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Phase change material coupled building envelope for thermal comfort and energy-saving: Effect of natural night ventilation under hot climate

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ABSTRACT

Incorporating phase change material (PCM) into buildings in hot climates is an excellent strategy for better thermal comfort and energy-saving in future smart cities. Nevertheless, PCM elements suffer from adverse temperature behaviour at night due to the dissipation of stored diurnal heat. Night ventilation has been proposed as a promising solution and clean strategy for decreasing indoor building temperature at night and increasing PCM benefits in the following cycle. In this study, the effect of the natural night ventilation (NNV) period on the thermal performance of a room-integrated PCM is investigated experimentally under hot summer conditions in Iraq. Six NNV periods (with 1 h increment) are studied for six consecutive days in terms of average indoor and operative temperature reduction. Moreover, the work is extended to study the average heat gain difference in each day cycle to show the contribution of PCM to energy-saving. The results showed a slight enhancement in the average indoor air temperature of the PCM room compared with another identical no-PCM room regardless of the NNV period due to high outdoor ambient temperature at night. However, NNV for 4 h can reduce the average indoor air temperature by 28.6% compared with 1 h of NNV, whereas a slight extra reduction was achieved for 5 and 6 h. Besides, NNV slightly affected the operative temperature at night against no impact during the day, which was more influenced by the solar radiation and high diurnal ambient temperature. The results further revealed that a total average heat gain difference of 63.1–87.9 W was achieved, in which the roof contributed by more than 44% in each cycle.

1. Introduction

Buildings are the most significant contributor to energy consumption and CO_2 emissions worldwide. In this regard, the International Energy Agency (IEA) reported that buildings were responsible for 36% and 39% of final energy use and CO_2 emissions in 2018 (IEA and UN Environment IEA UN Environment Programme, 2019). Compared with developed countries, these percentages are higher in the developing regions that still rely on fossil fuel sources to meet the energy demand. For instance, it has been reported that CO_2 emissions increased 300% in Iraq between 1990 and 2017 due to the continued reliance on traditional fuel sources for power generation and other energy sectors (Hashim et al., 2020). Therefore, urgent steps must be taken in the building sector to mitigate such alarming indicators and put the world on the right path to a cleaner future and smarter cities.

Phase change materials (PCMs) have been presented as an effective solution for building energy advancements (Wijesuriya et al., 2022), considering the seasonal and annual energy-saving (Tunçbilek et al., 2020). PCMs are unique materials that can store and release remarkable heat amounts during phase transition, managing the thermal requirements for buildings in hot and cold locations (Yıldız et al., 2020). However, some limitations regarding efficient PCM utilisation have been reported by researchers, such as uncontrollable stored-heat dissipation (De Gracia, 2019), inefficient PCM melting/solidification cycle (Sun et al., 2018), high indoor and building surface temperature at night, poor mechanical properties of construction materials when incorporated directly (Rao et al., 2018), and complex investigations needed to utilise the PCM optimally (Ramakrishnan et al., 2016). Night ventilation (NV) is a promising technique to maximise PCM benefits in

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Nomenclature

Abbreviations

ACH	Air change per hour
AHGD	Average heat gain difference (W)
AITR	Average indoor temperature reduction (%)
HG	Heat gain (W)
NNV	Natural night ventilation
NV	Night ventilation
OT	Operative temperature (°C)
OTR	Operative temperature reduction (%)
PCM	Phase change material

Symbols

A	Area of element (m^2)
h_i	Combined convective and radiative heat transfer coefficient for interior room elements and indoor air ($W/m^2.°C$)
T_i	Indoor air temperature (°C)
$T_{i,no\text{-}PCM\ room,avg}$	Average indoor air temperature of the no-PCM room (°C)
$T_{i,PCM\ room,avg}$	Average indoor air temperature of the PCM room (°C)
ΔT	The difference between element inside surface temperature and the indoor air temperature (°C)
τ	Time (h)
$\overline{T}_{mr}$	Mean radiant temperature (°C)

hot location applications (Ramakrishnan et al., 2016). In this regard, low-temperature air at night could minimise the high indoor temperature resulting from the PCM solidification phase and prepare it for the next working day. The use of external building openings (such as windows) to provide NV have proved a considerable energy enhancement through minimising accumulated heat inside indoor space and accelerating PCM solidification to be ready for the next day cycle (Prabhakar et al., 2020). The local temperature variation and the building thermal mass (Guo et al., 2021) significantly influence NV during the day and nighttime in the location under the application. Several concerns have been investigated in the literature studies considering NV, such as the NV quantity in terms of air change per hour (ACH) (Li and Chen, 2021), ventilation time and velocity (Gross, 2021), adopting passive/active NV (Zhou et al., 2020), etc. Many studies discussed the active NV using different mechanical means against a limited number of studies related to the passive technique of natural NV (NNV). In the latter technique, the wind predominantly forces the heat exchange between the indoor and outdoor air due to buoyancy forces (Zhang et al., 2021). However, this technique may not meet the thermal comfort requirements, especially in severe hot locations (Ahmed et al., 2021).

