \text{ when } \ T_i < 20\ °C \tag{2}$$

$$DI_{h,i} = T_i - 26\ °C \ \text{ when } \ T_i > 26\ °C \tag{3}$$

otherwise $DI_h = 0°C$;

where T_i is the internal air temperature of the i-th zone. Starting from the hourly index, a seasonal index of the whole building in winter period DI_w and summer period DI_s was calculated summing the corresponding hourly values and the values obtained for each single thermal zone. These indexes were evaluated for all the simulated scenarios. The greater the index the worse the temperature deviation in the indoor environments.

III. DISCUSSION AND RESULTS

A. *Winter results*

Fig. 2 reports the set of simulations conducted considering the three different typologies of external wall in winter conditions. In particular, the figure displays the building heating energy demand Q_w as a function of the winter temperature deviation index DI_w for different volumes of PCM, allowing also reading the energy demand decrement in the right y axis and the temperature deviation index reduction in the upper x axis. In all the considered cases, it is possible to appreciate that the implementation of PCM in the internal wall always produces an increment of the energy demand associated with the winter air-conditioning regardless of the melting temperature Tm and of the volume of material used. However, at the same time, a reduction of DI_w can be appreciated for W1 and W3, while for W2 an increase is highlighted.

For the non-insulated wall W1, in the reference case, without the use of PCM in the internal partitions, Q_w resulted as 5309 kWh with a DI_w of 83133 °C. The use of different volumes of PCM (Fig. 2 at the top) generate a building thermal response in a wide range. In particular, if Tm lower than 23 °C are considered, the increment of the PCM volume is associated with a reduction of both Q_w and DI_w. Above this T_m, better results are provided only in terms of DI_w, while Q_w mainly increases. The curve relative to 6 m³ is more markedly influenced by Tm and covers a wider range of results, while the curve relative to 2 m³ is the lowest variable. The use of a 4 m³ PCM volume generates an intermediate behaviour between the other two cases. In particular, in the case of application of the lowest amount of PCM (2 m3), Q_w rises by a minimum of 10.3 %, for a Tm of 20 °C, to a maximum of 13.1 %, for a T_m of 16 °C. Quite similar results are provided by the curve relative to the installation of 4 m³ of PCM. For the largest amount of PCM (6 m3), Q_w increases by 9.7 %, for a T_m of 20 °C, up to 12.8 %, in the case of a T_m of 30 °C. According to the shape of the curves, for each PCM volume, an optimum solution that minimizes simultaneously Q_w and DI_w can be determined. In all the three cases, the optimal T_m are between 21 – 22 °C.

When a slight level of insulation is added to the external wall (W2 case), the overall effect is a drastic reduction of the energy necessary for the building heating and the curves shift to considerably lower values of Q_w (Fig. 2 at the centre). The reference case, without the use of PCM, provided a value of Q_w equal to 3512 kWh with a DI_w of 58733 °C.

