A Study of Phase Change Materials for Energy Conservation in Classic Multi-Layered Victorian-era Buildings: A Practical Approach for Balancing Heritage Preservation and Climate Neutrality in Temperate Climates

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Abstract

An integration of phase change materials (PCMs) into building designs presents a promising avenue for energy conservation, temperature stabilisation and zero emissions. European countries, renowned for their historical Victorian-era buildings, grapple with the challenge of balancing preservation imperatives with modern energy efficiency requirements. This study investigates the high efficacy of PCM integration in a typical thick multi-layer structure characterised by the external walls of Victorian-era buildings in a temperate climate, aiming to align with the EU's climate-neutral strategy by 2050 while safeguarding heritage structures. The experimental findings have shown that PCM layers positioned near the outer wall of multi-layered structures in temperate climates often failed to attain the requisite phase change temperatures. However, the identified optimal placements between 88% and 93% away from the wall's external surface resulted in significant energy savings. Typically, a reduction in cooling energy consumption by 5.3% to 6.2% was observed. The strategic positioning of the PCM layers contributed to enhanced indoor comfort levels, as evidenced by an expanded temperature range up to 7.9°C and mitigated peak temperature fluctuations of 1.74°C to 2.0°C. These findings underscore the practical benefits of PCM application in thick and multi-layered building designs. By bolstering peak temperature reduction and thermal regulation without compromising architectural integrity, a PCM integration has the potential to be a viable solution to the challenges posed by energy consumption in historical buildings.

Keywords: **Thermal energy storage (TES), Phase change materials (PCMs), Multi-layer, Multi-layer, Buildings.**

1. Introduction

The building sector represents a substantial portion of global energy usage, comprising 40% of consumption, and contributes significantly to greenhouse gas emissions, accounting for one-third of total emissions worldwide [1]. Recent decades have witnessed a notable surge in energy demand within this sector, driven by population growth and heightened living standards [2, 3]. This trajectory forecasts a continued reliance on fossil fuels as the primary energy source unless stringent measures, such as the enforcement of minimum performance standards and building energy codes, could be implemented to align the sector with Net Zero Emissions goals by 2050 [4, 5]. However, finite fossil fuel reserves and escalating concerns surrounding greenhouse gas emissions underscore the urgent need to prioritise efficient energy utilisation [6].

The recent IPCC's Sixth Assessment Report emphasises the urgent need to mitigate global temperature rise and reduce carbon emissions to prevent surpassing critical climate thresholds [7]. Temperate climates, characterised by fluctuating temperatures ranging from -5°C to 30°C and marked by seasonal and daily fluctuations, pose unique challenges due to their significant heating and cooling demands. These conditions necessitate innovative energy-saving solutions. In light of these challenges, this study explores the application of phase change materials (PCMs) primarily as thermal storage systems rather than conventional insulation materials in classic multi-layered Victorian-era buildings. PCM surpasses the traditional insulation by actively storing and releasing latent heat to stabilize indoor temperatures, reducing reliance on active heating and cooling systems while offering adaptable, space-efficient thermal regulation and lowering peak energy demands. By balancing heritage preservation with the goal of climate neutrality, this research provides a practical solution for reducing energy consumption and carbon footprints in temperate climates. Aligned with the IPCC's call for urgent actions, this work contributes to the global effort to decarbonize infrastructure while safeguarding cultural heritage amidst the accelerating impacts of climate change.

Research into innovative technologies, particularly novel thermal energy storage (TES) systems, burgeons and aims to mitigate buildings' reliance on fossil fuels. TES implementation offers a pathway for augmenting energy conversion efficiency and optimising the utilisation of diverse heat sources [8]. Thermal energy can be effectively stored through the sensible heat of solids or liquids, the latent heat of Phase Change Materials (PCMs), or the chemical reaction of specific substances [9, 10]. PCMs are distinguished by their significant heat of fusion, enabling them to store and release substantial energy upon melting and solidifying at the predetermined temperature [11]. Consequently, PCMs operate as latent heat storage (LHS) units, as heat is absorbed or released during the solid-liquid phase transition [12]. Figure 1 illustrates the two typical types of PCMs used for thermal energy storage. Organic PCMs, such as paraffin and non-paraffin types, offer high heat storage density, long lifespan, and stable performance but are expensive to produce. Inorganic PCMs, like salt hydrates, are cost-effective and have high latent heat capacity and thermal conductivity but risk super-cooling, which can impact their performance. Eutectic PCMs combine organic and/or inorganic components, providing adaptable properties for specific applications.

a) Organic PCM b) Inorganic PCM

Figure 1. Typical types of PCMs: (a). Organic PCM. (b) Inorganic PCM

Kulumkanov et al [13] investigated the impact of PCMs on building cooling, heating and annual energy efficiency for future climate scenarios (2095) across 13 climate zones worldwide, using the Fanger comfort model and EnergyPlus simulations. A maximum reduction of 12.9% in annual energy demand with PCM integration was reported. Samiev and Ibragimov [14] conducted an exhaustive examination of the annual thermal performance of a passive solar heating system incorporating a Trombe wall enhanced with PCMs in a 3-room residential building in Uzbekistan in hot climatic, revealing a substantial reduction in energy consumption, with a minimum decrease of 36% attributed to the use of PCMs within the Trombe wall. Vukadinovic et al [15] investigated the energy performance implications of PCMs in thermal storage walls in detached residential buildings across five diverse locations in Serbia, revealing significant improvements in energy efficiency and identifying the mid-wall position as the most efficient configuration across all examined locations. Li et al. [16] conducted a comprehensive investigation into the influence of repositioning, thermo-physical properties, and the thickness of PCM relative to the wall thickness. It was reported that PCMs generally attenuated temperature fluctuations with the RT-27 type PCM of 1 cm thickness and reduced heat ingress by 12.06% during summer when the PCM melting temperature closely matched room temperature. However, doubling the PCM thickness did not proportionally reduce heat transfer. Dong et al [17] evaluated the energy flexibility and saving potential of PCM-integrated walls under different precooling strategies. They reported that optimised precooling and peak-to-valley electricity tariff differences can increase energy flexibility up to 69.7%, reduce total load by 1.3%, and save electricity costs by 51%, with PCM locations and melting point being the most significant factors.

The potential of phase change materials in reducing building energy consumption is significant [18], particularly in regions characterised by cold climates and prolonged winters. A study to explore PCM integration in retrofit panels for buildings in Ottawa and Brasilia yielded heating and cooling savings, with Ottawa achieving 13% and 8% savings, respectively [19]. Despite the positive results, the long payback period and climate dependence limit the broader applicability, justifying the need to focus on more cost-effective, localized retrofitting for historic buildings. Effective integration of PCMs requires careful selection of wall materials based on thermal performance analyses, making PCM walls versatile year-round. While most research has concentrated on warmer climates, there is significant potential to investigate their use in temperate regions to tackle specific heating challenges [20]. European countries, renowned for their Victorian architecture and history, often grapple with high energy consumption and costs due to outdated building designs lacking modern energy efficiency standards [21, 22]. PCM technology can stabilize indoor temperatures by storing and releasing heat, cutting the need for constant heating and cooling [23, 24]. This presents significant opportunities for energy savings and decreased reliance on traditional heating methods [25, 26]. As the construction sector increasingly prioritises sustainability, the adoption of PCM walls not only meets the growing demands of the market but also aligns with standards such as the EU 2050 long-term strategy [27], and could potentially make them eligible for incentives.

