

EXPERIMENTAL STUDY OF PCM EFFECTS ON INDOOR TEMPERATURE IN LIGHTWEIGHT BUILDINGS

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Phase change materials (PCMs) integrated into lightweight building envelopes were experimentally evaluated to assess their impact on indoor thermal performance. A PCM test house and a reference test house were examined under two conditions: without ventilation and with night ventilation. The experiments were conducted under the climatic conditions of the Republic of Serbia, in Belgrade, at the Vinča Institute of Nuclear Sciences. Two observation periods were defined to evaluate the thermal behaviour of the test houses, with four thermal cycles monitored in each period. Results indicate that, on hot sunny days, the PCM test house achieved maximal indoor air temperature reduction of 3.5-4.8 °C during the non-ventilated period and 4.2-5.9 °C during the night-ventilated period, while reducing thermal load levelling (TLL) by 64.1-72.5% and 45.5-49.5%, respectively. The average indoor temperature reduction (AITR) ranged from 0.03-6.12% in the first period and from 3.19-6.54% in the second, confirming the potential of passive PCM application for improving indoor thermal stability. These findings show the practical benefits of PCMs in enhancing energy efficiency and indoor thermal comfort in lightweight buildings.

Key words: PCM, Indoor air temperature, AITR, Thermal load levelling, Thermal comfort

1. Introduction

The increasing severity of the global energy crisis and environmental challenges has positioned sustainable development, energy efficiency, and emission reduction in the construction sector among the foremost priorities of professional practice [1, 2]. Buildings are responsible for about 36% of the global energy consumption [3] and buildings are currently responsible for 39% of global energy related carbon emissions: 28% from operational emissions, from energy needed to heat, cool and power them, and the remaining 11% from materials and construction [4, 5]. In Serbia, the structure of energy consumption reveals an even more pressing situation, as approximately 60% of the final energy demand is attributed to the building sector. Within residential buildings, the dominant share of energy use is dedicated to maintaining indoor thermal comfort through heating and cooling, which also

represent the largest share of both investment and operational costs [6]. In general, the demand for space cooling is projected to rise significantly in the coming decades as a consequence of ongoing global warming [7]. Phase Change Materials (PCMs) have emerged as a highly promising option for thermal energy storage, with strong potential to improve the performance of renewable energy systems, decrease overall energy demand, and support the transition toward nearly zero-energy buildings [8]. Among different energy-efficient strategies, the use of PCMs within building structures has attracted increasing attention due to their capacity to moderate indoor temperatures and lower cooling and heating requirements. The key advantage of PCMs lies in their ability to store and release heat during phase transitions. During melting, they absorb a large amount of heat from the environment, while during solidification, this energy is released in the form of latent heat [9]. Owing to these unique thermal properties, PCMs have been applied in various sectors, including buildings [10], electronics [11], and textiles [12]. The building sector remains one of the most explored fields for PCM applications, where they can be used either passively, by embedding them into construction materials, or actively, in combination with mechanical systems, to regulate indoor climate and improve thermal comfort [13]. Numerous studies have confirmed the considerable thermal storage potential of PCMs in building envelopes, emphasizing their role in advancing energy efficiency. Al-Yasiri et al. [14] conducted a numerical study investigating the effect of natural night ventilation on indoor temperature improvement in a PCM room, taking into account window orientation and window-to-wall ratio. They concluded that the direction of the wind significantly affects the orientation of the window. By increasing the ratio of windows and walls from 8.75% to 20% when the room is oriented northwest, the average temperature in the PCM room decreased by 27.5%. An experimental study [15] examines the use of PCM materials on interior walls and ceilings of residential premises. Compared to a standard room, the PCM room had an indoor air temperature higher by up to 7.3 °C, heat loss through the ceiling reduced by up to 50%, and energy consumption lower by up to 20%. The greatest effect was achieved when the PCM was placed on the ceiling, resulting in a heat transfer time delay of about 6 hours. In experimental research [16], the authors constructed two experimental rooms of the same dimensions with and without PCM in Qingdao and monitored the changes of indoor air temperature, wall surface temperature, and heat flux in different seasons. During the summer, due to the high outdoor night temperatures, the PCM usually remained in a liquid state, therefore its effect was limited, and the total average energy savings were relatively small. The most pronounced effect of PCM was recorded in the transition seasons when the external temperatures were the drivers for the phase change process. The maximum indoor air temperature was reduced by 8.23 °C, and the peak cooling load was reduced by 49.63%, and the average by 50.66%. In the winter period, the peak heating load improved by 24.68%, and the average by 37.59%. Li et al. [17] examined the thermal performance of the south and west walls with and without PCM thermal shield in two identical experimental houses. The PCM was placed at five different depths within the wall. Position 1 was the closest to the inner plasterboard, and each subsequent position was 1.27 cm away from the outer side of the wall. The results showed that the best position for the south wall was at 2.54 cm from the wallboard, where the maximum heat flux was reduced by 51.3%. For the western wall, the best effect was achieved at a distance of 1.27 cm from the wallboard, and the maximum heat flux was reduced by 29.7%. Alqahtani et al. [18] investigated the performance of a lightweight, unventilated building with the integration of coconut oil-based PCM into the envelope. Two identical houses were used, placed side by side, and five different cases were investigated: four based on

