USE OF PCM MATERIALS FOR THE REDUCTION OF THERMAL ENERGY REQUIREMENT IN BUILDINGS

Francesco Reda[1], Domenico Mazzeo[1], Natale Arcuri[1], Roberto Bruno[1]
[1]Mechanical Engineering Department - University of Calabria
Via P. Bucci 46/C – 87036 – Arcavacata di Rende (CS)
Corresponding Author: francesco.reda@unical.it

ABSTRACT

The well know insulation techniques of the building shell, if on the one hand ensure a reduction of energy requirements for winter heating, do not always allow a decrease in energy demand for the cooling of indoor environments and, in some cases, they cause an increase in thermal cooling requirement. For this reason it is necessary to use innovative passive techniques, which in summer are able to mitigate the indoor air temperature, thus limiting the use of air-conditioning plants, while in winter they contribute to achieve an energy savings. Among the solutions recently introduced to reduce the buildings energy requirement there are the phase-change materials or PCMs. These are thermal storage materials with low melting/solidification temperature, able to store and release heat during the phenomena of phase transition, limiting the indoor air temperature variations within a building. The PCM, placed in the walls, floors or ceilings, limiting thermal fluctuations also allows a more rational use of the heat gains.

Use of PMCs in summer, especially in locations characterized by a Mediterranean climate where the thermal energy requirement for cooling are comparable to those for heating is suggested.

In this work, through the use of the simulation code TRNSYS vs. 17, the efficacy of current insulation techniques combined with the benefits obtained with the use of PCMs is evaluated, through analysis conducted on a existing building sample.

It is investigated the effects of a layer of PCM mounted on the internal vertical and horizontal opaque walls. A preliminary phase in order to achieve the best PCM melting temperature as a funciton of the conditioning season was conducted.

The influence of the thickness of PMC on reducing energy requirement in winter and summer has been also investigated.

The study, quantifying the reduction of building sample energy requirement respect to the case of the same building without PMC, has unequivocally confirmed that the PCMs represent an innovative technological solution to be used both in the existing building and on new buildings. In Mediterranean-type climate contexts, the most obvious benefits are found in the summer, and their use contributes substantially to the reduction of pollution produced by the residential sector.

INTRODUCTION

The building sector has became (together with the industrial sector) the world dominant energy consumer with 28% of the worldwide energy consumption (Sarlos et al., 2003). As a consequence of the thermal comfort rise the energy consumption is increasing. Housing and tertiary buildings consume about 46% of all energies and they are responsible about 19% of the total CO_2 emissions (Climate plan, 2004). Referring to the building stock, buildings built before the emanation of restraining energy laws are the largest part. An easy and economic solution in order to achieve energy savings consists of utilizing thermal storage. Thermal energy storage for space heating and cooling of buildings is becoming increasingly important due to the rising cost of fossil fuels and to environmental concerns. Conventional walls can be seen as sensible heat storages and they have been used for centuries by builders to store/release passively thermal energy, but a much larger volume of material is required to store the same amount of energy in comparison to latent heat storages. Storage of latent heat is achievable by materials having low fusion/solidification points named Phase Change Materials (PCM). In particular, the thermal storage is obtainable by their fusion while the energy recovery by their freezing. Several studies have analyzed the use of PCM for building retrofitting to get an effective way to improve indoor thermal comfort, to reduce energy consumption and to alleviate the negative effect in the atmospheric environment (Athienitis et al., 1997; Banu et al., 1998; Rudd, 1993; Sary et al., 2001; Feldman et al., 1991; Dimaano et al., 1998; Feldman et al., 1995; Feldman et al., 1989; Ahmet et al., 2003) The utilization of latent heat storage, over a comfortable indoor temperature range in buildings, can result in an increase of the thermal storage capacity in the range of 100-130 % (Feldman et al., 1991; Feldman et al., 1989; Feldman et al., 1989; Hawes, 1991). The main disadvantage of light weight buildings is their low thermal mass. Obviously, they tend to large temperature fluctuations due to external conditions, solar gains and internal loads. Using PCM material in such building walls can decrease the indoor air temperature fluctuations, particularly in case of high solar radiations loads. Consequently it is a potential method for reducing energy consumption in passively designed buildings. This tendency is confirmed by numerous papers available in the literature during the last 20 years concerning the use of PCM in external walls (Tyagi et al., 2007; Khudhair et al., 2004; Zhang et al., 2007; Kuznik et al., Kuznik et al., 2009).

There are few studies on the PCM mounted on internal partitions (ceilings and vertical walls). Kuznik et al. in 2011 have tested two identical rooms of a renovated tertiary building: one equipped with PCM wallboard and the other conventionally renovated, showing a real enhancement of occupant thermal comfort. This improvement can be very efficient if the building before renovation is a low thermal inertia building and if the internal air temperature fluctuation are around the PCM melting temperature (PMT).

The purpose of this paper is to study the thermal performance of one building with PCM mounted in the internal ceiling or in internal vertical walls, considering two Italian locations corresponding to two different climates, varying the PCM thickness and comparing them with the cases without PCM taken as a reference. A specific PMT in order to decrease the building cooling energy need was chosen. The first part of this paper deals with the methodology used in order to carry out the energy savings analysis. The case study procedures in terms of building and PCM features and the simulation configurations descriptions are shown in the second part. In the third part results and a comparison of the considered solutions are exposed. The last part concerns the main conclusions of this research.