The prior research on integrating PCMs in building structures has predominantly focused on configurations and materials suited for warmer climates or those considered impractical for typical Victorian buildings in temperate environments [28]. A few studies provided a useful review of PCM benefits for passive cooling in hot climates; however, neither empirical data on integrating PCMs into heritage buildings is available, nor are practical or economically feasible solutions for scalability [29]. A study showed that granular PCM in lime-based plaster improves thermal performance by 9% to 18% in historical buildings [30]; however, it is narrower in scope compared to this study's focus on PCM integration in multi-layered wall systems for broader energy efficiency and heritage preservation. Another research effectively explored energy efficiency and retrofitting in non-residential public buildings, but its focus on modern structures and generalized strategies contrasts with the current study's targeted approach of integrating PCMs in multi-layered historical walls to address energy efficiency while preserving architectural heritage [31]. A separate study [32] examined energy retrofitting in historic buildings using gypsum composites, showing a 20-30% energy reduction and proving cost-effectiveness. While the simulation's reliability was demonstrated with a 13.06% error margin, its real-world applicability remains uncertain.

Additionally, the focus on PCM applications has often disregarded the specific requirements of thick, multi-layer walls characteristic of Victorian-style heritage buildings, particularly in temperate climates. Many studies have proposed wall construction materials that are prohibitively expensive and unsuitable for traditional heritage structures. A study on low-cost SiO_2 aerogel (WSA) showed its potential as a cost-effective insulation alternative, cutting costs by 53% compared to atmospheric pressure drying and 21.5% compared to commercial aerogels. WSA demonstrated excellent thermal conductivity (0.02114 W/(m·K)), high hydrophobicity (150°), and enhanced strength when integrated into ultrafine glass fibre wool felt (UGFW). These findings highlight the need for affordable, high-performance materials suited to heritage buildings and multi-layer wall systems [33]. Other studies often suggest simple two to three wall-layers employing local materials, diverging from multi-layer buildings in which authentic local materials are commonly used, such as the three-layer BioPCM27 and Infinite RPCM21C [34], which reflect modern construction techniques. These techniques diverge from the traditional thick, solid masonry walls of Victorian buildings, highlighting the need for further research into PCM integration with authentic heritage materials. Few investigations have explored integrating PCMs into structures made with local authentic materials in multi-layer wall constructions, typical of European heritage architecture. Most studies concentrate on single bricks or configurations combined with other materials, which are not economically viable for broader applications [35, 36, 37]. Addressing this gap is critical to explore the potential of PCMs in real, thick-walled, multi-layer Victorian structures to improve energy efficiency [38, 39] while preserving their architectural integrity. Such work supports both heritage conservation and aligns with the EU's climate-neutral goals by 2050.

To preserve the cultural significance of heritage buildings, PCM integration must also prioritise aesthetic and material compatibility. Any direct contact with decorated or fragile surfaces should be avoided to prevent thermal stresses or mechanical damage [40]. While simulation studies have explored PCM applications in heritage structures, real-world implementations remain scarce, underscoring the importance of careful design and placement to ensure compatibility with conservation principles.

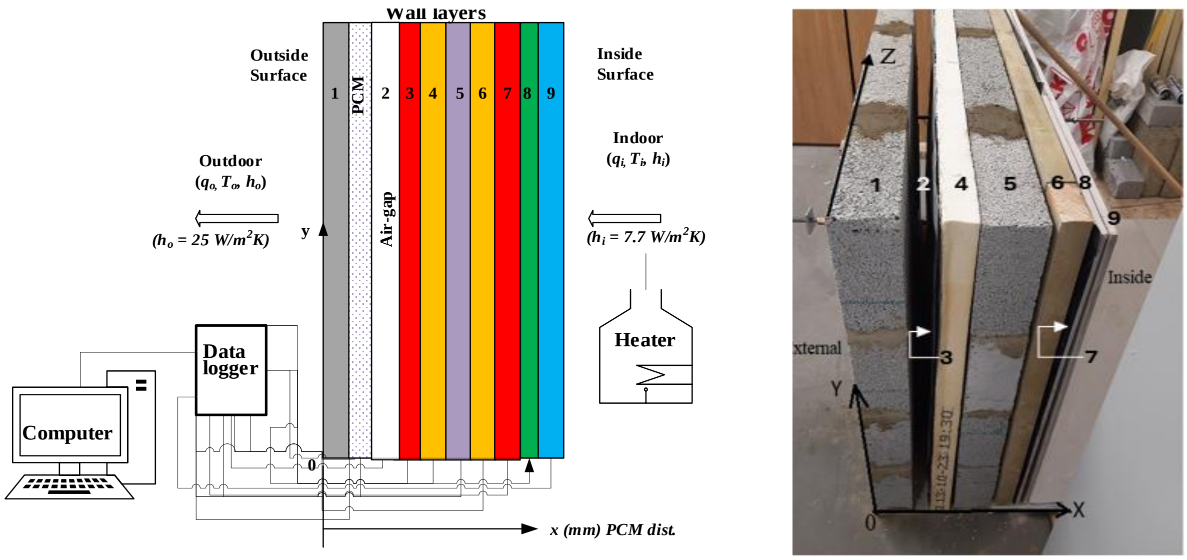
This paper investigates the potential of integrating PCMs to enhance energy savings in typical multi-layer thick-walled buildings, such as Victorian-style buildings, while preserving their architectural integrity. A multi-layer wall model from a typical Victorian-era building was constructed using locally available materials to assess energy efficiency in such standard building construction in a temperate environment. A PCM layer was incorporated into this multi-layer wall to optimise energy savings in this type of building while maintaining the heritage value of such structures. Although the study focuses on historic thick-walled buildings, the principles of PCM integration are equally applicable to other building structures or configurations, including modern lightweight constructions and retrofitted buildings. The findings offer a sustainable and promising solution to address the energy inefficiency challenges encountered by thick-walled buildings, particularly historic buildings in temperate climates. They also highlight the versatility of PCM technology for diverse architectural contexts.

2. The experimental setup

2.1 The PCM prototype wall

A prototype wall sample, identical to the external wall of a third-floor room in a thick multi-layer external wall of a four-story building in North London, UK, was constructed, and a PCM layer was introduced into this wall sample. A series of tests were conducted to investigate the impact of integrating a PCM layer into the room's north-facing multi-layer external wall. Temperature measurements were taken across various wall layers of the prototype to evaluate the effectiveness of PCM in regulating temperatures and its potential for energy-saving. The model dimensions were 1.2 m x 0.9 m x 1.0 m, with a wall thickness of 0.384 m, incorporating the PCM layer, as shown in Figure 2. The total thermal transmittance value (U-value) of the wall was determined to be 0.154 W/(m^2.K), meeting the UK minimum standards specified in the Approved Document Part L, Dwellings 2021 Edition guidelines [41]. The chamber edges were sealed with a thermal stability sealant (-40ºC to +120ºC) to prevent heat exchange. While the design prioritised energy efficiency and compliance with modern standards, the 0.384 m thickness and integration of PCMs may conflict with historical heritage legislation if they significantly alter the original wall dimensions or materials in historic buildings. Any modifications must adhere to preservation requirements, ensuring that the building's architectural and cultural integrity is maintained.

Figure 2 illustrates the wall configuration constructed in a laboratory at the University of Hertfordshire (51.7517° N, 0.2400° W). The wall assembly was comprised of an air gap and eight distinct layers, each serving a specific function in regulating heat transfer and maintaining thermal comfort. No inter-layer adhesives were used, as materials and air gaps were in direct contact, ensuring negligible thermal contact resistance. Temperature measurements of wall layers for various wall configurations, with and without the PCM, were conducted over 48-hour periodic intervals during the cold months from December to February.