different window orientations and a fifth when PCM was installed on a south-facing window. The best results were obtained in the fifth case, when the internal air temperature was 7.2 °C lower in the PCM house than in the reference case, and the relative air humidity was reduced by 20%. Experiments in Wuhan [19] showed that paraffin-based PCM materials show good heat storage capacity, acceptable thermal conductivity and moderate cost, which is why they are suitable for use in passive cooling in buildings. During summer conditions, the maximum indoor air temperature in the PCM house was lower by 1.9–2.4 °C, and the average temperature by 0.5–0.6 °C compared to the reference house, while during winter conditions, the maximum indoor air temperature in PCM was lower by 1.3 °C, while the average indoor air temperature was slightly higher. The study [20] examined the impact of installing shape-stabilized phase change material (SSPCM) panels on stabilising internal temperature and reducing energy consumption for heating in lightweight buildings during winter. Three identical houses were tested: one without PCM, one with PCM on the floor, and one with PCM on the floor, walls, and ceiling. The results showed that the installation method significantly affects thermal performance. House C, with multi-surface PCM, reduced maximum indoor temperatures by up to 2.6 °C and nighttime temperatures by up to 2.9 °C compared to the reference house. Simulations in different climate zones in Japan confirmed that SSPCM can reduce annual heating energy consumption by up to 54%. Kong et al. [21] developed a new composite wall panel with phase change material (CPCMW), produced by combining paraffin, expanded perlite, emulsion, and glass fibres. Tests showed that this material has a melting point of approximately 25.2 °C, a latent heat of 85.63 [Jg⁻¹], good strength, and a compact microstructure. Summer experiments in two identical rooms without air conditioning demonstrated that the room with CPCMW installed experienced smaller temperature fluctuations, a lower maximum temperature, and a longer heating time delay compared to the reference room. The research [22] examines the use of weather forecasting combined with price-based control in passive solar facilities. Two identical lightweight houses were used: one with ordinary gypsum boards and the other with PCM-impregnated boards. Price control alone resulted in 14% energy savings and a 32% cost reduction. When weather forecast data was incorporated into the strategy, significantly greater savings were achieved up to 90% in a single day, and 31% overall. The reduction in cost over eleven days amounted to 40%.

2. Methodology

The experimental studies were conducted under real climatic conditions on two test objects built in form of simple ground level houses at the Vinča Institute of Nuclear Sciences, University of Belgrade, located in Belgrade (Latitude: 44.76, Longitude: 20.60), Republic of Serbia. The aim of the experiments was to evaluate the effect of PCM integration on the indoor thermal performance of lightweight building envelopes. In one of the experimental houses, Phase Change Material (PCM) was incorporated into the walls and ceiling, (PCM house), while the second one, constructed without PCM integration, served as the reference (ref. house). The internal dimensions of each test house were 2.0 m in width, 2.0 m in length, and 2.1 m in height. The roofs and walls were constructed from commonly available lightweight construction materials, with layer thicknesses presented in Tab. 1.