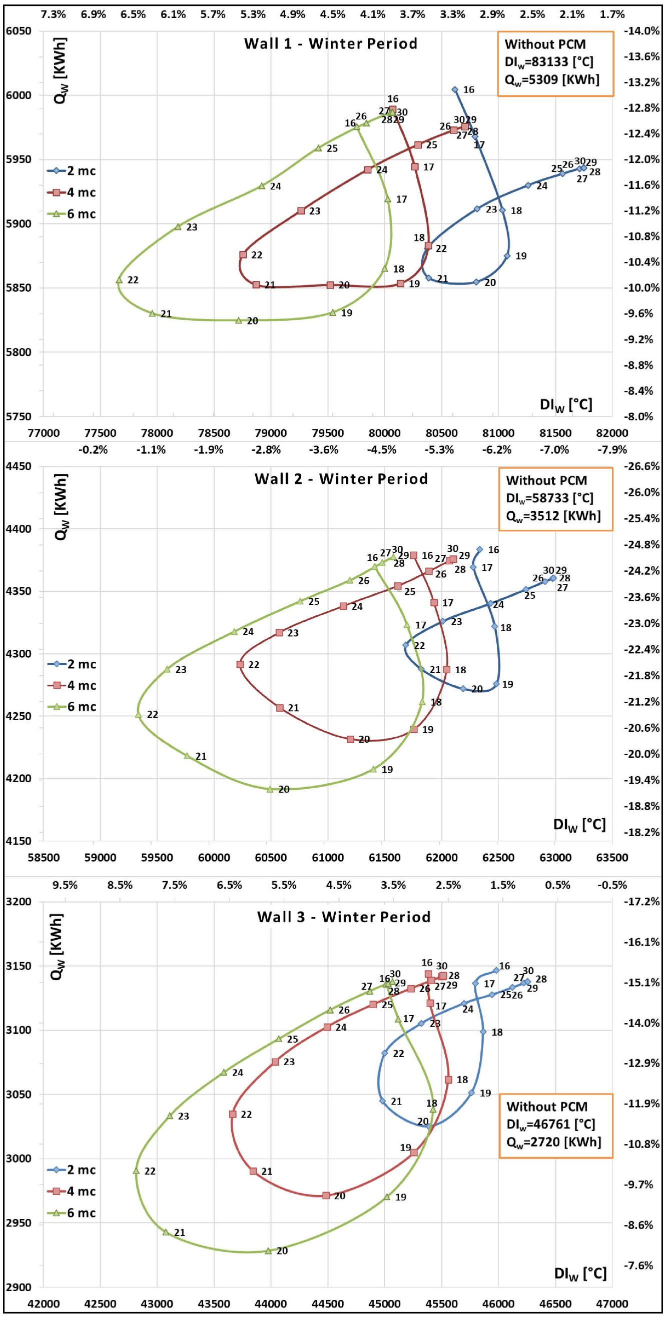

Fig. 2. Winter energy demand in function of the winter deviation index, varying the PCM volume and the melting temperature for the three types of external walls.

When the wall typology W2 is applied to the building envelope, the adoption of an increasing PCM volume produces an improvement of the building winter thermal performances for a given Tm since the increments of Q_w result in lower percentage values. For a PCM volume of 2 m^3, Q_w rises from 21.6 %, for a T_m of 20 °C, to 24.8 %, for a Tm of 16 °C. For the curve of 6 m^3, smaller Q_w increments can be detected with a minimum of 19.3 % corresponding to the T_m of 20 °C. As regards DI_w, its increment is higher for reduced PCM volumes, reaching a value close to 7%, for a volume of 2 m^3 and a T_m of 27 - 30 °C, while its increment is lower for the greatest PCM volume, reaching a value close to 1%, for a volume of 6 m^3 and a T_m of 22 °C.

As expected, a further increment of the level of insulation of the external walls (W3 case) led to a major reduction of Q_w (Fig. 2 at the bottom). The reference case provided a Q_w of 2720 kWh with a DI_w of 46761 °C. Still the introduction of PCM in the internal walls causes a growth of the Q_w, which can be contained moving towards higher volumes. The lowest increments of Q_w are found for a T_m of 20 °C: with the adoption of 2 m^3 of PCM, Q_w results 3025.2 kWh; for a volume of 4 m^3, Q_w is equal to 2971.4 kWh; for a volume of 6 m^3, Q_w is equal to 2928.6 kWh. However, for all the simulated cases, the introduction of PCM helps to attenuate the decline of the indoor air temperature in the hours when the air conditioning system is not operating, generating consequently lower temperature deviation indexes than the reference case. In particular, for a given Tm, a rise of the PCM volume guarantees a decrement of DI_w. In fact, for the curve of 2 m^3 the minimum value of temperature deviation index is attained at a T_m of 21 °C with DI_w equal to 44979.5 °C whereas moving to the curve of 6 m^3 the index fall to a value of 42814.0 °C obtained for a T_m of 22 °C. If both Q_w and T_m are considered, in the case of W2 and W3, for each volume of PCM adopted in the building, the optimum solutions appear to be in correspondence with a T_m of 20 – 22 °C.