(a) Schematic of the PCM prototype wall model with eight distinct layers (defined in Table 1), an air gap

(b) Layered Wall Construction

Figure 2. (a) Schematic of the PCM prototype wall model with eight distinct layers including an air gap, (b) Layered wall construction

Data acquisition was facilitated using a Pico data logger. An 800W (AirForce NDB-1Q-08 oil-filled radiator electric) oil heater equipped with a thermostat was utilised to heat the space [42, 43], and the indoor temperature was set to 26°C. The temperature readings were used to calculate the overall heat transfer through the wall layers using the overall heat transfer equation (1).

$$Q = \frac{A.\Delta T}{R} \qquad (1)$$

where Q is the heat transfer (W), A is the cross-sectional area of wall (m^2), ΔT and is the temperature change across the wall layers (K), R is the total thermal resistance for a given wall configuration (m^2.K/W). The energy consumption, E (Wh), is given by Q x t *where t is time in* hours. Several assumptions were made [44], based on recent studies to simplify the numerical calculations, which include: (1) one-dimensional heat transfer; (2) no heat generation; (3) homogeneous wall materials and constant specific heat of PCM; (4) constant freeze/thaw temperature; (5) negligible thermal contact resistance, and a constant convective heat transfer coefficient.

2.2 The experimental description

The thermophysical properties of the wall layers are shown in Table 1. The PCM was initially positioned at x =100mm from the wall's out surface and subsequently moved inwards to positions at x = 150, 153, 203, 303, 341, 344, and 356 mm, respectively, as shown in Figure 2. This positioning utilised the boundaries or splits to explore all theoretical possible PCM wall locations within the wall without compromising the thermal and structural integrity of the multi-layer wall [45]. Furthermore, the incorporation of the PCM did not affect the structural integrity of the multi-layer wall [46]. The convective heat transfer coefficients for the internal and external wall surfaces were 7.7 W/(m^2.K) and 25 W/(m^2.K), respectively. Thermal performance tests were conducted on the wall without the PCM (control), where no replacement material was used, followed by tests with the PCM.

Table 1. Thermophysical properties of the different layers of the wall construction

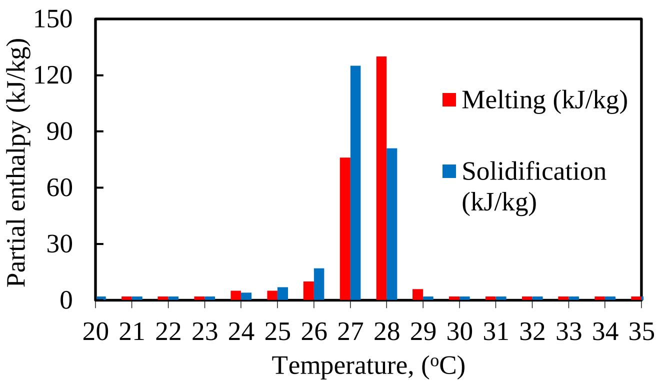
Wall layer number	Layer name	Thickness, x (m)	Conductivity, *k*, ($W.m^{-1}.K^{-1}$)	Resistance, R, ($W.m^{-2}.K^{-1}$)
1	Outer block	0.100	1.400	0.071
2	Airgap	0.050	0.024	2.083
3	Vapour -barrier	0.003	0.200	0.015
4	Outer-Kingspan (K118) in studs	0.050	0.021	2.381
5	Inner block	0.100	1.400	0.071
6	Inner-Kingspan (K112	0.038	0.021	1.810
7	vapour-barrier	0.003	0.200	0.015
8	Outer-Gypsum board	0.125	0.170	0.740
9	Inner-Gypsum board	0.125	0.170	0.740

K-type thermocouples [47] were used to measure the temperature of various wall layers. These thermocouples underwent in situ calibration [48], performed using ice, boiling water, and a thermo-bath [49, 50], with observed accuracy within ±0.5°C. Parameters selected for validation include the interior room temperature, the inner surface temperature, the outer surface temperature, the PCM temperature, the wall layers temperature and the heat necessary to warm the room. During the tests, the experimental data was gathered using a data collector.

2.3 The phase change material

A specific type of PCM, RT28HC PCM, enclosed in macro aluminium with a thickness of 15mm, as shown in Figure 3(a), and featuring a phase change temperature range from 27°C to 29°C, was selected for its high heat storage capacity. This paraffin based organic PCM was provided by Rubitherm Technologies [51], and was used without any modification. The manufacturer's PCM module enthalpy-temperature data relationship is shown in Figure 3(b). The specific properties of the PCM are listed in Table 2.

(a) macro aluminium casing



(b) RT28HC Enthalpy-temperature curve [165]

Figure 3. PCM Manufacturer's specifications. (a) PCM packaging, (b) PCM Enthalpy Vs temperature curve

RT28HC is highly effective for thermal regulation, storing and releasing heat at nearly constant temperatures with consistent performance over thousands of cycles. Operating across a broad range (-10°C to 90°C), it is durable, easy to handle, non-toxic, and well-suited for energy efficiency in temperate climates [51]. Its robust aluminium encapsulation ensures no leakage, resilience and sustainability for historical structures with limited maintenance access while contributing to the preservation of heritage buildings.

Table 2. RT28HC PCM properties

PCM	Thickness, (mm)	Conductivity, *k* (kJ/h.m.K)	Phase change temp (°C)	Density (kg/m^3)	Specific Heat (kJ/kg °C)	Latent & sensible heat storage (kJ/kg)
RT28HC	15	0.2	27-29	0.88(s) 0.77(l)	2.0	250

3. Experimental results and discussion

3.1 PCM temperature variations with positions

Figure 4 illustrates the temperature variations of RT28HC at different locations within the wall. As the PCM (RT28HC) was positioned closer to the heat source (inside), its temperature increased. Positions near the external surface of the wall (100 mm and 150 mm away from the out-surface) exhibited lower temperatures, suggesting that these positions are less effective at absorbing heat due to reduced exposure or the influence of external temperatures. A 25.2% temperature increase occurred at positions 100 mm to 153 mm, although the PCM does not reach its phase change temperature due to its proximity to the outer surface and the presence of an air gap (100 – 150 mm), which limits the heat transfer. At the PCM position of 153 mm, the temperature spike above that for PCM at positions 203 mm and 303 mm could be attributed to thermal bridging or heat accumulation after the air gap. The rapid change in thermal conditions at this depth could be causing a temporary heat buildup.

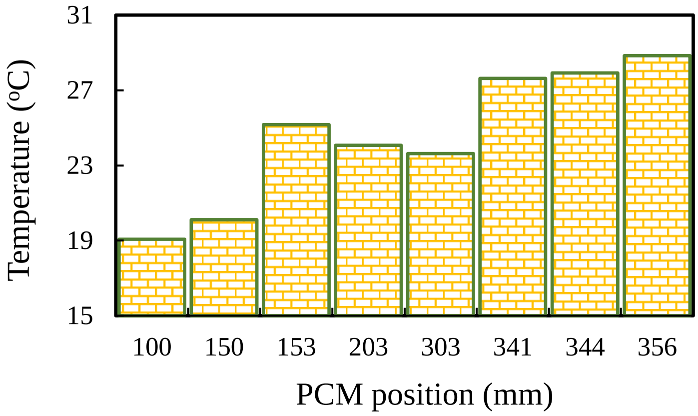


Figure 4. PCM temperature variation with PCM positions (measured from the wall out-surface)

PCMs at 203 mm and 303 mm positions show reduced temperatures due to slower heat conduction, preventing them from reaching their optimal phase change temperature. The lower temperatures at these positions suggest that insulation and material properties at these depths slow heat transfer, preventing them from reaching the phase change temperature. Therefore, PCM at these positions does not reach phase change activity, indicating that these locations within the cement block layers are unsuitable due to lesser exposure or earlier phase change incompletion.

When the PCM was placed further from the external wall surface, phase changes began at position 341 mm, with a 16.9% temperature increase to reach phase change temperatures ranging between 27°C and 29°C. The PCM temperature stabilised at positions between 341 mm and 356 mm, suggesting that the PCM reached its phase change threshold and was actively absorbing and releasing heat. Therefore, positions from 341 mm to 356 mm are identified as the most effective for this PCM under the given conditions.