The houses were built on an open grassy soil surface (Fig. 1a). A PVC door with dimensions of 0.7 × 2.0 m was positioned on the east wall, while a PVC-framed window with dimensions of 0.5 × 0.6 m was installed on the west wall of each house. A total of 110 kg of Rubitherm® phase change material type RT25HC was installed on the walls and ceiling of the PCM house (Fig. 1b). Detailed

information about Rubitherm® RT25HC is presented in Tab. 2. The PCM was integrated using the macro-encapsulation method, which prevents leakage and minimizes the impact on the structural function of the building elements. The PCM was encapsulated in aluminium panels measuring $450 \times 300 \times 15$ mm. These aluminium panels were covered with a 12 mm thick gypsum board, preventing the PCM from coming into direct contact with the indoor air.

Table 1. Construction materials for test houses

Building Element	Material (from outside to inside)	Thickness [mm]
Roof	Aluminium sheet	0.5
	Expanded polystyrene (EPS)	100
	OSB board	12
	Gypsum board	12
Walls	Expanded polystyrene (EPS)	100
	OSB board	12
	Gypsum board	12
Floor	OSB board	12
	Extruded polystyrene (XPS)	50

The experiment was carried out in two intervals: from June 15th to 19th, at the end of spring, and from July 22nd to 26th, during the summer. The selection of these two specific time intervals was strategically undertaken to evaluate the PCM's performance under the most demanding and representative summer heatwave conditions characteristic of the Belgrade climate. Indoor air temperatures were monitored at 2-minute intervals using a Testo 435-2 indoor air quality meter with an indoor air quality probe for CO₂, temperature, humidity and absolute pressure positioned at the centre of each test house (Fig. 1c). Simultaneously, outdoor air temperatures were recorded using radio probe with compact professional humidity module placed outside. The technical specifications of the measuring instruments are summarized in Tab. 3.

Table 2. Technical specification of Rubitherm® RT25HC [23]

The most important parameters	Typical Value	Unit
Melting range	22–26 (main peak: 25)	[°C]
Congeeing range	26–22 (main peak: 25)	[°C]
Heat storage capacity $\pm 7,5\%$	$230 \pm 7.5\%$	[kJkg ⁻¹]
Combination of latent and sensible heat in a temperature range of 16 °C to 31°C.	58	[Whkg ⁻¹]
Specific heat capacity	2	[kJkg ⁻¹ K ⁻¹]
Density solid (at 15 °C)	880	[kgm ⁻³]
Density liquid (at 40 °C)	770	[kgm ⁻³]
Thermal conductivity (both phases)	0.2	[Wm ⁻¹ K ⁻¹]
Volume expansion	12.5	[%]
Flash point	150	[°C]
Maximum operating temperature	65	[°C]

