Impact of Positioning Phase Change Materials (PCMs) within Building Enclosures on Thermal Performance

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ABSTRACT

Utilization of phase change materials (PCMs) in building enclosures as thermal energy storage systems (TES) has become a re-appearing topic within the research community in recent years. PCMs represent an innovative solution that can contribute to the improvement of energy efficiency and thermal performance of buildings. This paper aims to present results of experimental investigations regarding the effectiveness and differences of PCM positioning within building enclosures in terms of energy performance and thermal comfort. The experiments are conducted in a laboratory setting, more specifically in an environmental test apparatus, that allows for comparative testing of interior thermal and hygrothermal performance under different exterior climate scenarios. The paper discusses the experimental setup, the employed analysis methods, and findings of effects for different PCM positions in exterior wall configurations. It explores the observed differences and discusses potential opportunities that exist in regards to reducing overall thermal losses in enclosures and improving thermal comfort in interior spaces.

INTRODUCTION AND BACKGROUND

Phase change materials (PCM) are latent heat storage materials with a high heat of fusion that melt and solidify at a certain temperature (Kenfack and Bauer 2014). They have the ability to store and release high amounts of heat and energy for a required temperature range with lower temperature differences during phase transfer (Thomas et al. 2015). The temperature remains almost constant when these materials store and release thermal energy (Nkwetta and Haghighat 2014) and they can be used as a temperature controller (Cabeza and Mehling 2007). Typically, the heat storage capacity per unit volume of PCMs is much higher than the sensible heat storing capacity of materials (Williams 2009).

There is a worldwide focus on energy conservation and PCMs are expected to play an essential role in the near future. With PCMs features and products improvement for building applications, PCMs are expected to create new opportunities in the PCM market as well as their utilization as building materials (Mordor Intelligence LLP 2016).

PCMs have been studied for several years and considered for building applications to take benefit of the latent heat capabilities and high thermal storage densities. The characteristics of PCMs make them suitable to be used in buildings for energy savings, space/size saving, reducing building load, and reducing peaks in demand period (Kośny 2015). A PCM's main advantages come into play when they are used as building materials where spaces require more thermal storage capacity against changing boundary conditions that cannot be utilized through thermal mass layers within a building enclosure (Abuzaid and Reichard 2016). PCMs have been tested in various application as a thermal mass components in buildings, and most studies have found that PCMs enhance thermal performance in buildings (Kosny et al. 2007).

However, each building material has its advantages and limitations and new construction materials have emerged in the market. The selection of PCMs has to fit the application requirements (Gracia and Cabeza 2015). Moreover, any practical PCMs require at least: a proper melting point in the desired temperature range and high heat of fusion per unit mass and volume (Humphries and Griggs 1977), along with a suitable heat exchange surface and a suitable container compatible with the PCM (Sharma et al. 2009). In addition, there are a number of challenges and limitations of utilizing PCMs in building applications, such as: material compatibility, loss of phase-change capability, cost and availability, and health/safety and disposal (Richard 2013). These challenges and limitations generally depend on PCM type and properties and ultimately will have different impact at different positions within a construction assembly. While the motivation of utilizing PCMs in building construction has been discussed in aspects such as material properties and space applications and summarized by others (Pomianowski et al. 2013), the placement and effectiveness of products based on their positioning still needs more investigation.

PROBLEM STATEMENT

Air conditioning energy consumption in different seasons represents a challenge in many areas with hot and/or cold climates. Heating and cooling loads represent the largest part of energy consumption in buildings. According to the International Energy Agency (IEA), in most countries the average energy consumed by buildings represents 32% of all-inclusive worldwide energy consumption and with approximately 40% of the primary energy consumption (IEA 2015). Similarly, creating a thermally comfortable environment for occupants of buildings is highly desirable and maintaining indoor temperatures within the comfort zone is required in most occupied buildings. Saving energy and providing thermal comfort for building occupants are very important aspects to be considered by building designers, architects, engineers, and contractors, and these goals could be supported by utilizing PCM within building enclosure.

PCMs are still not commonly used as thermal storage in building construction as several challenges and questions exist regarding the application of PCMs as building materials within building enclosures. One of the questions is a lack of understanding the impact of PCM positioning within the building enclosure as a remaining challenge.

This paper assesses the effects of utilizing PCM in building enclosures and their benefits towards thermal performance by comparing interior versus exterior installation positions.