METHODOLOGY

In order to examine the energy saving potential benefits integrating PCMs into building internal walls, the building thermal behavior was simulated by using TRNSYS software (Solar Energy Laboratory University of Wisconsin-Madison, 2012). To model the building without PCM just the Type 56 has been used. The results of this analysis, in terms of energy needs, were taken as a reference for the comparison with the other considered solutions. As regard the building with PCM, in addition to Type 56, Type 1270 supplied by TESS must be used as well (Thermal Energy System Specialists, 2012). This component models a layer of a PCM that is entirely contained within a wall; in other words, the PCM is not directly adjacent to the zone air (figure 1). Type1270 is designed to interact with Type56 and can model a PCM located anywhere in the Type56 wall (figure 1). The user is able to specify the physical properties of the PCM: density, specific heat, PMT, solidification temperature and latent heat of fusion. The user has to split the wall containing the PCM into two parts (figure 1); each part containing the standard wall layers are located on one side of the PCM layer and they are set into the Type 56 as a BOUNDARY wall.

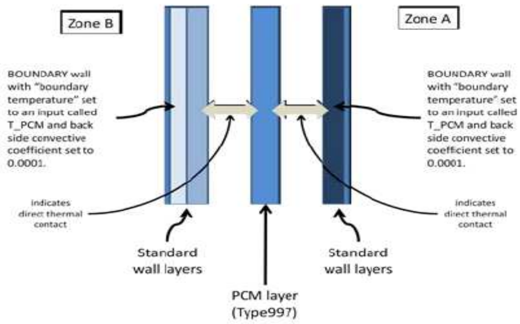


Figure 1. PCM layer model on TRNSYS.

It means that the building zone containing the wall with PCM sees the wall as a temperature node; therefore in this case, the node temperature is the temperature calculated by Type 1270. It makes the following assumptions:

1. The specific heat of the PCM is constant (it does not change with temperature) when fully solid. The user defines the solid-phase specific heat.
2. The specific heat of the PCM is constant (it does not change with temperature when fully liquid. The user defines the liquid-phase specific heat.
3. The thermal contact resistance to energy flow between the PCM layer and the standard material layers adjacent to it is negligible.
4. The solidyfing/melting process occurs at a constant temperature.

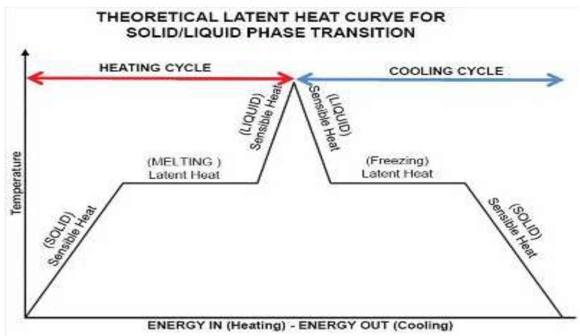


Figure 2.Simple PCM working chart

Indicating with $\dot{q}_1$ and $\dot{q}_2$ the quantities of energy entering the PCM from the adjacent wall layers, two circumstances are distinguished [24]:

- when the PCM material is fully solidified, the node temperature at the end of a timestep is given by:

$$T_f = T_i + \frac{(\dot{q}_1 + \dot{q}_2)}{m_{PCM} c_{p_s}} \qquad (1)$$

- when the PCM material is fully melted, the node temperature at the end of a timestep is given by:

$$T_f = T_i + \frac{(\dot{q}_1 + \dot{q}_2)}{m_{PCM} c_{p_l}} \qquad (2)$$

When the PCM material is in the melting/freezing phase (figure 2) the final temperature and initial temperature are equal (provided that the PCM does not become fully solid or fully liquid during the time step) and Type1270 simply keeps track of how much energy the PCM has absorbed or given off. If the energy absorbed by the PCM during a particular time step exceeds the PCM's latent storage capacity then Type1270 computes how much of the energy was needed to fully melt the PCM, then applies the remaining energy to a temperature change in the liquid phase using Equation 2. Likewise, if the PCM is giving off energy to the surrounding wall layers, and it gives off more energy than has been stored in a particular time step then Type1270 computes how much energy was required to fully solidify the PCM and applies the remaining energy to a temperature change in the solid phase using Equation 1 (figure 2). Furthermore the quantities $\dot{q}_1$ and $\dot{q}_2$ are supplied by Type 56. The PCM was added first in the ceiling and then in internal vertical walls. In the first case, just a single Type 1270 was used. Instead, in the other case, for each internal vertical wall containing PCM one Type 1270 has to be used. In the preliminary phase an optimization analysis regarding the effect of the variation of PMTs, fixing an average PCM thickness rgarding the considered range and considering two Italian cities, Milano (Latitude 45.45°) and Cosenza (Latitude 39.29°), was evaluated, leaving unchanged the PCM thermo-physical properties. This analysis was done in order to find the best PMT for cooling energy saving purpose. Once chosen the best PMT, the energy savings analysis regarding different PCM thickness relating to the two localities were carried out. Concerning the climate data of the abovementioned cities, they refer to Italian Standard UNI 10349 (Ente Nazionale di Unificazione, 1994). All the analysis refer to yearly simulations based on hourly timestep. The last part of the research is the comparison between the energy performance of the building with PCM and the reference cases.