B. Summer results

Simulations results for the summer season are visible in Fig. 3, which shows the building cooling energy demand Q_s as a function of the summer temperature deviation index DI_s for different volumes and melting temperatures T_m of PCM employed in the building internal walls. In summer, all the combinations of PCM quantities and melting temperatures determine substantial reductions of Q_s and DI_s. For each value of PCM volume, there is a specific melting temperature that minimizes Q_s, whereas a different one minimizes DI_s

For the non-insulated wall W1 (Fig. 3 at the top), in the reference case without the use of PCM, Q_s resulted as 8416 kWh with a DI_s of 49984 °C. With the application of 2 m^3 of PCM in the internal wall, an increase of T_m, starting from the value of 16 °C, determines a reduction of Q_s, with a moderate reduction of DI_s, until a minimum is found for a T_m of 25 °C. After that, further increases of Tm lead to augments of Q_s, while the DI_s keeps declining until it reaches its minimum in correspondence with a T_m of 30 °C. Greater volumes of PCM generate a greater reduction of both Qs and DI_s. A similar pattern is observable for the curve of 4 m^3. However, in this case, T_m that minimizes DI_s is 27 °C. A similar shape is found for the curve of the case of 6 m^3, where the best performances are observed: Q_s reduced by 8% for T_m of 25 °C and DI_s reduced by 26.2 % for a T_m of 27 °C.

As can be expected in typical Mediterranean climates, the addition of 2 cm of thermal insulation on the external walls (W2 case, Fig. 3 at the centre) determined a consistent increment of Q_s, which for the reference case amounted to 11701 kWh with a corresponding DI_s of 62137 °C. The introduction of PCM in the inner walls, with the effect of an augment of the building thermal mass, gives a consistent contribution in the mitigation of Q_s. The curve of the three different PCM volumes displays patterns similar to the previous W1 case, but with more significant decrement of Q_s and DI_s. In particular, with a volume of 2 m^3, Q_s dropped to a value of 8747.9 kWh, for a T_m of 25 °C, whereas the minimum value of DI_s is obtained again for T_m of 30 °C and is equal to 41881.3 °C. The curve of the configuration with 4 m^3 shows a similar pattern to that of 2 m^3 with lower values of both Q_s and DI_s. In this case, the minimum Q_s is 8696.9 kWh for a T_m of 25 °C, while the minimum DI_s is attained, instead, at a melting temperature of 28 °C and it is equal to 414841.0 °C. The best result for the W2 type of external wall is achieved with the use of 6 m^3 of PCM in the internal walls that allows for a decrease of Q_s by 26.0 % in correspondence with T_m equal to 25 °C, and a decrease of DI_s by 33.9 % for T_m equal to 27 °C.