3.2 Effects of the PCM positions inside the wall on temperature

Figure 5 shows the temperature distribution across different PCM positions. At shallower depths (100 mm to 150 mm), the PCM temperature was significantly lower, indicating that the PCM was too close to the external surface and, as a result, did not absorb sufficient heat to stabilise the indoor environment. This led to lower inner surface and room temperature as well as PCM temperatures. Notably, the room and inner surface temperatures were almost identical at the PCM positions of 153 mm, 203 mm, and 303 mm. This suggests that the PCM at these depths functions primarily as a passive insulation layer rather than an active thermal buffer through phase change. At those positions, the PCM did not fully reach its phase change temperature (27-29°C), which resulted in minimal heat transfer between the room and the inner wall surface, creating a thermal equilibrium between two wall layers. Because the PCM did not absorb or release significant heat, the limited heat flow at these depths further reduced the thermal exchange between the room and the wall. Additionally, the air gap or additional insulation layers at these positions likely increased the wall's thermal resistance, minimising the temperature difference between the inner surface and the room.

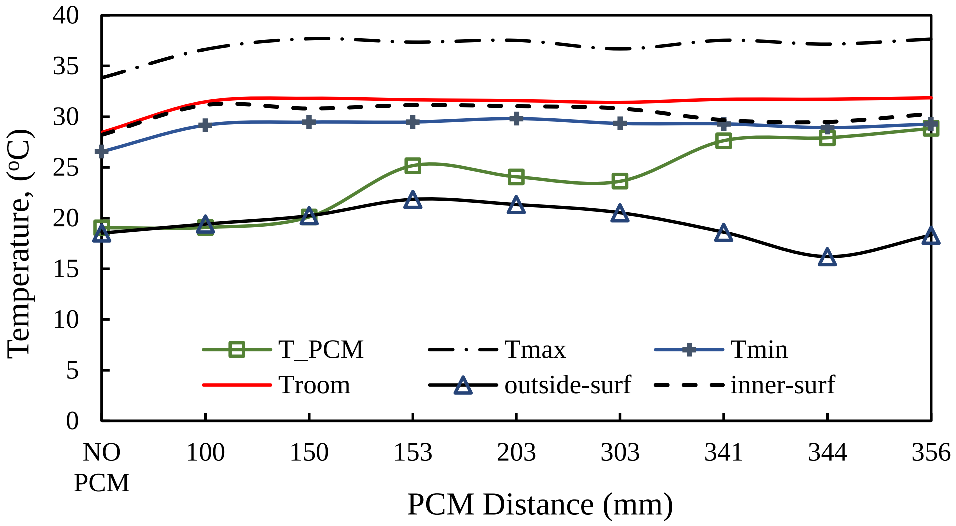


Figure 5. Temperature distribution against various PCM positions

As shown in Figure 4, at deeper PCM positions, the temperature approached or exceeded the phase change range, indicating that the PCM was optimally placed to absorb and release heat. The closer alignment of PCM, room, and inner surface temperatures at these depths suggests more effective thermal regulation as the PCM undergoes its phase change, helping to stabilise the indoor temperature.

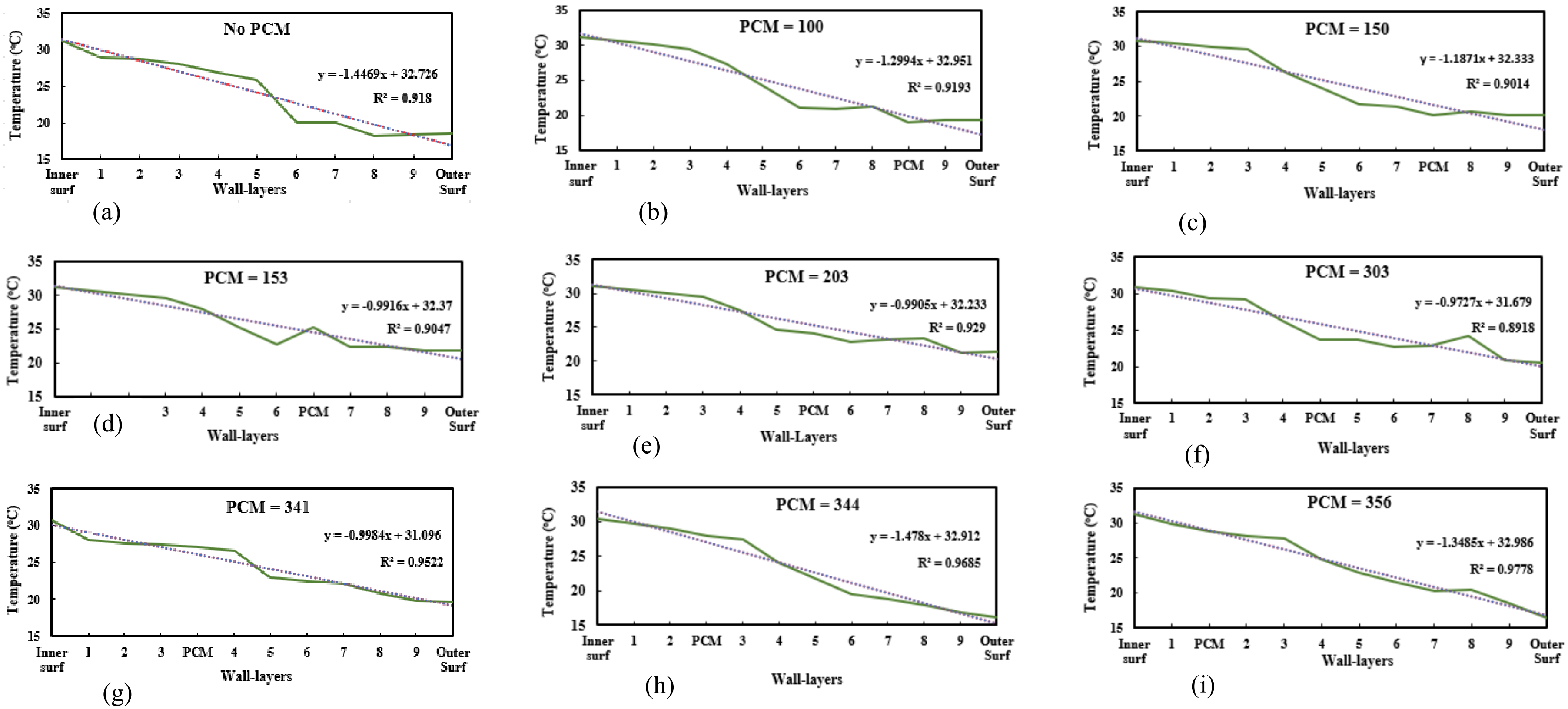


Figure 6. Temperature distribution across the wall thickness against PCM position

3.3 Temperature distribution across various PCM wall configurations

Figure 6 shows temperature gradients from the outer to inner wall surfaces, indicating greater heat loss without PCM (gradient of 1.4469). PCMs near the outer surface (100 mm, 150 mm and 153 mm positions) have limited impact on inner wall temperatures but improved thermal regulation by absorbing and delaying heat transfer as the PCM acted as an insulation layer. Mid-layer PCM positions (203 mm, 303 mm away from the wall out-surface) provided better temperature moderation with low-temperature gradients of 0.9905 and 0.9727, respectively. The PCM acts as a passive insulation layer but poses installation challenges for retrofitting Victorian-era buildings, making them uneconomical. This PCM positioned closer to the inner surface (at 341 mm, 344 mm & 356 mm) effectively maintained high-temperature gradients of 0.9984, 1.478 and 1.3485, respectively, as this PCM reached its phase change temperature, actively absorbing and releasing heat into the inner space. PCM at 341 mm demonstrated a moderate temperature value, with a temperature gradient of 0.9984, highlighting its efficiency in balancing heat transfer and thermal regulation. Therefore, as a trade-off, the optimal PCM placement was determined to be 344 mm from the wall out-surface for efficient thermal regulation and easier installation, considering environmental conditions, desired temperatures, and wall properties.