Many researchers in recent studies have investigated emerging NV with PCM-based building applications. For instance, Piselli et al. (2020) numerically investigated the impact of controlled NV on building efficiency when PCM was integrated with the building envelope in different Italian zones. They proposed two control strategies, NV and whole-day temperature-controlled ventilation, to assess the charging-discharging process of integrated PCM. Results showed that the second strategy enhanced the indoor temperature and reduced the cooling needs by up to 65% in mild zones. In the same approach, Saffari et al. (2019) analysed the effectiveness of controlled NNV in saving cooling energy for an office building coupled with PCM in temperate zones. Simulation results showed that building cooling requirements were reduced by 8%–15% using NNV. Furthermore, the ventilation has increased the efficiency of used PCM, which became more effective in the next day-cycle. Zhang et al. (2017) numerically analysed the summer ventilation effect on a building coupled-PCMs in indoor thermal performance and energy efficiency in five different Chinese cities from June to September. They considered 48 ventilation arrangements, including eight ventilation periods (3 h per period) and six ventilation quantities (0.5 ACH to 3 ACH). Simulation outcomes showed that the ventilation significantly enhanced the building's thermal comfort and improved energy-saving in the summer months. Moreover, the larger ventilation quantity has improved the indoor thermal comfort, and the best case was obtained when the ventilation was provided with greater than 2 ACH. In the same course, Soudian and Berardi (2019) conducted a numerical study considering the effect of NV quantity and period on a building-integrated PCM under Toronto and New York City weather conditions. The study concluded that applying NV with higher quantities and longer time has improved the building's operative temperature in the following days. The NV quantity up to 5 ACH resulted in remarkable enhancement. However, increasing the NV flow rate from 5 ACH (i.e., 0.26 m^3/s) to 10 ACH (i.e., 0.53 m^3/s) has maximised energy-saving by only 1.6%. Aamodt et al. (2021) studied the influence of NNV and hybrid ventilation strategies on the thermal behaviour of a building integrated microencapsulated PCM under weather conditions in Oslo, Norway. The cooling load reduction and energy-saving were analysed using the above two strategies with 0.5–5 ACH airflow and 2–4 mm PCM thickness. Numerical results showed that higher airflow rate and PCM thickness resulted in better energy-saving over NV alone. The cooling load was reduced by 11.5%, 40.2% and 59.8% when NV has been applied with 1, 3 and 5 ACH, respectively. Moreover, the cooling load reduced by 19.5%, 78.2% and 95.5% at these flow rates when NV has been coupled with 4 mm PCM thickness. Mechouet et al. (2021) studied the effect of mechanical NV on the thermal performance of building masonary walls incorporated PCM under different climate zones of Morocco. They studied the ventilation rate along with the PCM thickness and melting temperature. Numerical results revealed that increasing PCM thickness and mechanical NV rate resulted better thermal comfort and lower cooling energy consumption. However, they stated that increasing NV rate has limited the PCM thickness effectiveness. The results further indicated that using PCM of 6 mm with 6 ACH reduced the indoor temperature and the cooling energy consumption by 1.92 °C–2.33 °C and 19.5%–62.9%, respectively compared with 30 mm PCM thickness without mechanical NV, showing the importance of NV for PCMs-integrated built environment.

The above-analysed literature indicated some research gaps, including limited studies that considered the NNV utilisation for PCM building applications in severe hot climates (Solgi et al., 2018). Furthermore, according to the authors' best knowledge, no studies have presented the effect of the NNV period on thermal comfort in such locations. Likewise, the influence of NNV on the PCM thermal performance in terms of experimental studies is lacking in the literature. Such studies are essential to show the actual behaviour of PCMs in buildings compared with numerical investigations that rely on software approximations.