CASE STUDY

Building features

The considered building is a two - storey house, which is built on two floors, and it refers to a real building. The dwelling typology is an apartment and it is into a typical residential apartment building of four - storey (figure 4). It is oriented and located within the whole building as the next figure shows.

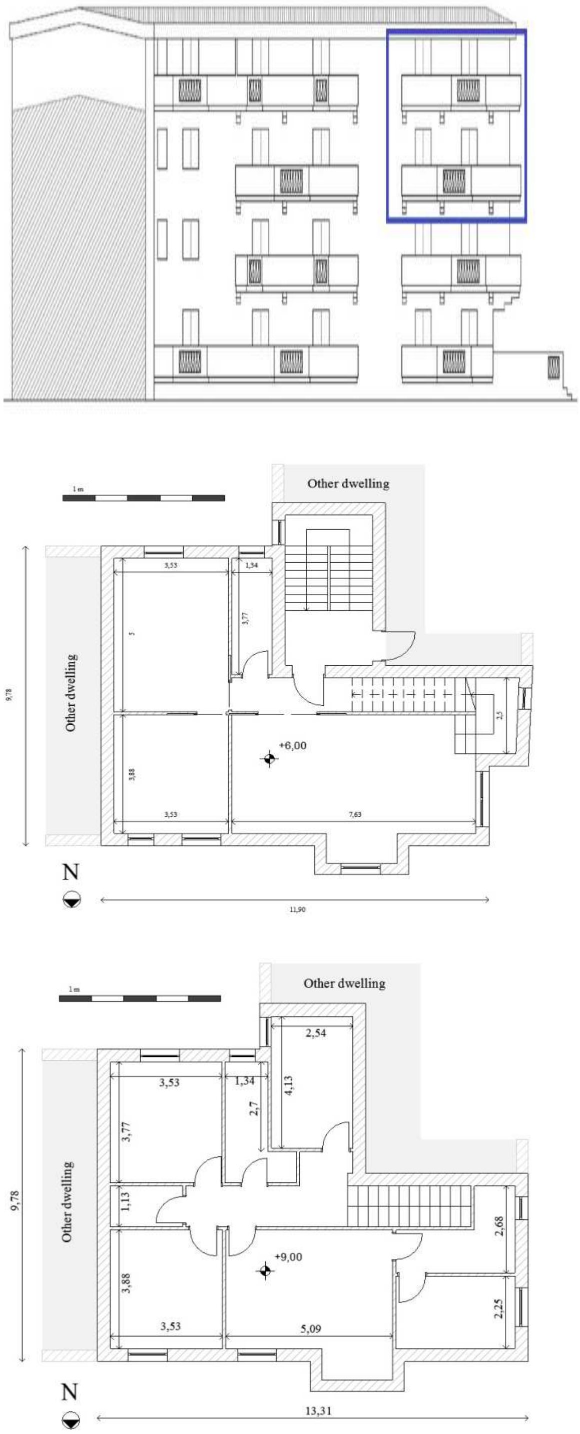


Figure 3. Location and orientation of the considered dwelling.

The analyzed house is adjacent to other conditioned apartments on the east and bottom sides as the previous figure illustrates. Therefore the boundary wall with the other apartments and the internal ceiling were set with adiabatic conditions in the TRNSYS environment. The mean thermal properties of the opaque structural elements are reported in the table below.

Material	Thickness [m]	Conductivity [W/mK]	Heat Capacity [J/kgK]	Density [kg/m^3]
Partition				
Plaster	0,02	0,7	1000	1400
Cored Brick	0,06	0,46	840	666,7
Plaster	0,02	0,7	1000	1400
External Wall, type1				
Plaster	0,02	0,7	1000	1400
Brick	0,30	0,35	840	686,7
Plaster	0,02	0,7	1000	1400
External Wall, type2				
Plaster	0,02	0,7	1000	1400
Insulation	0,06	0,036	1200	20
Brick	0,30	0,35	840	686,7
Plaster	0,02	0,7	1000	1400
Ceiling				
Ceramic tile	0,01	1	840	2300
Mortar	0,05	1,4	1000	2000
Concrete	0,22	0,46	840	666,7
Plaster	0,02	0,7	1000	1400
Ceiling Roof				
Plaster	0,02	0,7	1000	1400
Concrete	0,22	0,46	840	666,7
Bitumen	0,004	0,7	1000	1200
Insulation	0,12	0,036	1200	20
Air	0,04	0,31	1008	1,3
Tile	0,01	0,13	840	600

Table 1. Opaque structural elements stratigraphy and thermal properties.

Furthermore the configuration and the mean thermal properties of the window systems are reported in the table 2.

Window System (WS)						
Material	Thickness [mm]	Conductivity [W/mK]	Frame	R_{frame} [m^{2}K/W]	Solar factor	U_{window} [W/m^{2}K]
Glass	5,7	1				
Argon	6,4	0,017	40% of A_w	0,33	0,703	2,01
Glass	5,7	1				

Table 2. Window system stratigraphy and thermal properties.