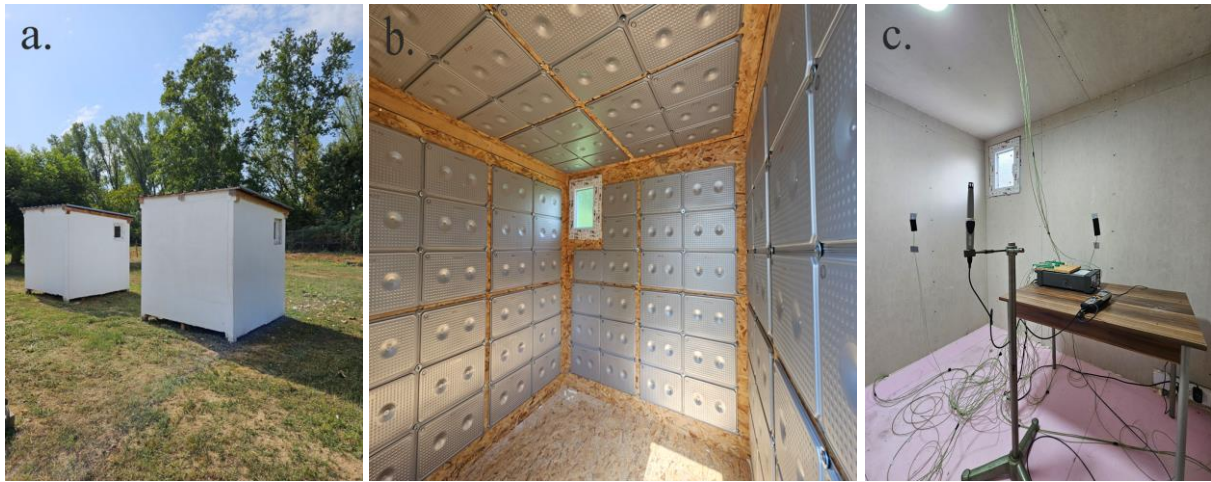


Figure 1. Experimental setup (a. Outside view of test houses, b. Incorporation of PCM inside of the test house, c. Placement of measurement equipment inside of the test house)

Table 3. The technical specifications of the measuring instruments

Name	Type	Range	Accuracy
Testo indoor air quality meter	435-2		
Testo Probe	IAQ	0-50 °C	±0.3 °C
Testo Radio probe	Compact professional humidity module	-20-70 °C	±0.3 °C

3. Results and discussion

3.1. Analysis of indoor temperature variation

The experiments were conducted in Belgrade, Republic of Serbia, at the Vinča Institute of Nuclear Sciences. According to the Köppen–Geiger climate classification, Belgrade is characterized by a humid subtropical climate (Cfa), typical for regions with warm summers and cold winters [24]. Two observation periods were defined to evaluate the thermal behaviour of the test houses. During the first period, four thermal cycles were monitored from 05:00 on June 15th until 05:00 on June 19th under non-ventilated conditions. During the second period, four thermal cycles were recorded from 05:00 on July 22nd to 05:00 on July 26th under natural night-ventilation conditions, with ventilation starting at approximately 21:00 by opening the doors and windows, ending at around 06:00 by closing them.

During the first observation period (Fig. 2), the indoor air temperature of the reference house ($T_{in,ref}$) was lower than the indoor air temperature of the PCM house ($T_{in,pcm}$) at the beginning of the first and second thermal cycles, when the early-morning outdoor air temperature (T_{out}) was approximately 10 °C. As the outdoor air temperature increased in the morning hours, the cooling rate of both houses decreased. The indoor air temperature in the reference house did not drop below the indoor air temperature in the PCM house. Throughout all four thermal cycles, the indoor air temperature in the PCM house remained within the PCM phase-change temperature range of 22-26 °C, showing a slight upward trend due to the absence of cooling and the inability of the PCM to fully solidify. The maximum differences in indoor air temperature between the reference house and the

PCM house occurred around 20:00, reaching 3.5 °C, 4.8 °C, 3.9 °C, and 4.0 °C for the first, second, third, and fourth thermal cycles, respectively.

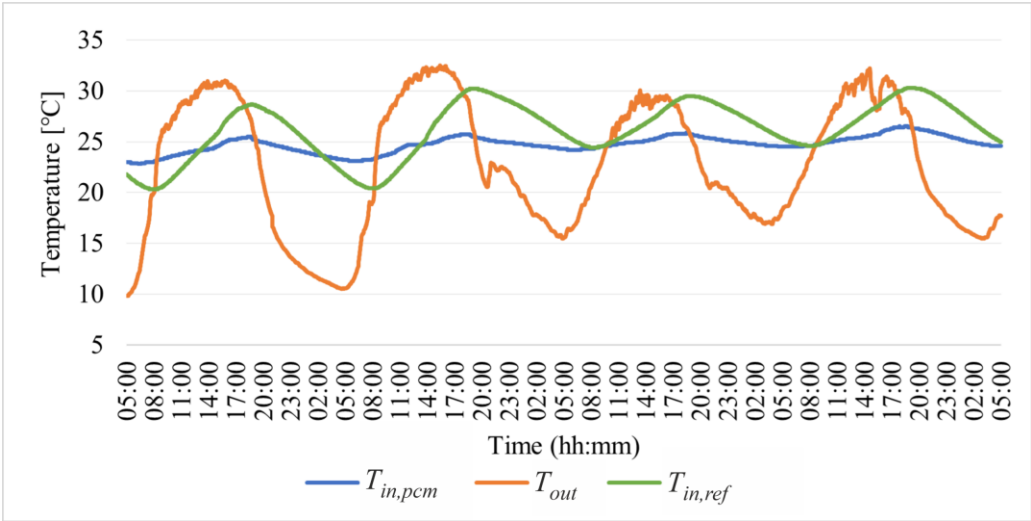


Figure 2. Indoor air temperature profiles of the reference house and the PCM house, as well as the outdoor air temperature during the first period