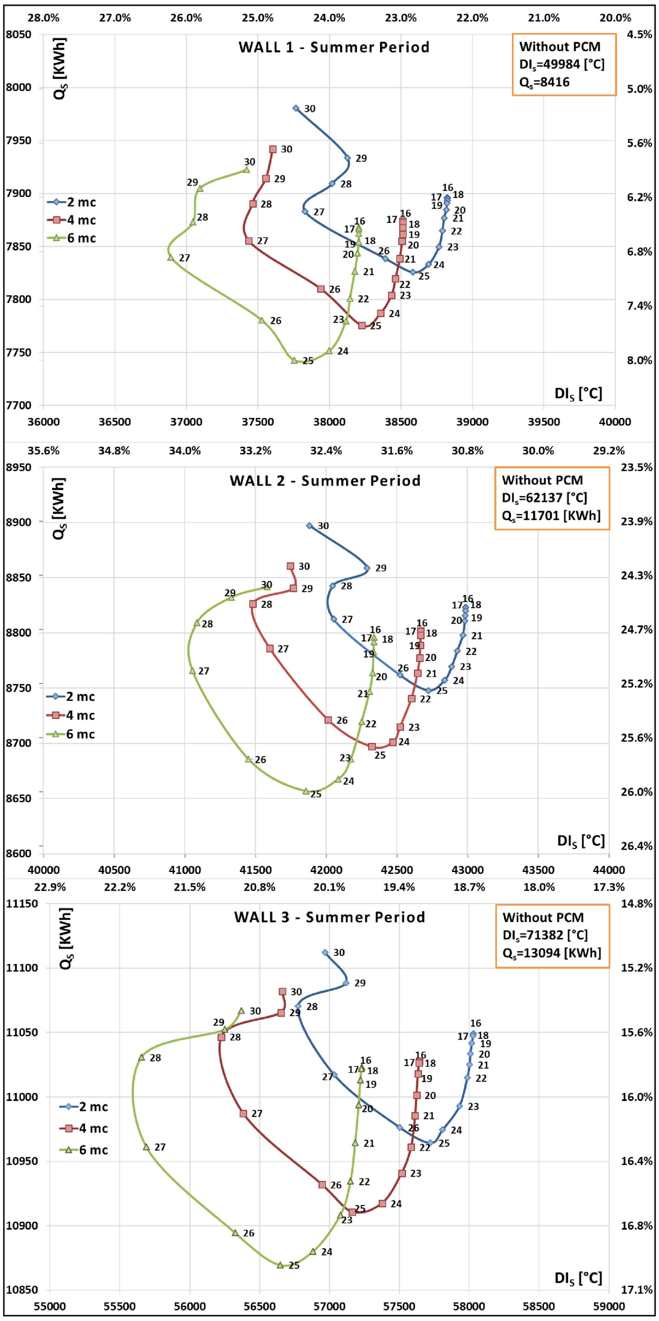

Fig. 3. Summer energy demand in function of the summer deviation index, varying the PCM volume and the melting temperature for the three types of external walls.

A further increment in the external wall insulation thickness (W3 case, Fig. 3 at the bottom) generates further increment of both Q_s and DI_s. For this type of wall, the reference case indeed provides a Q_s of 13094 kWh and a DI_s of 71382 °C. The patterns of the curves of the three PCM volumes considered in the analysis are very similar to those obtained for the W2 case. With the employment of 2 m3 of PCM, a maximum reduction of Q_s of 16.3 % is found for a T_m of 25 °C, whereas the maximum reduction of DI_s of 20.5 % results in a T_m of 28 °C. The configuration with 4 m3 of PCM provides better results for a given value of T_m, maintaining a shape very close to that of 2 m^3. The maximum reductions of Q_s and DI_s are found for the same values of T_m (25 °C and 28 °C). Again, the best results are offered by the configuration with 6 m^3 of PCM integrated in the inner walls. The maximum reduction of Q_s amounts to 17.0 %, for a Tm of 25 °C, whereas the maximum reduction of DI_s amounts to 22.0 %, for a T_m of 28 °C. It is interesting to note that in all the three different scenarios of external wall typology, it emerges that the value of T_m of 25 – 27 °C is at the same time capable of minimizing Q_s and DI_s.

IV. CONCLUSIONS

The parametric analysis developed, with the aim to evaluate the energy demand reduction and temperature deviation reduction of highly-glazed buildings with PCM integrated in the internal walls, highlighted the strong dependence on the season. In the winter, for all the building envelopes considered, insulation level, PCM volume and melting temperature, the implementation of PCM in the internal wall always produces an energy demand increase for the building air-conditioning regardless of the melting temperature and volume of material used. However, at the same time, important reductions of the temperature deviation index can be obtained. This is owing to the high amount of solar radiation entering the indoor environment through the wide envelope glazed surfaces, which is stored in the morning in the internal PCM walls, instead of contributing to the reduction of heating demand, and is released in the nocturnal hours allowing the temperature deviation to be reduced. Consequently, the results highlight how in winter the adoption of phase change materials in the inner walls can contribute to the mitigation of the attenuation of the indoor zones air temperature when the air conditioning system is switched off, thanks to the release of the latent heat stored during the night. To reduce this disadvantage, a high PCM volume and a melting temperature slightly higher than the winter set-point temperature guarantee limiting the heating energy demand increase and obtaining a remarkable reduction of the temperature deviation index. The best winter results are achieved for the W3 external wall type with the use of 6 m^3 of PCM, obtaining a reduction of the temperature deviation index by 6.2 % with a corresponding increment of the heating demand of 9.8 %.

In summer, the results showed the important role played by PCM in the significant reduction of the building cooling demand and in the reduction of the temperature deviation of indoor spaces, regardless of the typology of external building envelope. This is owing to the storage of the solar radiation incident on the internal walls allowing reduction of the overall cooling load. When the air-conditioning system is switched off, the internal walls continue to store energy, leading to a temperature deviation reduction, until sunset. The release of the latent energy in the night does not contribute to the reduce of the temperature deviation, since it happens when the indoor air temperature is lowered due to the exchange through the large glazed surfaces. Consequently, the indoor temperature increases without exceeding 26 °C. The results demonstrated that a melting temperature slightly lower than the indoor air set-point value (26 °C) allows exploitation of the latent heat for the limitation of inner surfaces temperature rise and consequent thermal exchange with the node air, contributing to lowering the cooling load requested to the air-conditioning system.