EXPERIMENTAL SETUP

To investigate the impact of using PCM on energy reduction and improving thermal comfort, laboratory experiments have been conducted. The aim of the laboratory experiments was to evaluate the implementation of PCMs in different positions by carrying out a comparative study. The tests have been conducted in an indoor environment to enable testing of PCMs under controlled climate conditions, while focusing on different positions for fixed periods of time. Placing the tests in an indoor laboratory allows for monitoring and controlling the experiment's environmental conditions and parameters as well as for moderating outside influences that would otherwise affect test results. The experiments were conducted in the same laboratory space, utilizing the same material properties, dimensions, equipment, and temperature ranges to study the differences of results among different positions (exterior and interior sides of a wall cavity) of a PCM in a building enclosure and compare results with a wall without utilization of PCMs. These experiments were conducted under controlled conditions for a set running time for heating and cooling periods of 12 hours each. The evaluation included monitoring how PCMs overall behave in different temperature ranges and positions, as well as their ability to reduce temperature fluctuations across wall components and influence on peak-load shifting.

For this test, a 5.0 cu ft chest-freezer was used to facilitate the cold exterior temperatures and three light bulbs (40 watts each) to create the hot exterior temperatures within the chest for comparison. Figure 1 shows the experimental setup of the study and illustrates how equipment and devices have been connected. Wireless HOBO ZW data nodes and sensors were used to measure and log inside and outside temperatures for both surfaces, interior (room-side) and exterior (chest-side) air temperatures, and several temperatures across the different layers of the wall components. The data loggers were configured to collect data at 1-minute intervals. For controlling the time of heating and cooling periods, wirelessly programmable WEMO switch devices were used to program and monitor the On/Off timing cycles. To maintain the periods of predefined "exterior" temperatures within the chest chamber, this study used digital temperature controllers (WILLHI WH 1436) to control set point temperatures of heating and cooling for each scenario. Figure 2 shows the control panel utilized in the study and devices that have been used in the experiments.

To record temperatures, eight thermocouple sensors were used (type TMC-HD and TMC-HC). Three sensors were used to measure temperatures with relative humidity (type RHPCB) to capture exterior and interior climate, as well as one cavity position. To capture the changes in the PCM phase a temperature sensor was placed on each side of the PCM. Figure 3 illustrates the test apparatus with interior and exterior setup configurations as well as the position of sensors utilized in the study.

Figure 1 Experimental setup with data logger and computer

a) b) c) d)

Figure 2 a) Control panel assembly; b) data logger node and receiver; c) timer modules; and d) temperature controller

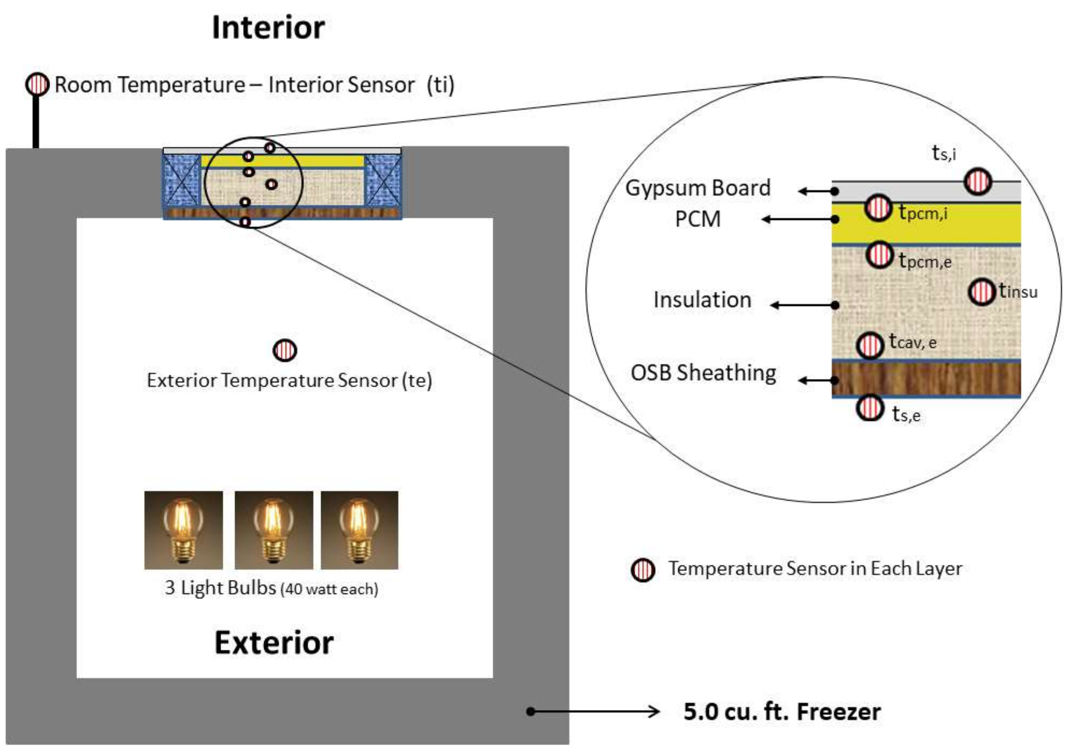


Figure 3 Schematic diagram of the experimental setup and sensor positions

In total, nine sensors were used throughout the experiments. Table [1] shows the taxonomy used for these sensors and their correlating positions.