Concerning the radiative coefficients, the long wave emissivity (ε), assumed equal to the long wave absorption coefficient, of the window frame and of the walls is 0.9, while it is 0.837 for the glass. Instead, regarding the short wave absorption coefficient (α), the window frame has a value of 0.4, the wall 0.35 and the glass 0.04. The figure 4 shows the location within the indoor environment of the different wall and ceiling typologies and the window systems.

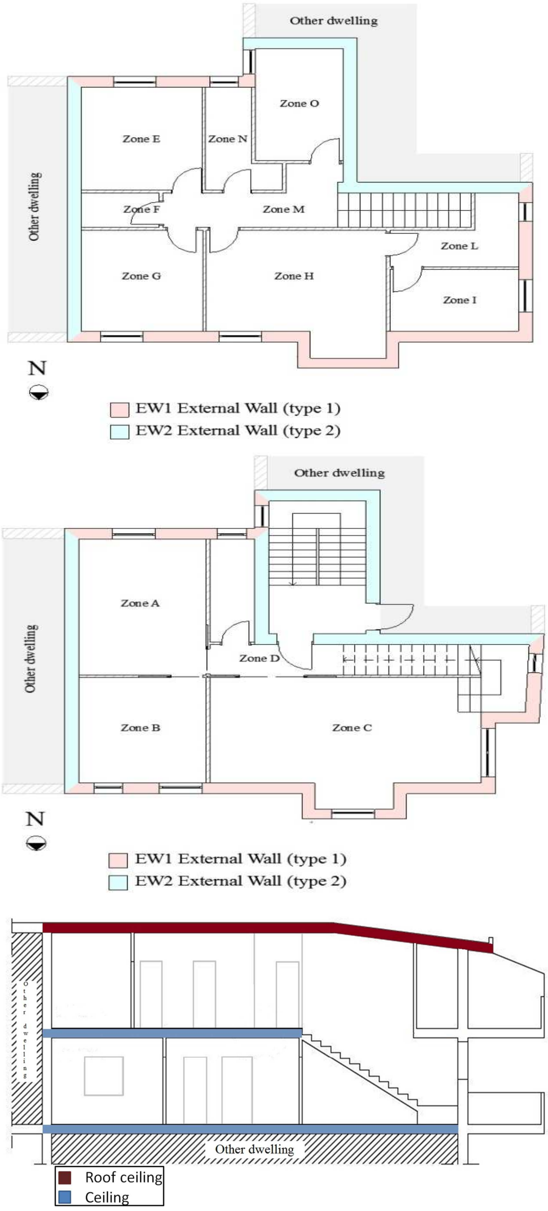


Figure 4. Location of the external wall types, house zone map and ceilings location.

The values of the internal and external superficial thermal resistances are respectively 0.2 and 0.05 m^2 K/W and the infiltration rate is 0.3 ac/h as the Italian standard suggests (Ente Nazionale di Unificazione, 2007). Moreover, the cooling and heating set point temperatures are respectively 26°C and 21°C.

PCM features

The PCM used in this research consist of hydrate salts; it is the SP25 PCM produced by Eps ltd. The related thermal properties are shown in the table 3. The parametric analysis related to the PCM thickness refers to a range of 5 - 15 cm considering a 2.5 cm pitch for both configurations, mounted into the ceiling and into the internal vertical partitions. The PMT related to this PCM is 25°C, but, concerning the melting temperature optimization analysis, a range of temperature (table 2) was taken into account leaving unchanged the PCM thermal properties.

PCM (SP25)	Melting Temperature [°C]	19 - 27
	Density [kg/m^3]	1530
	Heat Capacity (cp$_s$ and cp$_l$) [kJ/kgK]	2,2
	Latent heat [kJ/kg]	180
	Conductibility [W/mK]	0,54

Table 3. PCM thermal properties.

PCM mounted into the ceilings and into internal vertical walls

The figure below shows the ceiling configuration with PCM. The PCM is mounted exactly in the middle of the ceiling between the storey of the considered dwellings.

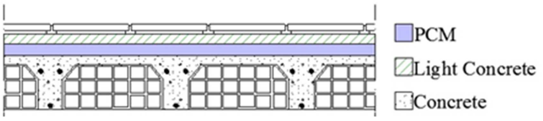


Figure 5. PCM ceiling stratigraphy.

Instead, the configuration of the case with the PCM mounted in the internal vertical walls are shown in the figure below. The PCM is located on one side of the cored brick of the partition as shown in the figure6.

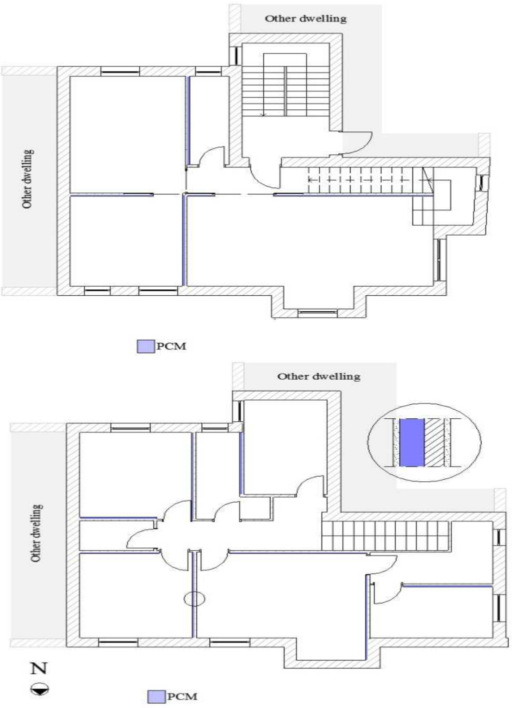


Figure 6. PCM internal vertical partition configuration.