R^2 values in Figure 6 indicate the integrity of fit for the temperature distribution across wall layers for different PCM positions. PCM at 341 mm achieved a relatively a high R^2 value of 0.9522 (Figure 6(g)), followed closely by PCM at 344 mm ($R^2 = 0.9685$, Figure 6(h)) and PCM at 356 mm with the highest $R^2 = 0.9778$ (Figure 6(i)). These values reflect an effective thermal regulation, strong temperature stability, and impact on maintaining indoor thermal comfort. PCM at 344 mm demonstrates superior linearity in temperature distribution, ensuring optimal heat absorption and release while balancing the internal environment. Although PCM at 356 mm exhibits a slightly higher temperature gradient (1.3485), indicating more pronounced heat flux near the inner surface, all positions contribute to reducing temperature fluctuations, enhancing occupant comfort and overall thermal performance.

It can be seen from Figure 6 that the temperature gradients and R^2 values demonstrate that the effectiveness of the PCM layer is significantly influenced by the arrangement of surrounding wall layers, which affect heat transfer and temperature regulation. Conductive materials enhance heat transfer, increasing the PCM's responsiveness, while insulating layers slow the process, improving its buffering capability. Key factors such as proximity to heat sources, layer thickness, air gaps, and the alignment of phase change temperatures also play critical roles. A well-designed layer arrangement is essential for maximising PCM efficiency and achieving optimal energy savings.

3.4 The PCM position effect on heat transfer across the wall

Figure 7 delves into the PCM position's effect on heat transfer, calculated using equation (1) across the wall, highlighting the parabolic relationship between PCM positions within the wall and heat energy transfer. The moderate R^2 value (0.7016) illustrates this relationship, showing a gradual decrease in heat transfer as the PCM is shifted from the 100 mm position to approximately 203 mm, reaching a minimum around this midpoint. Beyond the position of 203 mm, as the PCM position nears the position of 356 mm, the heat transfer begins to rise again, forming the other half of the parabola.

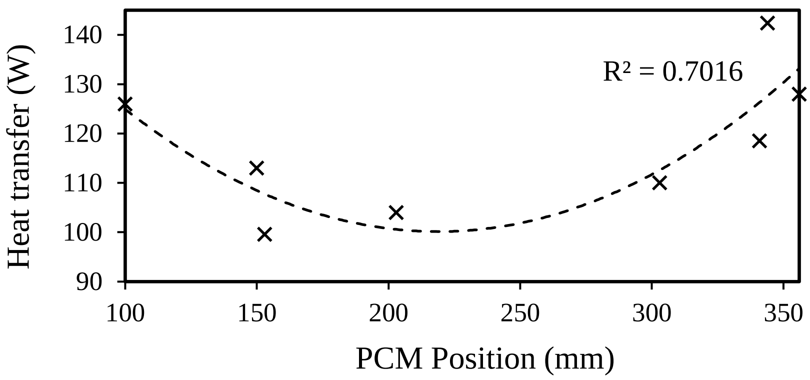


Figure 7. Variation of PCM position on heat transfer across the wall

At the PCM position of 100 mm, closer to the outer wall, there is a notable heat energy transfer, likely because the PCM effectively absorbed incoming heat from the outdoor environment and became saturated too early during sharp temperature episodes, leading to increased heat transfer across the rest of the wall. Conversely, the significant heat transfer observed towards the end of the curve at the PCM positions 341 mm, 344 mm, and 356 mm suggests that heat is absorbed and stored in the PCM. This process diminishes its effectiveness in moderating the temperature gradient across the wall but helps to stabilise indoor temperatures. As the PCM is at its phase change temperature at these positions, it acts as a thermal buffer by absorbing excess heat from the indoor environment and releasing it back when the indoor temperature drops. This behaviour indicates that strategically placing PCM near the interior while ensuring it is effectively insulated from external temperature swings can optimise the thermal regulation properties of buildings.

As shown in Figure 6, heat transfer is less pronounced in the middle positions than in the wall's outer regions. As observed earlier in Figure 4, the PCM in these positions did not reach the required phase change temperature. Without this phase change, the latent heat absorption and release processes, essential for maximising the PCM's thermal buffering capacity, were not fully activated. Consequently, the PCM might primarily act as sensible heat storage, which limits its efficiency in stabilising heat transfer. Therefore, the observed reduction in heat transfer observed in these middle positions can be attributed to the PCM serving more as an additional insulation layer rather than providing the full benefits of thermal regulation through phase change. While there were still some heat transfers, the PCM's optimal thermal performance was not achieved due to the absence of the phase change.

Therefore, based on these results, the hypothesis is that placing the PCM closer to the interior of building walls while insulating it from external temperature variations will enhance thermal regulation. This configuration will stabilise indoor temperatures by allowing the PCM to absorb excess heat when indoor temperatures rise and release it when they drop. Such an approach enhances temperature and reduces energy consumption in a targeted and efficient manner, thus serving as a crucial strategy in a sustainable building design under BS EN ISO 15251:2007 for the indoor environmental criteria [52].

3.5 Regression analysis

Table 3 shows the Pearson correlation coefficients [53], for various PCM positions on energy savings and requirements for heating and cooling. The correlation coefficient was used to measure the strength and direction of the linear relationship between two variables, ranging from -1 to 1, to help identify whether variables are positively, negatively, or not correlated. The high correlations indicate strong relationships, which are useful in selecting features for models and detecting multicollinearity. The exploratory data analysis reveals patterns and informs decision-making by highlighting key relationships [54], such as the optimal placement of phase change materials for energy savings.

3.5.1 Heating and cooling energy analysis

The correlation of experimental results between the PCM distance from the out-wall surface and energy requirements for heating and cooling of the room space is shown in Table 3**,** and the following observations are deduced:

- **Heating energy**: An observed correlation of 0.610 between PCM distance and heat energy suggests that heat energy utilisation increases as the PCM is positioned further away. While this may not be ideal for energy conservation, it indicates enhanced heat storage and gradual release, which would improve thermal management.
- **Cooling energy**: The strong positive correlation of 0.830 indicates that greater distances of PCM locations (341 mm, 344 mm & 356 mm) lead to higher cooling energy requirements, which is suboptimal for energy conservation and highlight a potential area for efficiency improvements.

3.5.2 Statistical significance testing

To assess the statistical significance of the correlations in Table 3, a hypothesis test is performed for each correlation coefficient. The t-statistic, for a correlation coefficient, is calculated using the formulae in equation (2) and equation (3) [55], and as follows:

$$r = \frac{\sum(X_i - \overline{X})(Y_i - \overline{Y})}{\sqrt{\sum(X_i - \overline{X})^2 \sum(Y_i - \overline{Y})^2}} \qquad (2)$$

$$t = r \times \sqrt{\frac{n - 2}{1 - r^2}} \qquad (3)$$

where: r is the Pearson correlation coefficient between two variables X and Y. The X variable represents the PCM distance, and the Y variable represents the cooling time, temperature loss, cooling energy and ambient temperature, respectively. n is the sample size, t is the calculated t-statistic, $\bar{X}$ average of all observations of the variable X and $\bar{Y}$ average of all observations of the variable Y.

The degrees of freedom (*df*) for this test is (*n-2*). The t-statistic is used to compare with a critical value from the t-distribution table or to calculate a p-value, which indicates the probability of observing such a strong association if the null hypothesis is true [56]. A p-value of 0.05 in Microsoft Excel is a common threshold researchers use to determine statistical significance. This cutoff helps to decide whether observed differences or relationships are likely to be true and not merely because of a random variation. Similarly, a p-value less than 0.05 was selected as the criterion for statistical significance in this study [57].