Table [1] Sensors and Positions

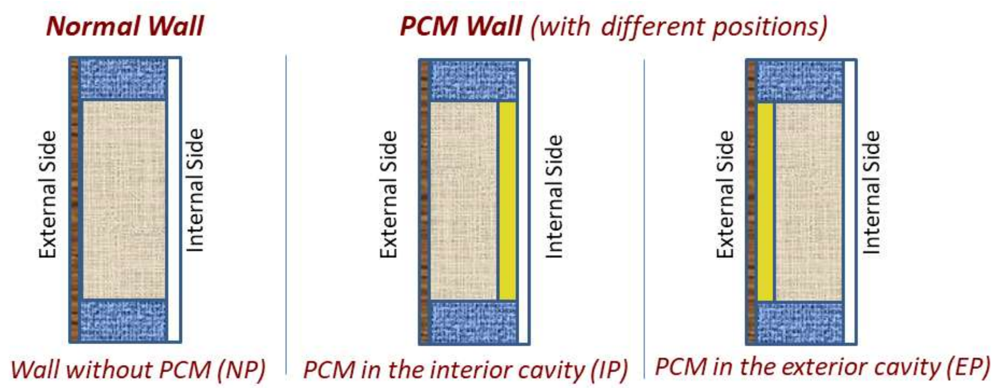
Sensor Name	Position
t_i	Temperature of interior
$t_{s,i}$	Temperature of surface (interior)
$t_{cav,i}$	Temperature of cavity (interior)
$t_{pcm,i}$	Temperature of PCM (interior side)
$t_{pcm,e}$	Temperature of PCM (exterior side)
t_{insu}	Temperature of insulation
$t_{cav,e}$	Temperature of cavity (exterior)
$t_{s,e}$	Temperature of surface (exterior)
t_e	Temperature of exterior

Description of Specimens:

The studied specimens were based on a common cavity filled stud wall, which was then expanded with different PCM configurations. In total, three specimens were used in the laboratory experiments:

1. A specimen without any PCM layer (NP),
2. A specimen with a PCM layer at the exterior side of the cavity (EP), and
3. A specimen with a PCM layer at the interior side of the cavity (IP).

The wall specimens were mounted into frames made of extruded polystyrene (XPS) foam and contained gypsum board for the internal sheathing layer, a cellulose insulation layer, the PCM (Bio-based PCM mat), and an oriented strand board (OSB) for the external sheathing layer (Figure 4 . All specimens had the same dimensions of 40 cm x 40 cm with a total thickness of 15 cm.



	Wall without PCM (NP)		Wall with PCM (IP)		Wall with PCM (EP)	
Layers	Material	Thickness	Material	Thickness	Material	Thickness
	Internal surface	--	Internal surface	--	Internal surface	--
	Gypsum board	1 cm	Gypsum board	1 cm	Gypsum board	1 cm
	Insulation	12 cm	PCM	1.5 cm	Insulation	10.5 cm
			Insulation	10.5 cm	PCM	1.5 cm
	OSB sheathing	2 cm	OSB sheathing	2 cm	OSB sheathing	2 cm
	External surface	--	External surface	--	External surface	--

Figure 4 Sections of wall specimens and utilized materials

The utilized PCMs had the following properties and dimensions as shown in Table [2].

Table [2] PCM`s Properties

Item	Description / Value
Manufacturer	Phase Change Energy Solutions – (USA- Asheboro, NC)
Material Name	ENRG Blanket Q23/M27 - Bio-based PCM mat - Solid/Liquid phases
Filling	Natural vegetable oils and proprietary blend of emulsifiers, gelling agents, fatty acids, and their derivatives
Encapsulation (thickness)	15 mm (Multilayer white polyfilm)
Melting Point	23°C
Latent Heat Storage Capacity	175-250 J/g
Weight	2.49 kg/m²

Experimental Limitations:

This study is limited to thermal aspects in building enclosures, specifically in an external wall. Outdoor temperatures were controlled at fixed temperature differentials for exactly timed hot and cold periods. Phase change processes were limited to solid-liquid transformations as the utilized PCM was a bio-based matt with a melting point of 23 °C and the temperature differential never exceeded more than 25 °C.

Detailed assessments of HVAC loads, heat flux, or overall energy consumptions, variations of design materials, or impact of relative humidity were not addressed. The experiments were focusing on temperature changes only and the effects of the PCM during heating and cooling in different positions within the building enclosure.