DISCUSSION AND RESULT ANALYSIS

Reference case

The reference cases results, in terms of monthly and seasonal thermal energy requirements, both for cooling and heating related to the two considered cities are shown in the table 4.

	COSENZA	MILAN
MONTH	ENERGY NEED [kWh]	ENERGY NEED [kWh]
JANUARY	-1306.79	-2314.89
FEBRUARY	-1037.87	-1754.13
MARCH	-670.37	-1091.23
APRIL	-259.99	-372.28
MAY	10.35	-50.57
JUNE	432.73	281.77
JULY	820.14	613.60
AUGUST	732.76	419.43
SEPTEMBER	285.21	48.01
OCTOBER	-53.16	-455.86
NOVEMBER	-523.18	-1430.14
DECEMBER	-1145.39	-2180.81
HEATING ENERGY NEED [kWh]	-4996.76	-9649.92
COOLING ENERGY NEED [kWh]	2281.20	1362.81

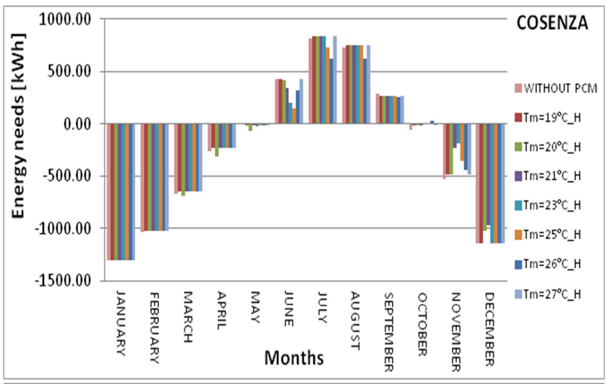
Table 4. Reference cases energy needs.

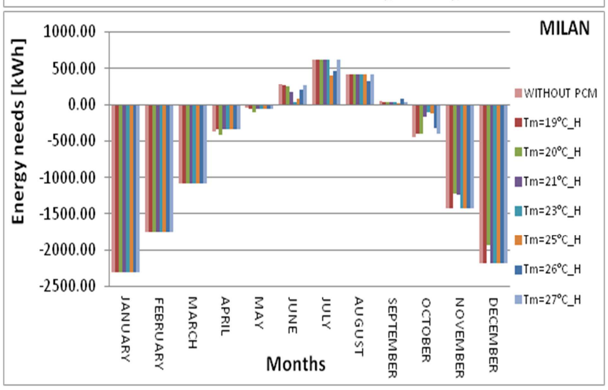
It is important to notice that the cooling loads are grater in the city of Cosenza than in Milan, while as regard the heating loads the situation is the opposite.

Melting temperature optimization analysis

The figures below show the monthly thermal energy needs considering a PMT range of 19 - 27 °C, fixing a PCM thickness of 7.5 centimeters, related to each considered cities for both mounting solutions, PCM mounted into the ceiling and into the vertical internal walls. The first two figures refer to the ceiling PCM configuration, while the others to the vertical internal walls PCM configuration.

CEILING





INTERNAL VERTICAL WALLS

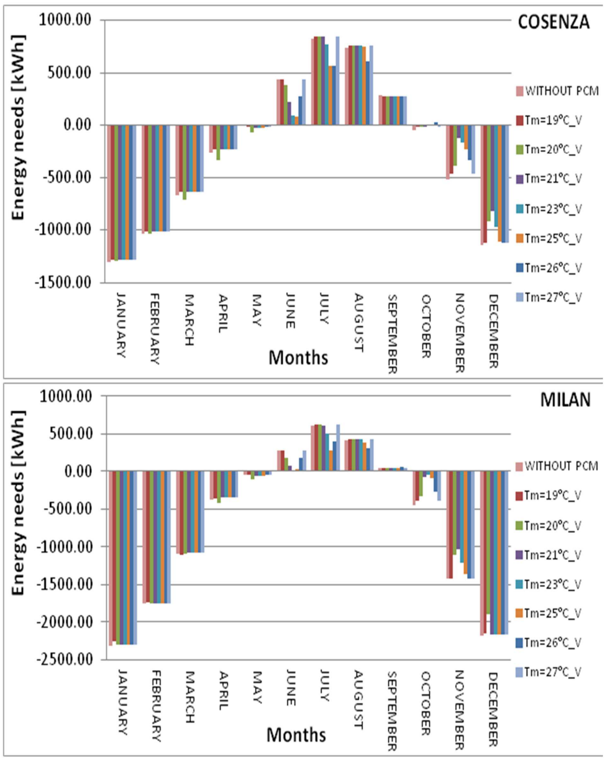


Figure 7. Monthly thermal energy needs considering a PMT range of 19 - 27 °C related to both mounting solutions for the two cities.