Conversely, in terms of temperature deviation, the best configuration appears to be with a melting temperature slightly higher than the set point value since once the system is switched off, the latent heat of the phase change material can be better exploited to attenuate the augmentation of the surfaces temperature of the indoor spaces that tend to rise, above the set point value of 26 °C, because of the heat stored in the wall thermal mass. Best results are achieved for W2 external wall type for a melting temperature of 26 °C with a reduction of the cooling demand by 27.8 % and a reduction of the temperature deviation index of 33.3 %.

Finally, these parametric and optimization analyses demonstrate that high-performance glazed buildings, in the summer season of the Mediterranean climate, could be retrofitted with a very limited worsening expected in the winter season by increasing the thermal inertia of the internal walls. This requires a careful design of the PCM layer in relation to the insulation level of the opaque building envelope.

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REFERENCES

[1] K. O. Lee, M.A. Medina, E. Raith, X. Sun, Assessing the integration of a thin phase change material (PCM) layer in a residential building wall for heat transfer reduction and management, Applied Energy,Volume 137,2015,Pages 699-706, ISSN 0306-2619.

[2] D. Mazzeo, G. Oliveti, Thermal field and heat storage in a cyclic phase change process caused by several moving melting and solidification interfaces in the layer, International Journal of Thermal Sciences, Volume 129, July 2018, Pages 462-488, ISSN 1290-0729,

[3] D. Mazzeo, G. Oliveti, N. Arcuri, Definition of a new set of parameters for the dynamic thermal characterization of PCM layers in the presence of one or more liquid-solid interfaces, Energy and Buildings, Volume 141, 2017, Pages 379-396, ISSN 0378-7788.

[4] D. Mazzeo, G.Oliveti, N. Arcuri, A Method for Thermal Dimensioning and for Energy Behavior Evaluation of a Building Envelope PCM Layer by Using the Characteristic Days, Energies 2017, Volume 10(5), Page 659, https://doi.org/10.3390/en10050659.

[5] X. Jin, M. A. Medina, X. Zhang, Numerical analysis for the optimal location of a thin PCM layer in frame walls, Applied Thermal Engineering,Volume 103, 2016, Pages 1057-1063, ISSN 1359-4311.

[6] A.Jayalath, L.Aye, P. Mendis, T. Ngo, Effects of phase change material roof layers on thermal performance of a residential building in Melbourne and Sydney, Energy and Buildings, Volume 121, 2016, Pages 152-158, ISSN 0378-7788.

[7] G. Evola, L. Marletta, F. Sicurella, A methodology for investigating the effectiveness of PCM wallboards for summer thermal comfort in buildings, Building and Environment, Volume 59, 2013, Pages 517-527, ISSN 0360-1323, https://doi.org/10.1016/j.buildenv.2012.09.021.

[8] F. Ascione, N. Bianco, R. F. De Masi, F. de' Rossi, G. Peter Vanoli, Energy refurbishment of existing buildings through the use of phase change materials: Energy savings and indoor comfort in the cooling season, Applied Energy, Volume 113, 2014, Pages 990-1007, ISSN 0306-2619, https://doi.org/10.1016/j.apenergy.2013.08.045.

[9] Y. Cascone, A. Capozzoli, M. Perino, Optimisation analysis of PCM-enhanced opaque building envelope components for the energy retrofitting of office buildings in Mediterranean climates, Applied Energy, Volume 211, 2018, Pages 929-953, ISSN 0306-2619.

[10] Solar Energy Laboratory University of Wisconsin-Madison,TRNSYS, Version 17.

[11] TESSLibs 3-Mathematical Reference, 2012.

[12] UNI 10349-1 Heating and cooling of buildings - Climatic data - Part 1: Monthly means for evaluation of energy need for space heating and cooling and methods for splitting global solar irradiance into the direct and diffuse parts and for calculate the solar irradiance on tilted planes, 2016, UNI - Ente Nazionale di Unificazione, Milan.M. Young, The Technical Writer's Handbook. Mill Valley, CA: University Science, 1989.

[13] L.F. Cabeza, A. Castell, C. Barreneche, A. de Gracia, A.I. Fernàndez, Materials used as PCM in thermal energy storage in buildings: A review, Renewable and Sustainable Energy Reviews, Volume 15, Issue 3, 2011, Pages 1675-1695, ISSN 1364-0321.