A future study with test cycles replicating real climate data and measurements of heat flux along with energy consumption will provide a broader understanding of PCMs' impact on the thermal performance of the building enclosure.

METHODOLOGY

Experimental Procedure

The objective of this study was to experimentally evaluate the impact of different positions of a PCM within the building enclosure on thermal performance. The study employed the same experiment with three different specimens to assess the impact of the different PCM positions: 1) a wall with a PCM at exterior side of the wall cavity (labeled as EP for *exterior PCM*), 2) a wall with a PCM at the interior side of the wall cavity (IP for *interior PCM*), and 3) a wall without PCM application (NP for *no PCM*). Each experiment was conducted for 48 hours with two cycles of 12 hours of cooling and 12 hours of heating each. Each experiment started with a cold period by turning on the freezer for 12 hours to make sure that the PCM completely reached the solidifying phase. Then, the warm phase was initiated by turning on three light bulbs within the chest freezer to reach and maintain the hot climate setpoint for 12 hours alternately. The 12-hour cycle was selected to achieve complete melting and freezing phases of the PCM through each cycle.

The controlled setpoint temperatures for the exterior climate were based on the maintained interior laboratory room temperature. Exterior temperatures were held at 45 °C for the hot periods and at 0 °C for the cold climate periods, while the set point of the room temperature was kept between 22-23 °C, which represents the range of the melting point of the utilized PCM. The recorded indoor temperatures across all experiments showed less than 2 °C of fluctuation. Figure 5 shows an overlay of all recorded interior and exterior temperatures across all the different 48-hours experiment cycles. Relative humidity was monitored and recorded, but not considered for the analysis of this study.

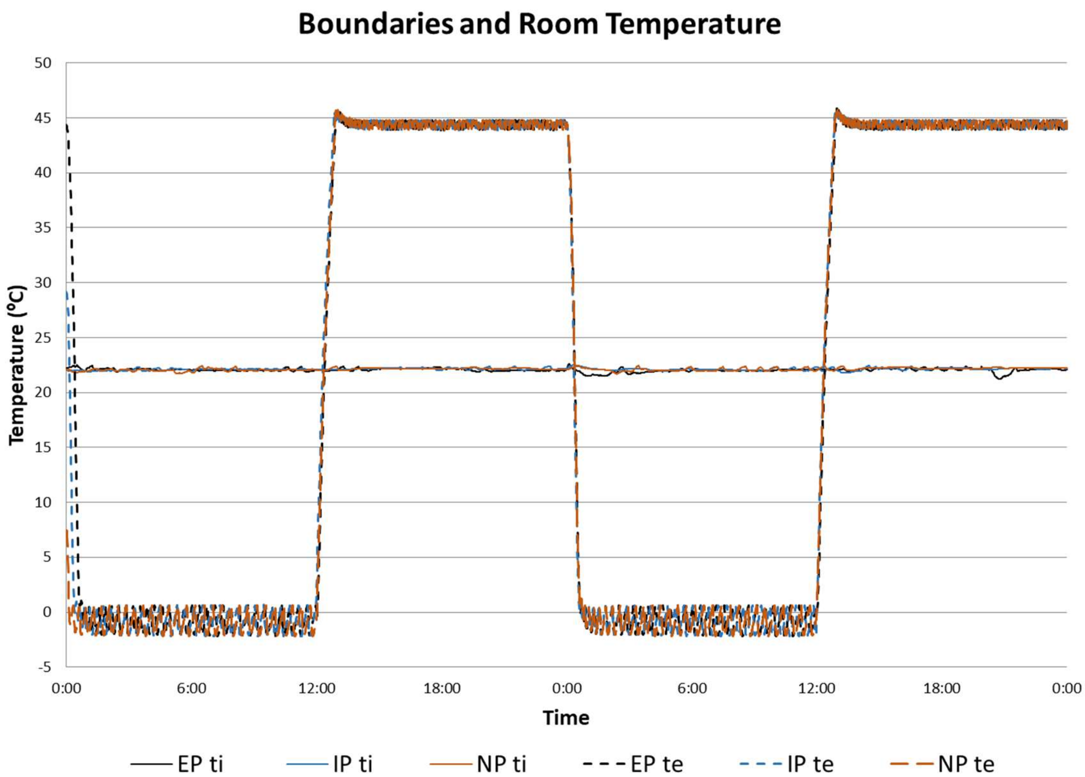


Figure 5 Recorded interior and exterior temperatures during cycles

Analysis Methods

The analysis of the experimental results focused on the impact of PCMs in different positions in terms of thermal performance and peak-load shifting during heating and cooling times. The study therefore focused on three stages of analyses:

Differential Result Patterns of PCMs in different Positions

In a first analysis stage, a quantitative comparison of temperatures over time was carried out to identify areas of difference for further investigation and discussion. The experimental results were cleaned and then presented in graphical form. A comparative discussion of temperature data during the hot and cold phases for each PCM position was conducted.