The best value of the PMT varies along the year (figure 7), moreover that value for a certain month changes as a function of the climate conditions and it depends on the considered mounting solution as well. It follows that, in order to achieve the optimized PMT, related to a conditioning season, a seasonal energy need analysis is necessary (figure 7). The percentage reduction between the winter and summer overall energy needs achieved by different PMTs and the reference cases energy needs are shown in next figures. In addition, the light colored bars refer to the horizontal wall (ceiling) solutions, while the dark bars to the vertical wall solutions.

It is easy to understand that there is one optimized PMT for each conditioning season. In particular, concerning the winter it is in all cases 21°C. Instead, there are two optimized PMTs for summer season: 26°C for the ceiling solution located in Cosenza, while 25°C for the others cases. Whereas the aim of this research is to compare different internal mounting solutions to decrease the building cooling loads an unique value of PMT has to be chosen. Therefore, a value of 25°C as PMT is considered.

PCM mounted into the ceilings and into the vertical internal walls

The figure 8 shows the energy needs as a function of the PCM thickness, mounted into the ceiling for the two different considered cities.

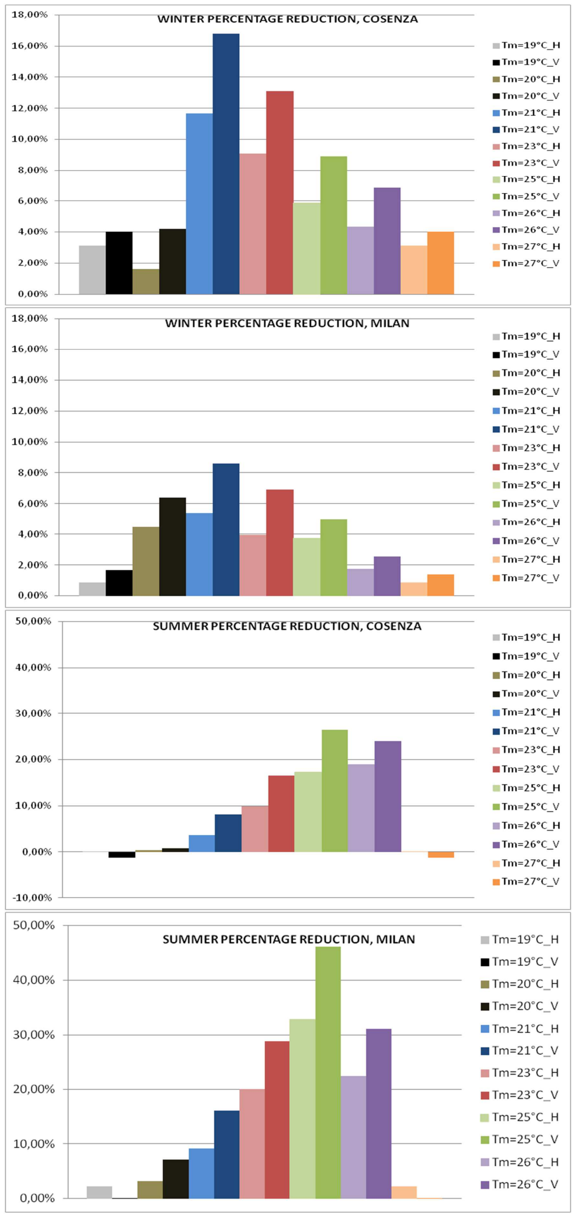


Figure 8. Percentage reduction between the winter and summer overall energy needs for different PMT value solutions and the reference cases energy needs.

As was to be expected, the chosen optimized PMT reduces much more the thermal cooling requirement rather than the heating loads (figure 9), because the latent effect of PCM during the heating season does not occur.

Along the year, it is possible to identify four different periods: the charge period, characterized by indoor superficial PCM wall temperature fluctuations that go over the PMT with an average value less than the PMT and a temperature increasing trend, the charged period, where the average indoor superficial PCM wall temperature is greater than the PMT, the discharge period, characterized in the same way of the charged period but with a temperature decreasing trend and the uncharged period, where the indoor superficial PCM wall temperature is below the PMT.

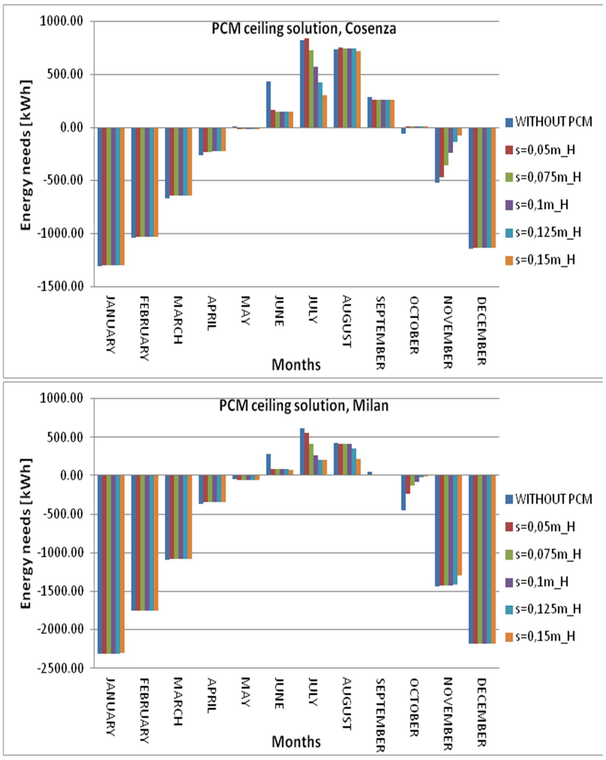


Figure 9. Ceiling solutions energy needs as a function of the PCM thickness for the two different considered cities.