During the second observation period (Fig. 3), four thermal cycles were monitored under night-ventilation conditions. As a result of nighttime cooling, the indoor air temperature dropped below the lower limit of the PCM phase-change temperature range (22 °C for the PCM used), enabling the solidification process of the PCM. Under daytime conditions, it can be observed that the indoor air temperature in the PCM house did not exceed 26 °C, which represents the upper limit of the PCM phase-change temperature range and falls within the range of thermal comfort. In contrast, the indoor air temperature in the reference house was significantly higher during the same daytime periods, exceeding 30 °C. The maximum differences in indoor air temperature between the reference house and the PCM house during the second period occurred around 20:00, reaching 4.2 °C, 4.5 °C, 5.8 °C, and 5.9 °C for the first, second, third, and fourth thermal cycles, respectively (Fig. 4).

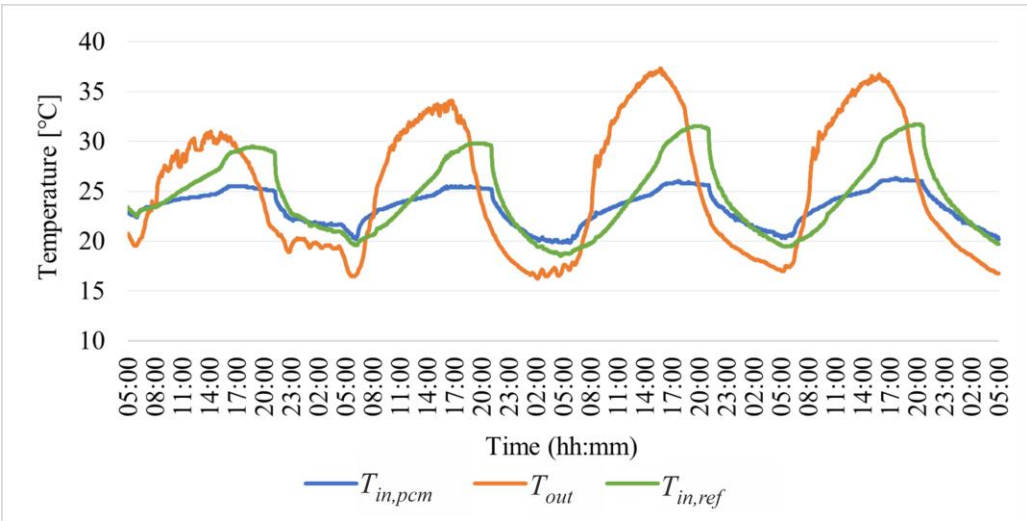


Figure 3. Indoor air temperature profiles of the reference house and the PCM house, as well as the outdoor air temperature during the second period