Analysis of impact of PCM positioning on thermal comfort

The second analysis stage focused on evaluating the impact of PCM position on thermal comfort by observed and analyzing differences in surface temperatures. As surface temperatures are critical indicators for thermal human comfort, this analysis developed a metric termed *Comfort Degree Minutes* that integrates the difference between room temperature set points and recorded surface temperatures against a temperature threshold (replicating the thermostat reaction range) for each PCM position.

$$CDM_{th} = \sum \mid t_{s,i} - t_{th} \mid \cdot \Delta m \quad for\ all \quad t_{s,i} \geq t_{th}$$

where

$t_{s,i}$ … the interior surface temperature in °C
t_{th} … the reference (threshold) temperature in °C
Δm … the time interval in minutes

Analysis of impact of PCM positioning on peak load shifting

The third analysis stage investigated the impact of PCM positions on peak load shifting. This analysis was based on the comparison of the crossover points of temperatures when changing from cold to warm phases and vice versa in the different experimental cycles. The recorded time was considered an indicator of the amount of peak-hour shift that could be achieved for a given assembly. The underlying assumption is that any capability of capturing internal thermal loads of heating or cooling cycles and shifting them to off-peak periods could contribute to energy savings, either through short-term changes in climatic boundary conditions at the shifted time (e.g. use of economizers), or alternative grid demand and generation cost. The analysis used a graphical assessment method through scaled result diagrams to evaluate the ability of latent heat storage in different positions to shift peak loads and discuss notable savings potentials.

RESULTS AND DISCUSSION

Overall, the results of the experiments confirmed the latent changes through delayed changes of temperatures in different positions of the specimen profiles of specimen layers that were to be expected when utilizing PCMs.

Differential Result Analysis of PCMs in Different Positions

There were several observation made in the first analysis stage that utilized graphical methods for comparison of recorded results. A graphic overlay of all experiments confirmed that the results showed reasonable repeatability of the PCM behavior in each position during the various solidifying and melting phases with consistent performance in each cycle. Similarly, the PCM specimen showed the same behavior under repeated tests.

In terms of temperature differences over time, it was observed that when the PCM was placed on the exterior side of the cavity (EP), the temperature differences between interior ($t_{pcm,i}$) and exterior ($t_{pcm,e}$) side of the PCM were more pronounced than when placed on the interior side (IP) of the cavity. For EP experiments, the melting and freezing periods are clearly visible where the temperature difference widens and becomes larger than the standard proportional difference of the material's thermal resistance.

Furthermore, when the PCM was utilized in the exterior position (EP) of the wall, it reacted faster, but it did not reach its steady state in either cycle. In contrast, when the PCM was utilized in the interior position (IP), it reached a steady state condition in each phase after 4-6 hours. In both positions, the PCM activated its thermal storage capacity, but its performance during the freezing phase was slightly better than its performance during the melting cycle (Figure 6).