As regard latent contribution it occurs only in the charge and in the discharge periods. All the abovementioned concepts deal with the set point temperatures. Specifically, the superficial temperatures of the internal structural element with PCM remain constant, equal to PMT, when the latent contribution occurs, on the contrary they always vary if the element does not contain PCM. This brings to an energy need variation as a function of the before defined periods. Therefore, benefits, in terms of energy needs, occur only during the charge and the discharge periods. The figure 9 shows that the charge period, in both cities, occurs in June and July, the charged period in August and September, the discharge period in October and November regarding Cosenza, while in Milan it occurs only in October and the uncharged period in the others months. In particular, in June a small PCM thickness is sufficient to reduce the cooling energy need and incrementing it no additional benefits are obtained. In July the positive effects of the charge period are much marked as much the amount of PCM is greater. The figure 10 shows this behaviour, in terms of superficial trend temperatures with different PCM thicknesses, without PCM and the external air temperature, for the external wall of the zone C (figure 4), in which there is the maximum advantage using PCM. Principally the internal superficial temperature decreases by increasing the PCM amount into the ceiling.

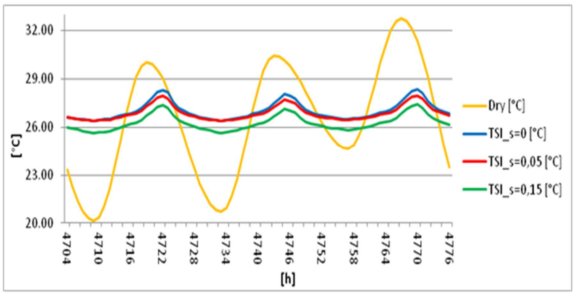


Figure 10. External wall indoor superficial trend temperature of the C zone and external dry temperature, location: Milan, month: July.

It is interesting to observe that in Milan a PCM thickness of 12.5 cm leads to the maximum benefit (figure 9) in July. In the charged period the PCM is in the overheating phase and the benefits that happen in Milan in August with an high PCM thickness are not due to the latent contribution, but to the largest PCM wall sensible heat capacity. In the discharge period the heat energy needs decrease by increasing the PCM thickness. Finally, in the uncharged period there are not advantages using PCM except in November in Milan, but this benefit is due to the increased PCM wall sensible heat capacity. The next figures show the energy needs as a function of the PCM thickness, mounted into the internal vertical walls for the two different considered cities.

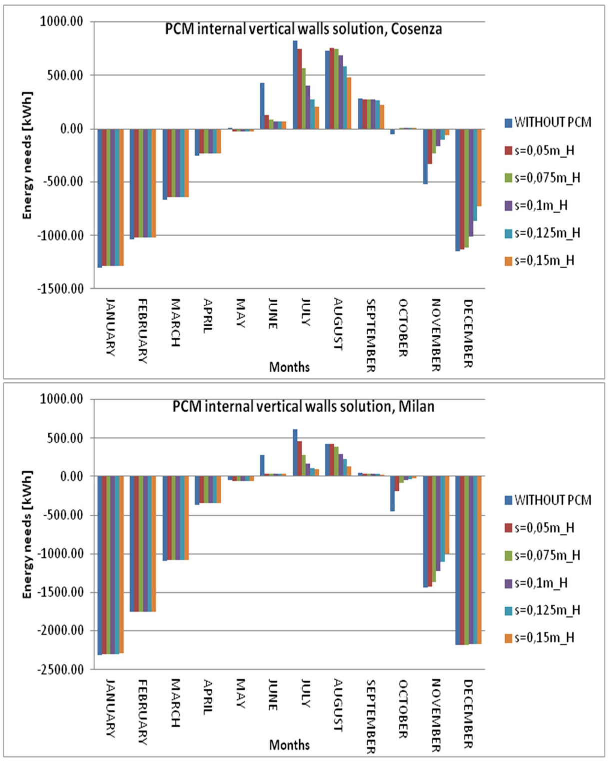


Figure 11. Internal vertical PCM wall solutions energy needs as a function of the PCM thickness for the two different considered cities.

In this case is possible to identify only the uncharged period: in Cosenza it goes from January to May while in Milan it goes from December to May. It is not possible to classify the remaining periods because there are at the same time zones characterized by a different PCM phases.