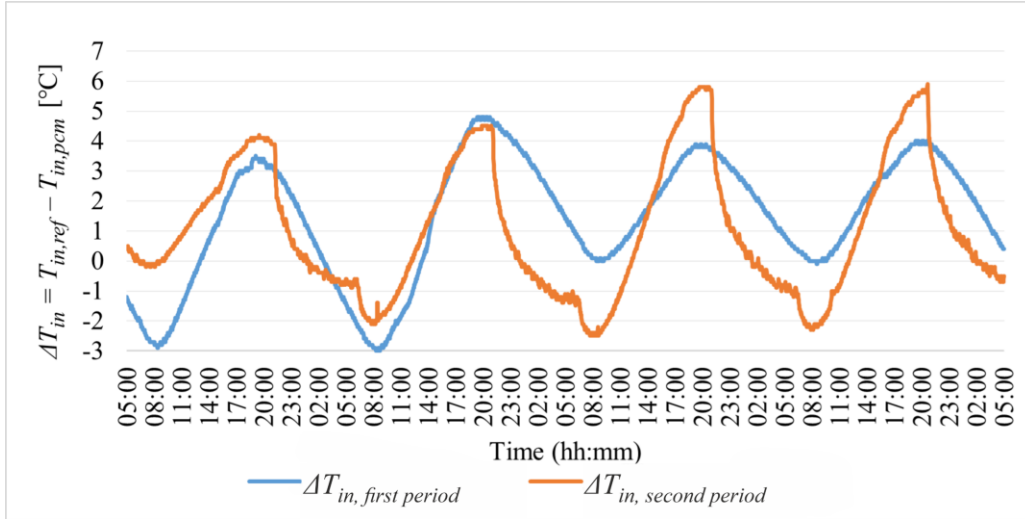


Figure 4. Difference in indoor air temperature between the reference house and the PCM house during the two observation periods

Improving indoor environmental conditions is one of the primary objectives of integrating PCM into building components, as it directly affects occupants' thermal comfort. In this study, the effect of PCM was assessed by comparing the indoor air temperatures of the PCM and reference houses, focusing on the average temperature reduction and the levelling of thermal loads.

3.2. Analysis of average indoor temperature reduction

The average indoor temperature reduction (*AITR*) for the PCM house, compared to the reference house, was calculated using the mean indoor air temperature during daytime hours only (from 05:00 to 20:00 for each day), as expressed in Eq. (1) [25]:

$$AITR = \sum_{\tau=5:00}^{\tau=20:00} \frac{T_{in,ref,av} - T_{in,pcm,av}}{T_{in,ref,av}} \times 100, \quad (1)$$

where $T_{in,ref,av}$ and $T_{in,pcm,av}$ represent the average indoor air temperatures in °C of the referent and PCM houses, respectively, from 05:00 to 20:00. As mentioned earlier, indoor air temperatures were recorded on 2 minutes. The calculated *AITR* and the average indoor temperatures (*AIT*) for both houses across the thermal cycles in the two observation periods are presented in Fig. 5 and Fig. 6, respectively.

The results show that the PCM house consistently maintained lower *AIT* values compared to the reference house in both periods. During the first period, the *AIT* of the reference house was 24.5 °C, 26.0 °C, 26.9 °C, and 27.3 °C on the first, second, third, and fourth days, respectively, whereas the PCM house recorded 24.1 °C, 24.6 °C, 25.0 °C, and 25.3 °C. Consequently, the *AITR* during this period ranged from 0.03% to 6.12%, with an average value of 3.26%, showing a clear trend of indoor temperature reduction in the PCM house.

In the second period (with night ventilation), the *AIT* of the reference house reached 25.0 °C, 23.7 °C, 24.3 °C, and 24.8 °C on the first, second, third, and fourth days, while the PCM house recorded 23.7 °C, 23.1 °C, 23.3 °C, and 23.6 °C, respectively. The *AITR* in this period ranged from

3.19% to 6.54%, with an average value of 4.49%. This improvement demonstrates the beneficial impact of PCM integration on thermal comfort, while simultaneously lowering the cooling energy demand of air- conditioning systems.

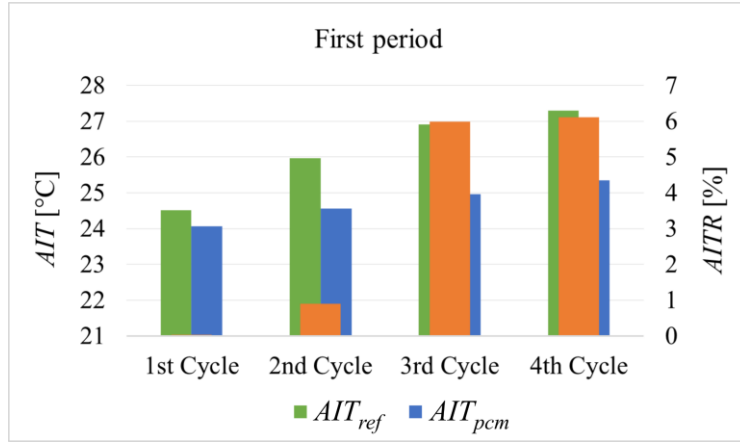


Figure 5. The calculated $AITR$ and the average indoor temperatures (AIT) in first period