Using Table 3, and equations (2) to (3), Table 4 results were obtained to highlight the significant correlations, t-statistics and p-values between PCM distance (D_{ist}) and several key variables, namely cooling time, temperature loss (T_{loss}), cooling energy, and external temperature (T_{Ext}). Specifically, the correlation between PCM distance and Cooling energy, with a p-value of 0.0056, is statistically significant as it falls below the standard threshold of 0.05. This evidence robustly supports the hypothesis (section 3.4) that the positioning of the PCM critically influences cooling energy requirements and suggests that incorporating this PCM may be advantageous for energy savings and minimising energy losses. On the contrary, the external temperature (T_{Ext}) showed non-significant statistical correlations with the PCM distance, suggesting that other factors may influence its relationships or require more complex modelling to decipher.

Table 3. A correlation table for various PCM positions on energy savings

	PCM distance	Heating time	Temp gain	Heat energy	Max temp, (T_{max})	Cooling time	Temp loss, (T_{loss})	Cooling energy	Min temp, (T_{min})	Ext temp, (T_{Ext})	PCM temp, TPCM	Room Temp (T_{room})	Heating rate	Cooling rate	Cooling time	Wall energy loss
PCM distance	1.000															
Heating time	-0.229	1.000														
Temp gain	0.468	-0.605	1.000													
Heat energy	0.610	-0.731	0.843	1.000												
Max temp	0.655	-0.292	0.393	0.672	1.000											
Cooling time	-0.760	0.044	-0.400	-0.529	-0.686	1.000										
Temp loss	0.799	-0.241	0.754	0.743	0.629	-0.792	1.000									
Cool energy	0.830	-0.224	0.652	0.750	0.761	-0.909	0.897	1.000								
Min temp	0.617	-0.200	0.159	0.532	0.957	-0.591	0.445	0.638	1.000							
Ext temp	-0.514	-0.102	-0.244	-0.062	0.139	0.552	-0.432	-0.427	0.216	1.000						
PCM temp	0.927	-0.228	0.461	0.537	0.535	-0.491	0.702	0.634	0.510	-0.374	1.000					
Room temp	-0.038	0.274	0.385	0.232	0.366	-0.229	0.408	0.363	0.217	0.259	-0.052	1.000				
Heating rate	0.620	-0.715	0.852	0.999	0.683	-0.549	0.758	0.764	0.539	-0.077	0.544	0.251	1.000			
Cooling rate	0.830	-0.184	0.669	0.707	0.697	-0.930	0.912	0.986	0.555	-0.536	0.637	0.349	0.725	1.000		
Cooling time	0.561	0.399	0.213	0.119	0.274	-0.812	0.607	0.651	0.189	-0.757	0.372	0.269	0.150	0.741	1.000	
Wall Energy	0.535	0.419	0.202	0.095	0.242	-0.793	0.587	0.630	0.158	-0.762	0.348	0.272	0.126	0.723	0.999	1.000

(Dark green: very strong positive correlation, Dark red: very strong negative correlation, Light green/red: average correlation, White: weak or no correlation)

Table 4. Statistical significance test summary

PCM Distance	Statistical significance test		
Distance	correlation	t-statistic	p-value
Cooling time	-0.760	-3.090	0.018
Temperature loss	0.799	3.515	0.010
Cooling energy	0.830	3.943	0.0056
External temperature	-0.514	-1.585	0.157

3.5.3 Comfort analysis

Room comfort is shaped by various temperature metrics, as well as the time required for effective heating and cooling [58]. To support optimal indoor environmental quality, the British Standards Institution (BSI) has published standards through the Chartered Institution of Building Services Engineers (CIBSE), notably in CIBSE Guide A: Environmental Design. This guide provides recommendations for building designs that prioritize both thermal comfort and energy efficiency. Implementing these guidelines often involves adaptive thermal comfort strategies that accommodate broader temperature ranges and control methods to ensure consistently comfortable indoor environments [59].

In line with these principles, the study's findings reveal a positive correlation between PCM distance from the outer wall and room temperature metrics (minimum, maximum, and average), suggesting an improvement in thermal regulation as PCM distance increases. Specifically, as indicated by a correlation of 0.617 in Table 3 with minimum room temperature indicates that increasing the PCM distance helps maintain higher minimum temperatures, thereby enhancing thermal comfort. However, negative correlations with heating time (-0.229) and cooling time (-0.76) suggest that greater PCM distances lead to longer cooling periods, which could contribute to more stable internal temperatures. This balance between temperature stability and energy efficiency highlights how strategic PCM placement directly influences both thermal comfort and the effectiveness of temperature regulation processes in line with CIBSE's guidance.

3.5.4 Minimising energy transfer/loss

To minimise energy loss across a wall, the correlation analysis (Table 3) reveals a high positive correlation (0.799) between the PCM distance from the wall outside surface and temperature loss (T_{loss}), indicating that as the PCM distance increases, thermal loss also rises. Similarly, a positive correlation (0.535) between the PCM distance and wall energy loss suggests that the locations with greater PCM distances lead to an increased energy transfer across the wall. These findings indicate that increasing PCM distance is not optimal for minimising energy loss, highlighting a need for strategic PCM placement to optimise the thermal efficiency.

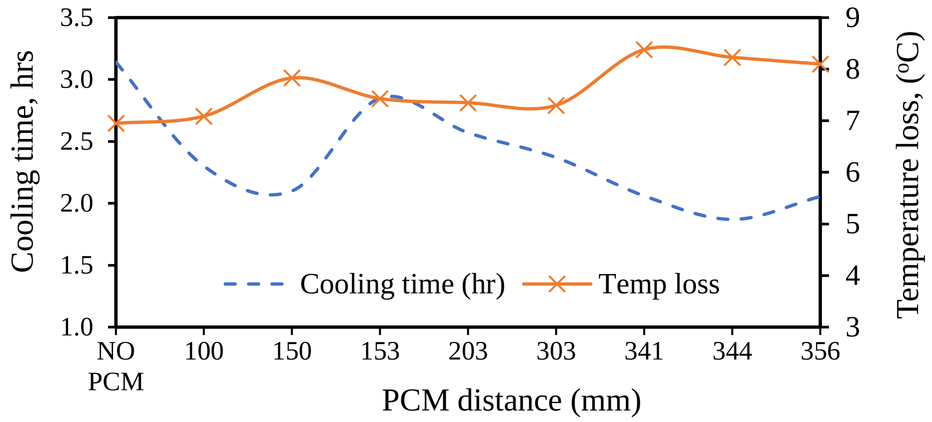


Figure 8. PCM position sensitivity on cooling time and temperature loss

Figure 8 illustrates the relationship between the PCM distance from the external wall surface and two key metrics: cooling time (in hours) and temperature loss (in °C). The x-axis represents the PCM distance from the outer wall, ranging from 0 to 356 mm, while the left y-axis shows cooling time, and the right y-axis displays temperature loss. It can be seen that in the "No PCM" condition, cooling time is longest (approximately 3.2 hours), and temperature loss is lower (~6.2°C), indicating that the absence of PCM reduces the building's ability to regulate temperature effectively. Without PCM, heat transfers more directly through the wall, leading to higher cooling times and less stable temperature control, emphasising the importance of PCM integration for improved thermal performance.