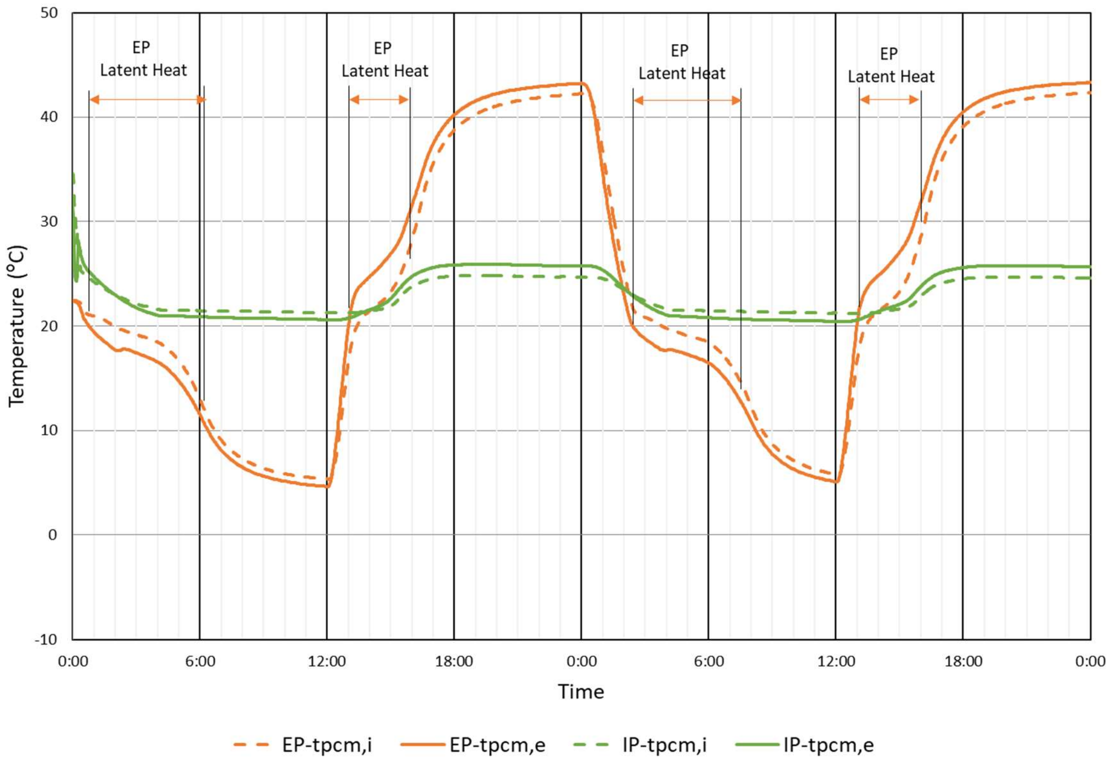


Figure 6 Comparison of temperatures showing PCM activation during exterior (EP) and interior (IP) cavity placement

For the warm exterior climate periods, an effect of increased heat transfer at the exterior surfaces was detected, where surface temperatures exceeded the recorded exterior air temperatures that were controlled by the thermal sensors of the switching device. The increased heat transfer effect can be attributed to an increased radiant heat exchange through the utilization of light bulbs as a heating source, which in turn has an impact on temperature of the external surface ($t_{s,e}$) of the specimen. This effect was observed across all experiments. More specifically, the effect accrued over time, as more and more heat is absorbed through radiation, bypassing the conduction and convective exchange through air.

There are differences between the scenarios at which time the $t_{s,e}$ exceeded the exterior air temperature t_e. Notably, this delay was most pronounced (4 hours) for the experiment when the PCM was placed in the exterior position of the cavity (EP). For the interior position (IP), the effect of radiant heat exchange made $t_{s,e}$ exceed t_e within 2 hours. Figure 7 shows the effect of radiant heat exchange on the external surface temperature during heating cycles.

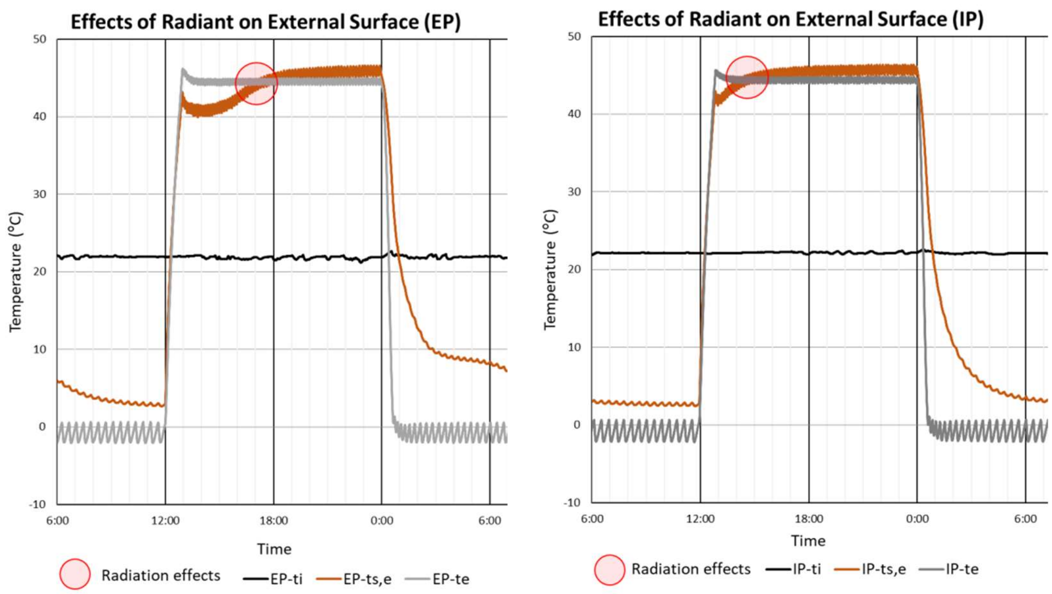


Figure 7 Effect of the radiant heat exchange observed at external surface

Analysis of impact of PCM positioning on thermal comfort

This phase of the study analyzed the measured temperatures of the experiments in terms of their effect on thermal comfort. For this evaluation, calibrated and measured interior surface temperatures were utilized as contributing metrics towards broader comfort considerations. Figure 8 shows a comparative distribution of the measured surface temperatures of all specimen types across the entire experimental cycle. However, the first cold and hot temperature cycles are less practical for evaluation but are rather considered as a "swing-in" phase as a starting vector of boundary conditions. For detailed analytical evaluations, only the second cold and hot temperature phases were evaluated (hours 24-48).