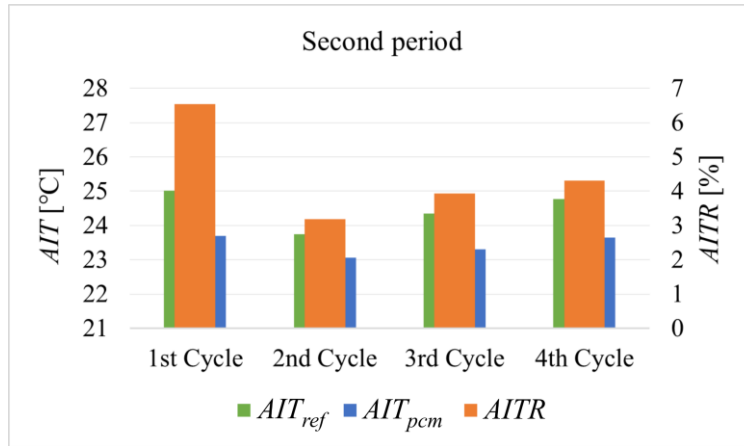


Figure 6. The calculated $AITR$ and the average indoor temperatures (AIT) in the second period

3.3. Analysis of thermal load levelling

The thermal load levelling index (TLL) indicates daily variations in indoor temperature and is calculated as the difference between the maximum and minimum air temperature in the room. This index is important in building thermal design because it reflects how effectively the building envelope mitigates thermal loads. This directly influences the required power and operating costs of the air conditioning system. By achieving effective thermal load levelling, excessive power consumption and unnecessary losses are reduced. This improves thermal comfort and contributes to energy savings and environmental sustainability. A lower TLL value signifies enhanced thermal stability of the indoor environment and better overall performance of the building envelope. The TLL for the reference and PCM houses was calculated according to Eq. (2) and Eq. (3) [26]:

$$TLL_{ref} = \frac{T_{ref,max} - T_{ref,min}}{T_{ref,max} + T_{ref,min}} \quad (2)$$

$$TLL_{pcm} = \frac{T_{pcm,max} - T_{pcm,min}}{T_{pcm,max} + T_{pcm,min}}, \quad (3)$$

where T_{max} , and T_{min} represent the daily maximum and minimum indoor temperatures recorded for each house. The calculated values of TLL and the corresponding $TLLR$ are presented in Fig. 7 for the first period, and in Fig. 8 for the second period.

The results demonstrate that the PCM house consistently exhibited better thermal performance, with TLL values remaining lower than those of the reference house during all four thermal cycles in both periods. Specifically, the TLL of the reference house was 0.17, 0.19, 0.09, and 0.1 compared to 0.06, 0.05, 0.03, and 0.04 for the PCM house in the first period. The $TLLR$ values reached 67.4%, 72.5%, 64.1%, and 62.2% for the four cycles, respectively. These findings indicate that the indoor temperature in the PCM house was more stable than in the reference house over the experimental period.

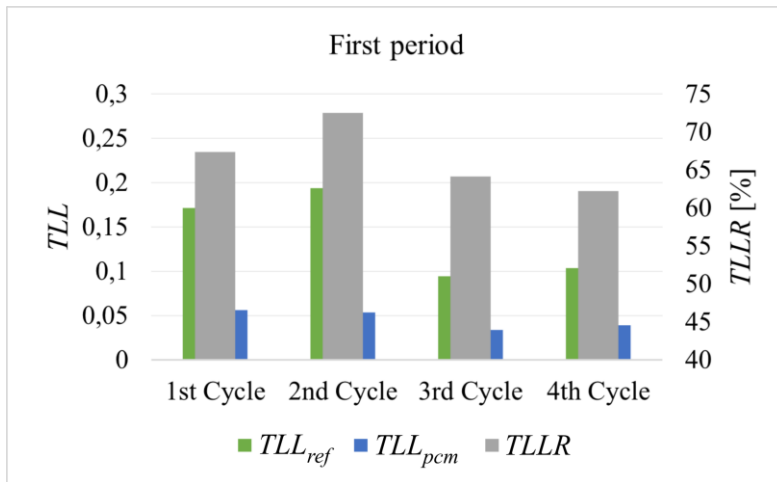


Figure 7. TLL and $TLLR$ values in the reference and PCM houses during first period