At three specific depths of 341 mm, 344 mm, and 356 mm, the high temperature loss occurred. This indicates that the PCM reaches its phase change temperature (27-29°C), allowing it to absorb heat during warmer periods and release it slowly, which enhances temperature regulation. It is suggested that these positions represent the optimal PCM placement, providing a balance between cooling time (remaining consistent between 2.3 to 2.5 hours) and temperature stability, effectively supporting thermal comfort by preventing rapid overheating and maintaining a stable indoor environment

However, at shallower PCM positions, between 100 mm and 153 mm, temperature loss increases (6.4°C to 7.2°C), but cooling time remains relatively high (around 3 hours), suggesting that the PCM is not optimally absorbing and releasing heat. The presence of a physical air gap between 100 mm and 150 mm may contribute to thermal resistance, reducing the efficiency of the PCM's heat buffering.

At the PCM position of 203 mm, both temperature loss and cooling time appear at their lowest, with temperature loss at approximately 7.9°C and cooling time at 2.5 hours. This indicates that the PCM is not fully activated for phase change at this depth, resulting in less effective heat transfer and potentially compromising energy efficiency.

Therefore, it is suggested that PCM positions at 341 mm, 344 mm, and 356 mm offer the best combination of cooling time and temperature loss, providing optimal thermal performance by stabilising indoor temperatures and reducing heat transfer. Shallower PCM positions (100 mm to 153 mm) demonstrate less effective thermal regulation, while the 203 mm position shows underperformance in heat transfer.

PCM positions at 341 mm, 344 mm, and 356 mm offer the best combination of cooling time and temperature loss, providing optimal thermal performance by stabilizing indoor temperatures and reducing heat transfer. Shallower PCM positions (100 mm to 153 mm) demonstrate less effective thermal regulation, while the 203 mm position shows underperformance in heat transfer. While the initial costs for PCM materials, encapsulation, and installation are high, these positions maximise energy savings by significantly reducing heating and cooling demands and lowering peak load demands. In a long period, these benefits, coupled with economies of scale, enhance the cost-effectiveness of PCM systems, making them a practical and viable solution for improving energy efficiency and thermal comfort in buildings [60].

3.6 Evaluation of attenuation factor and peak temperature reduction

The attenuation factor, *f*, measures how much the amplitude of the temperature waves is reduced as they pass through the PCM wall configurations [61], indicating the PCM's effectiveness in moderating temperature fluctuations. A higher attenuation factor signifies better thermal regulation by reducing the temperature wave amplitude. It is determined by the ratio of the temperature amplitude of the outer surface to the inner surface, as defined by equation (4) [62], as follows:

$$f = \frac{T_{out(surf),max} - T_{out(surf),min}}{T_{in(surf),max} - T_{in(surf),min}} \qquad (4)$$

where $T_{out(surf),max}$ and $T_{out(surf),min}$ are the maximum and minimum outer surface temperatures, $T_{in(surf),max}$ and $T_{in(surf),min}$, are the maximum and minimum inner surface temperatures. To assess the PCM wall prototype effective management of peak temperatures, Peak Temperature Reduction (PTR) is introduced which is defined by equation (5) [62] as follows:

$$PTR = t_{in(surf)peak} - t_{out(surf)peak} \qquad (5)$$

where $t_{in(surf)peak}$ and $t_{out(surf)peak}$ refer to the peak temperature of the inner surface and outer surface wall in °C. High values of both f and PTR are desirable for applications requiring thermal stability and peak load shifting, respectively, but optimising both parameters requires a trade-off.

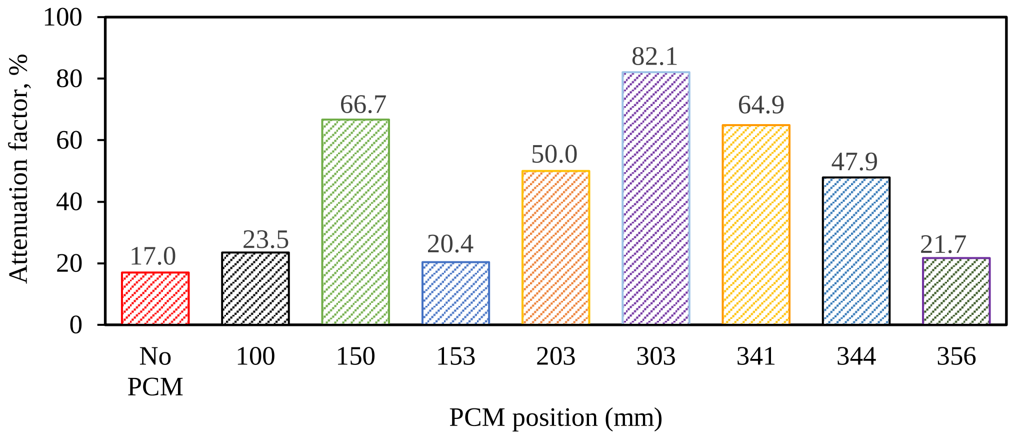


Figure 9. Attenuation factor at various PCM positions within the multi-layer wall

Figure 9 shows the attenuation factors for the various PCM positions. As indicated in Figure 9, the attenuation factors for the "no PCM" and PCM positions of 100, 150, 153, 203, 303, 341, 341 and 356 (mm) are obtained using equation (4) as: 17.0%, 23.5%, 66.7%, 20.4%, 50%, 82.1%, 64.9%, 47.9% and 21.7%, respectively. It can be observed that the wall without the PCM has the lowest attenuation factor, implying less temperature reduction and thermal buffering. Analytically, the mid-layer PCM at 150 mm, 203 mm, and 303 mm showed the most significant modulation of temperature fluctuations of 66.7%, 50% and 82.1%. Conversely, while the PCM at these positions exhibited higher attenuation factors, it had not yet reached its phase change temperature. The high attenuation values are likely because of their increased thermal insulation and or in a combination with their proximity to the external surface, enabling greater heat absorption and trapping heat in the air gap on warmer days. The graph shows that the attenuation factor for each corresponding PCM position was greater than that of the wall without any PCM (17%). The low attenuation value for PCM at 153 mm is likely due to the presence of the air gap on one side (150 mm) of the PCM, which effectively reduces heat transfer. Additionally, the air gap, in combination with the external surface, localizes trapped heat in the air gap on warmer days and leads to incomplete phase transition, resulting in poor thermal regulation. The PCM at the positions of 341 mm and 344 mm, having reached phase change temperature, exhibited relatively high attenuation factors of 64.9% and 47.9%, respectively. These positions, therefore, appear to offer the optimal PCM placement. However, their PTR needs to be analysed.

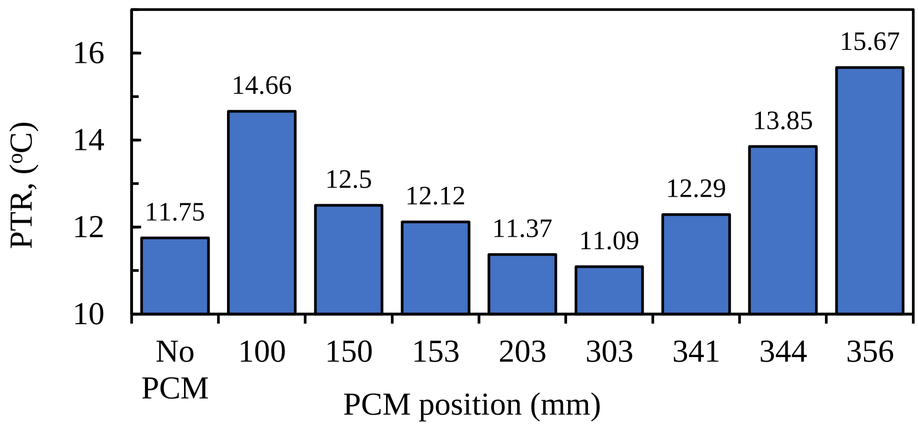


Figure 10. Peak Temperature Reduction (PTR) versus PCM positions

Figure 10 compares the Peak Temperature Reduction (PTR) at various PCM positions within a multi-layer wall system. The “No PCM” condition shows a baseline PTR of 11.75°C. The highest PTR is observed at 356 mm with a value of 15.67°C, indicating that placing PCM at this depth is effective in stabilising indoor temperatures by absorbing peak heat and gradually releasing it. At shallower positions between 100 mm and 150 mm, the PTR varies notably. The PTR at 100 mm is 14.66°C, suggesting heat absorption due to the proximity to the wall surface. However, the presence of an air gap in this range likely adds thermal resistance, impacting heat flow and resulting in a decreased PTR of 12.5°C at 150 mm. This implies that the air gap reduces the thermal interaction between the PCM and wall layers, limiting its temperature moderation capabilities.