The impact on comfort was assessed through calculating a specific metric that was developed for this study and termed "comfort degree minutes" (CDM), as it captures temperature differences between interior surface temperature ($t_{s,i}$) and its offset from the interior setpoint or threshold temperature. Figure 9 illustrates this method graphically, where the area between $t_{s,i}$ and the cut-off threshold temperature represents the CDM value.

The comfort degree minutes for the different specimen were calculated as follows:

Table [3] Comfort Degree Heating Minutes (CDM-H) when switching to hot climate

	EP	IP	NP
CDM-H-22.5	281	343	664
CDM-H-23.0	46	112	359

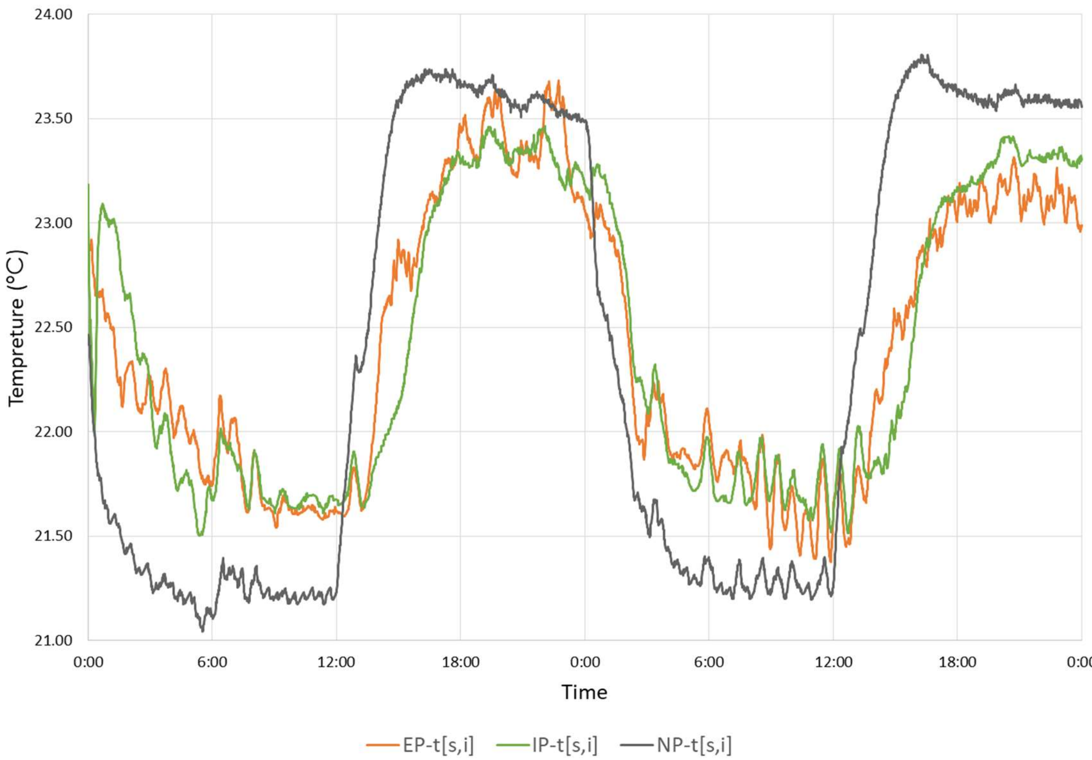


Figure 8 Interior surface temperatures ts,i for the different wall specimens

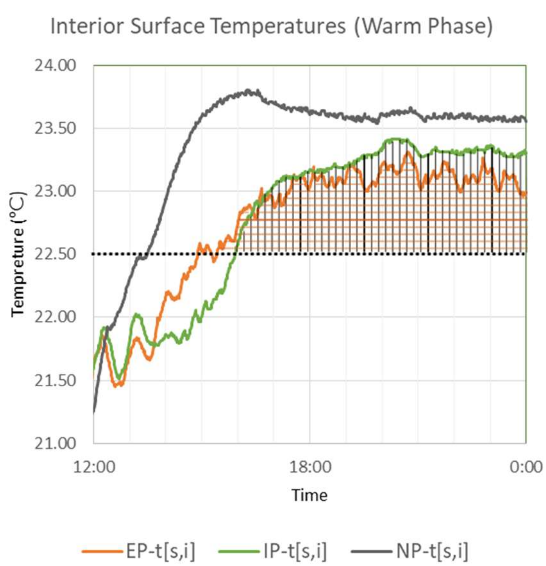


Figure 9 Visualization of assessment of Comfort Degree Minutes CDM-22.5

Table [4] Comfort Degree Cooling Minutes (CDM-C) when switching to cold climate

	EP	IP	NP
CDM-C-22.5	394	413	852
CDM-C-22.0	116	117	383

The results of these assessments illustrate that specimen EP shows the smallest number of CDMs followed by specimen IP when moving from a cold to the hot climate. When undergoing the reverse change moving from the hot to the cold exterior phase, no significant difference is observed between the two PCM positions EP and IP, while again a notable difference can be observed for the specimen without PCM (NP). These results indicate a slight advantage for PCMs in the exterior position of the cavity, but further tests will have to be conducted to verify this observation in connection with other material combinations.

Analysis of impact of PCM positioning on peak load shifting

PCMs are known to help deflect or at least defer cooling or heating demand over a certain time while actively changing their phase. This effect shows well throughout the experiments of this study. To compare the different positions of PCM placement in terms of contributing to any load shifting effect, a graphical analysis was utilized to measure the achievable lag during hot and cold periods.

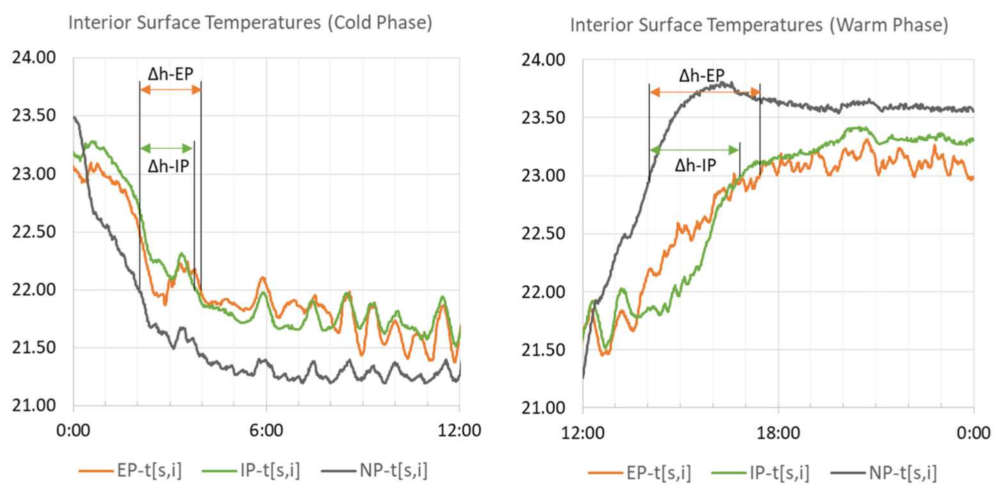


Figure 10 Interior surface temperatures ts,i for the different wall specimen