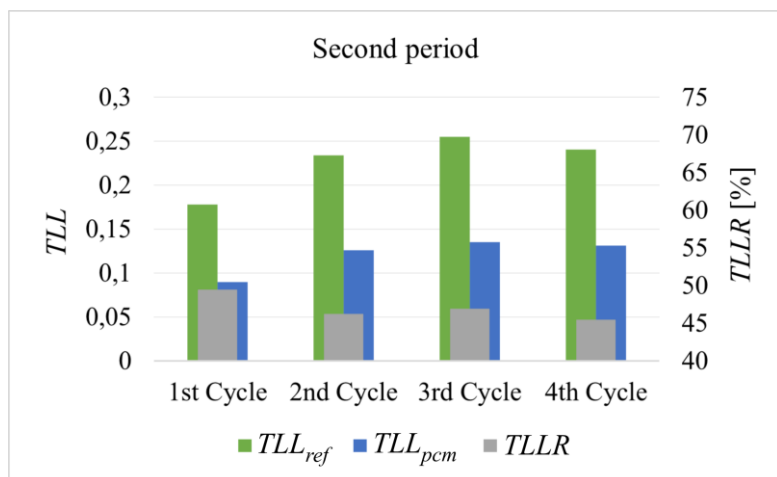


Figure 8. TLL and $TLLR$ values in the reference and PCM houses during second period

During the second period the TLL of the reference house was 0.18, 0.23, 0.25, and 0.24 compared to 0.09, 0.13, 0.14, and 0.13 for the PCM house. The difference in TLL between the two

houses during was approximately 0.1, while the *TLLR* values reached 49.5%, 46.2%, and 46.9%, and 45.5% for the four cycles, respectively.

4. Conclusion

This experimental research was conducted on two test houses under the real climatic conditions of Belgrade, which has a humid subtropical climate (Cfa). One house had PCM installed in the building envelope, while the other did not. The aim was to investigate how PCM affects the thermal performance of a lightweight building. The results showed that the house with PCM had lower average indoor air temperatures and smaller daily temperature fluctuations in both measurement periods. The maximum temperature difference reached 5.9 °C in the second period. The average indoor temperature reduction was 3.26% in the first period and 4.49% in the second period when night ventilation was used. The results indicate that PCM reduces peak heat loads and maintains the temperature within the comfort zone for longer during heat waves. Analysis of the *TLL* index showed more stable indoor conditions in the house with PCM. The decrease in *TLL* value was up to 72.5% in the first period compared to the reference house. This means that PCM reduces overheating and moderates temperature changes, thus reducing the need for cooling. Incorporating PCM in lightweight constructions is an effective measure to improve comfort and reduce energy consumption. For future research, a longer measurement period is recommended to ensure the results are more representative. Different start and end times of natural night ventilation should be investigated to better understand its impact on PCM activation and cooling effect. It is also necessary to measure the temperature inside the wall layers, the heat flux through the walls and ceiling, as well as the relative humidity. Such an approach would enable a more detailed analysis of heat transfer and a more precise optimization of PCM application in different climatic conditions.

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Nomenclature

<i>AIT</i>	-	average indoor temperature, [°C]			<i>Subscripts</i>
<i>AITR</i>	-	average indoor temperature reduction, [°C]	<i>av</i>	-	average
<i>T</i>	-	temperature, [°C]	<i>in</i>	-	indoor
<i>TLL</i>	-	thermal load levelling index, [-]	<i>max</i>	-	maximum
<i>TLLR</i>	-	thermal load levelling index reduction, [%]	<i>min</i>	-	minimum
<i>Greek symbol</i>			<i>out</i>	-	outdoor
τ	-	time, [h]	<i>pcm</i>	-	house with PCM
<i>Acronym</i>			<i>ref</i>	-	reference house
PCM	-	phase change material			

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