In mid-layer positions (153 mm to 303 mm), the PTR fluctuates between 12.12°C and 11.09°C, with the lowest reduction at 303 mm. This suggests that PCM at these depths do not reach phase change temperature for optimal heat absorption and release. The reduced PTR could be due to thermal bridging, where heat bypasses the PCM because of structural elements like studs or insulation discontinuities. The PTR increases again at deeper positions (341 mm to 356 mm), peaking at 356 mm, representing improvements of 4.6%, 17.9% and 33.3%, respectively. This indicates that placing PCM near the inner surface enhances thermal interaction and phase change activation. The PCM absorbs and releases heat efficiently at these depths, stabilising temperatures and reducing heat transfer through the wall. These PCM positions, ranging from 341 to 356 of the distance from the exterior wall surface, represent the fraction of the PCM distance to the total PCM wall thickness of 88% to 93%. These positions help maintain thermal comfort and reduce the energy load on heating and cooling systems.

Therefore, from Figure 9 and Figure 10, it can be suggested that the PCM positions in the range of 341 mm and 344 mm appear to offer the optimal PCM positions that have a high attenuation factor and a significant PTR desirable for applications requiring thermal stability and peak load shifting. These findings present energy-saving strategies for multi-layer walls, typical of historical buildings where a lower carbon footprint is needed without compromising traditional aesthetics or resorting to demolition. Additionally, this approach allows for the retention of the external facade while facilitating cost-effective internal enhancements, such as installing a plasterboard. Placing the PCM discreetly behind plasterboards preserves internal decorations. This study underscores the PCM's ability to effectively drive sustainability energy efficiency.

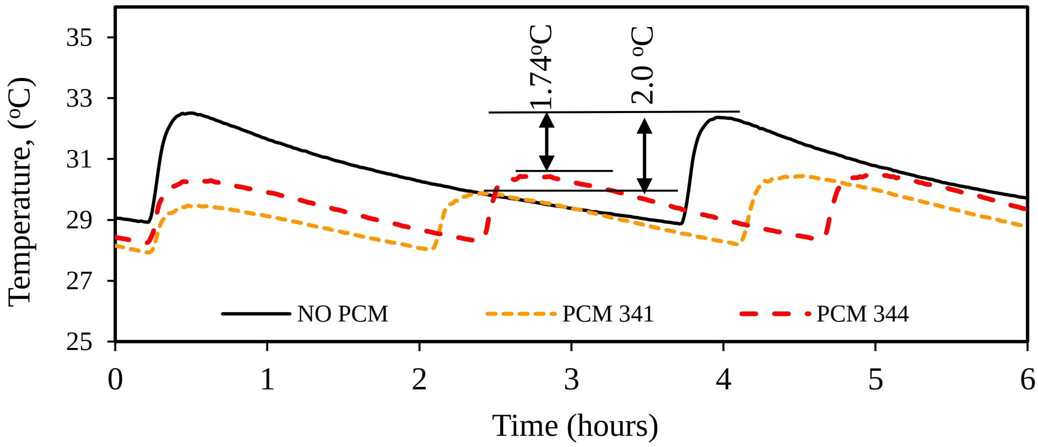


Figure 11. Variation of inner surface temperatures with PCM positions

Figure 11 illustrates the wall's inner surface temperature variations over six hours for different PCM positions. The data shows that placing the PCM at the positions of 341 and 344 in the multi-layer wall significantly reduced the temperature amplitude on the inner surface compared to that of the wall without PCM. This positioning greatly influenced the ability to regulate inner surface temperature, leading to a more uniform temperature distribution that enhances indoor thermal comfort. The energy consumption for various PCM positions were calculated using Equation (1), as shown in Table 5. The peak temperature flow shown in Figure 11 decreased by 2.0°C at the PCM position of 341 and by 1.74°C at 344 mm compared to that of the wall without PCM. This temperature decrease corresponds to cooling energy savings of 6.2% and 5.3%, respectively, demonstrating the effectiveness of these PCM positions in reducing heat transfer and enhancing thermal regulation.

Table 5. PCM positions with corresponding energy saving in percentages

PCM position	Energy consumption (Wh)	Energy savings
Without PCM	117.38	-
100	91.26	22.3%
150	82.17	30.0%
153	72.22	38.5%
203	75.40	35.8%
303	79.89	31.9%
341	110.15	6.2%
344	111.16	5.3%
356	116.06	1.1%

4. Conclusions and future work

This study has inspected the optimal placement of a PCM layer within a multi-layer wall of a typical structure characterised by external walls of Victorian-era architectural buildings in a temperate climate. The primary focus was on reducing energy consumption in Victorian-era buildings, stabilising indoor temperatures, and aligning with the EU's climate-neutral strategy by 2050 while balancing the preservation of architectural heritage features with modern energy demands. Based on the results and discussion, the following conclusions can be drawn:

i). The most effective positions for a PCM layer are in the range of 341mm (88%) to 356 mm (93%) from the outer surface of the wall or between 7% and 12% of the wall thickness from the inner surface. An installation of PCMs at these locations reduces the peak temperature by 1.74°C to 2.0°C, thereby boosting air-conditioning performance and reducing energy consumption by 5.3% to 6.2%. The results show that integrating phase change materials in historical buildings reduces energy consumption and enhances energy efficiency without altering traditional aesthetics.

ii). The efficacy of PCM in thicker multi-layer walls is greatly influenced by its proximity to the external surface, particularly in temperate regions that experience extreme freezing conditions. In such an environment, the specific PCM type (RT28HC) may struggle to reach its phase change temperature when placed near the outer wall. This indicates that this PCM may be better suited for warmer climates or seasons, where higher external temperatures can activate its thermal regulation properties. PCM with lower phase change temperatures may be more effective in these conditions, particularly when applied in mid-layer positions, where they can efficiently absorb and release thermal energy.

iii). The PCM acts as a thermal buffer when it is positioned near an internal heat source since it may consistently reach and maintain its phase change temperature at such a position. This stable functionality ensures that the room's internal temperature is maintained within a range of 7.9°C, significantly enhancing occupant comfort by providing a broad spectrum of room temperatures under a vast external temperature change, approximately between 14°C and 25°C.

iv). The findings demonstrate that the principles of PCM integration, while optimised for temperate climates and Victorian-style multi-layered wall constructions, are adaptable to other climatic conditions and architectural styles. Adjusting PCM properties, placement, and encapsulation can enhance energy efficiency, occupant comfort, and air-conditioning performance, making them applicable to diverse historical buildings while supporting heritage conservation. This adaptability highlights the potential of PCM systems to significantly contribute to heritage conservation and energy performance advancements in a variety of contexts.

This study underscores the necessity for additional research under various seasonal conditions to assess the dynamic response of PCM in multi-layer buildings. Future work should focus on assessing PCM performance during extreme summer temperatures and heat waves, particularly its effectiveness in preventing overheating without degradation. An investigation of its ability to enhance passive heating during deep winter freezes is also essential for ensuring year-round energy savings, durability, and broader applicability.

Declaration of Competing Interest

The authors declare that they have no known competing interests or personal relationships that could have appeared to influence the work reported in this paper.

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