Comparison

In order to compare the proposed solutions, winter and summer energy needs percentage reduction respect to the reference cases for different PCM thickness are reported in figure 12. The best solution, in terms of energy needs, is PCM mounted into the internal vertical partitions, though the PCM quantity of the best solution is much higher than the PCM ceiling solution, because the internal vertical partition surface is more than the internal horizontal partition surface. Furthermore, it is important to notice that the winter energy savings in Cosenza are greater than in Milan for all cases, the opposite situation happens during summer. This is due to the fact that PCM benefits are much more significant during the conditioning system intermittence periods that happen during the charge and discharge periods.

CONCLUSION AND NEXT STEPS

In this research the thermal performance of one building with PCM mounted in the internal ceiling and in internal vertical walls varying the PCM thickness and comparing them with the cases without PCM taken as a reference, considering two Italian locations corresponding to two different climates, were studied. Furthermore a PMT optimization analysis were carried out as well in order to decrease the building cooling energy need. The results of the optimization analysis have showed that a deeper thermal analysis considering a zone level should be done in order to exploit the potential of PCM because its performance strongly depend by the thermal internal specific loads and especially by the zone orientation. A optimized PMT about 25°C was evaluated. The best solution, in terms of energy needs, is PCM mounted into the internal vertical partitions. As regard the cooling season an energy need reduction between 18% and 58% concerning Cosenza and between 30% and 80% for Milan related to a PCM thickness range from 5 to 15 cm were achieved. Instead, concerning the heating season the benefits are less showing a reduction about 20% in Cosenza and 9.2% in Milan related to the maximum PCM thickness of 15 cm. Furthermore, it is important to notice that the winter energy savings in Cosenza are greater than in Milan for all cases, the opposite situation happens during summer. The same analysis should be done at level zone, besides an energy savings analysis considering a PCM mounted on the external vertical wall solution should be studied in order to have a clear and more understandable pictures of the PCM building application.

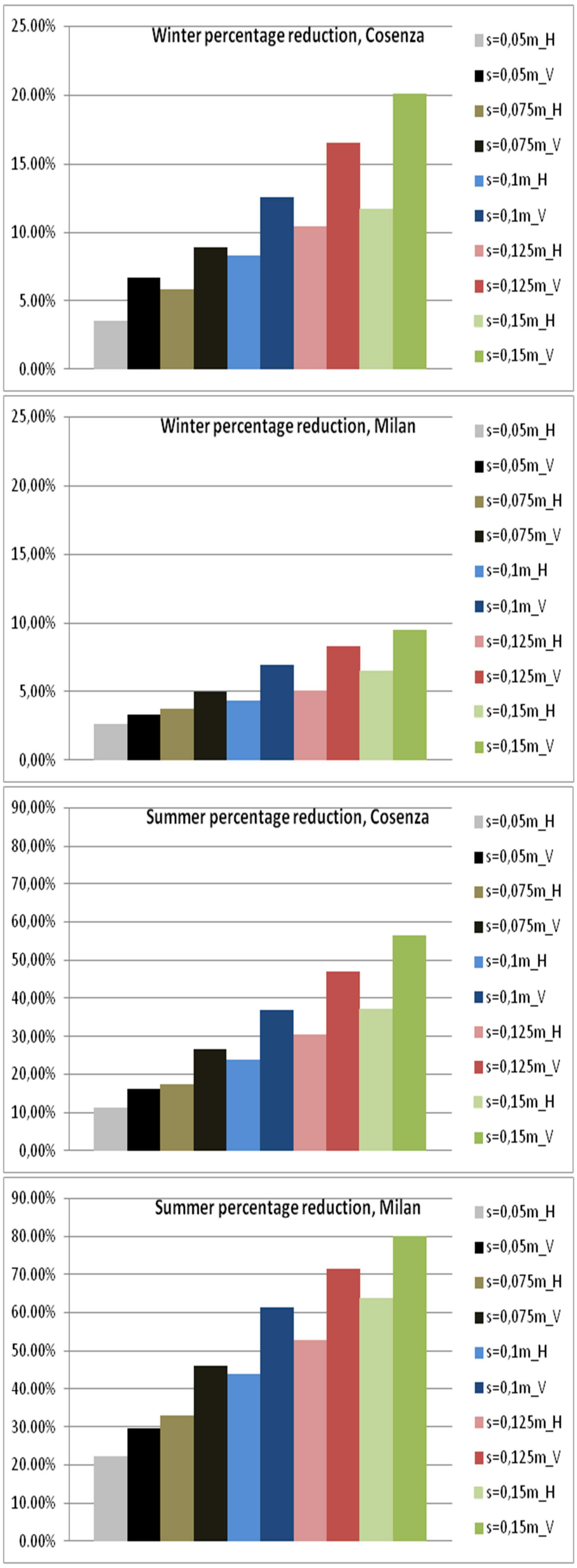


Figure 12 Percentage reduction between the winter and summer energy needs for different PCM solutions and the reference cases energy needs.

NOMENCLATURE

Symbols

T_f: temperature at the end of a timestep (°C).
T_i: temperature at the start of a timestep (°C).
$\dot{q}_1$, $\dot{q}_2$: quantities of energy entering the PCM from the adjacent wall layers (kJ/(h·m^2).
m_{PCM}: mass of the PCM (kg).
c_{p_s}: specific heat of the PCM when it is fully solid (kJ/(kg·k)).
c_{p_l}: specific heat of the PCM when it is fully liquid (kJ/(kg·k)).

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