Both positions showed significant lag times when shifting from the cold to the warm exterior climate periods. However, the EP specimen achieved a slightly bigger lag of more than 3 hours in these experiments, while the IP position only achieved around 2.5 hours. Interestingly enough, when switching to cold periods the effect becomes less visible and the differences are less pronounced between the two PCM positions. In both scenarios, it can be observed how the temperatures of the interior surface ($t_{s,i}$) start merging again as the phase change effect wanes off.

Obviously, the amount of time lag that can be achieved is in direct relation to the amount of PCM utilized, which can be altered by design if needed. The purpose of this study was only to investigate eventual differences between positioning the PCM. From the preliminary results obtained in this study, it seems that the exterior position provides some advantage in terms of deflecting and deferring eventual cooling loads, while there is only limited evidence of impact in terms of positioning for postponing heating loads. Further studies in larger scale experiments will be pursued to verify these initial findings.

CONCLUSION

Experiments have been performed on three types of specimens incorporating a PCM in the different positions of a wall cavity. Both numerical and graphical result of PCM responses across all experiments have been studied. The effects of PCM positioning on thermal comfort and load shifting were measured for alternated but periodically fixed cold and warm exterior climate cycles. The results of these assessments indicate that wall elements with PCM in exterior cavity positions show a more practical position towards thermal comfort. Either position showed significant lag times, specifically when moving from cold to warm exterior climate periods. There again, walls with PCM in the exterior position achieved a slightly bigger lag time than walls with PCMs on the interior side.

This study did not take into account broader impacts on overall energy consumption, or measurements of median radiant temperatures for an entire space, which could add further evidence to the comparison. Overall, the study demonstrates some advantages for PCMs to be installed towards exterior positions of a wall cavity, but further studies will be conducted to verify this observation with larger-scale experiments and in connection with other material combinations.

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