In this study, a PCM room was built and tested for six consecutive days under severe hot climate conditions against another room without PCM to investigate the effect of NNV on thermal comfort and energy-saving. To this aim, the influence of NNV on the average indoor temperature reduction at the end of each day and thermal comfort reduction during each day were investigated. According to our latest research, this technique is required to maintain the negative behaviour of PCM heat discharging during the solidification phase (Al-Yasiri and Szabó, 2022). Besides, the diurnal heat gain reduction by each element of the PCM room was also studied as a crucial indicator for building energy-saving. The results highlighted in this work are believed to give a broad vision of the NNV effect when applied with PCM in severe hot locations.

2. Methodology

2.1. Experimental set-up

The field test was conducted on two rooms with dimensions of 1 × 1 × 1 m. PCM was macroencapsulated in the roof and walls of one room (calls as a PCM room), whereas the other was left without PCM for control (calls as a no-PCM room). Rooms were built using local construction materials, popular in residential constructions with poor thermal performance, resulting in high cooling loads. The experimental rooms were situated on wooden foundations, spaced by 120 cm and positioned in an open atmosphere with an east-south orientation. Fig. 1 shows the schematic illustration of the experimental rooms.

Several considerations were taken into account to build the experimental rooms, as follows:

- *Roof construction*: the roof of both rooms was constructed from a 4 mm Isogam finishing layer, 50 mm concrete layer and 2–3 mm gypsum mortar cladding layer. These are the main construction combination in the Iraqi residential buildings for low and medium-income inhabitants (The Ministry of Construction, Housing Municipalities and Public work, 2013). In the PCM room, a PCM layer was added, made with 1.5 cm thickness according to our earlier study that indicated better energetic performance during melting and solidification processes at this thickness compared with other PCM thicknesses (Al-Yasiri and Szabó, 2021a). Moreover, the PCM layer was placed between the concrete and Isogam layers to reach the best thermal behaviour, according to our previous investigation (Al-Yasiri and Szabó, 2021b).
- *Walls construction*: walls of each room were built from pre-fabricated concrete bricks of dimensions 24 × 12 × 7 cm. Moreover, a cement mortar layer of ~2 cm thickness was added to the exterior walls to support the walls and ensure no air leakage through the joints and slots of connected bricks. In the PCM room, PCM capsules were inserted in every brick, and these capsules were the best-thermally acted among many examined PCM capsules of different shapes and heat transfer areas (Al-Yasiri and Szabó, 2021c). It is worth mentioning that concrete layers and concrete bricks were fabricated according to the Iraqi procedure and mixing ratios of raw materials following the Iraqi construction blog directions (The Ministry of Construction, Housing Municipalities and Public work," 2013).
- *Windows*: an openable wooden-framed window of 25 × 35 cm was installed on the east-oriented wall of each room. This position results in a high energy load in the summer season compared with other walls (Kim et al., 2016), having the worst impact on the indoor environment and showing the role of PCM in mitigating the indoor temperature. The windows were kept close during the day hours (i.e., from 6:00 to 18:00) and then opened for one to 6 h in an increasing pattern during the experiments starting at 18:00. Then, windows were closed after the period specified on each day. The windows played the primary role in this study, providing NNV for the indoor environment (single-sided ventilation). The position/location of the window is essential for NNV since it enhances the wind to be circulated inside the room and decreases the indoor temperature (Elshafei et al., 2017). Besides, the one-sided ventilation does not induce appreciable wind as cross-ventilation (double-sided) does (Ghiabaklou, 2010). However, the ambient air temperature and speed are among the essential parameters for NV (Tian et al., 2011), which are the core of the current study.

2.2. PCM macroencapsulated panel and capsules

As mentioned earlier, a PCM panel was inserted into the roof, and PCM capsules were immersed inside the wall bricks of the PCM room. The PCM used in this work is locally available petroleum-based paraffin wax produced from crude oil in the Iraqi refineries. This PCM has good thermo-physical properties for thermal energy storage applications and was selected in this work due to its melting temperature of 40 °C–44 °C appropriate for the temperature variation in the studied site. Besides its thermo-physical and economic advantages, this organic PCM is preferable for macroencapsulation applications due to its durability, eco-friendly characteristics and compatibility with many encapsulation and building materials (Sheikholeslami et al., 2020). It is worth mentioning that this PCM type could be provided freely by the government for research purposes and investigated by several Iraqi researchers in different applications, including solar distillation systems (Chaichan et al., 2016), solar air heating systems (Habib et al., 2021), electrical distribution transformers (Hasan, 2017), and photovoltaic module application (Chaichan et al., 2022).

However, paraffin wax generally suffers from poor thermal conductivity, influencing its thermal performance. Therefore, different techniques have been used to enhance its thermal behaviour, such as

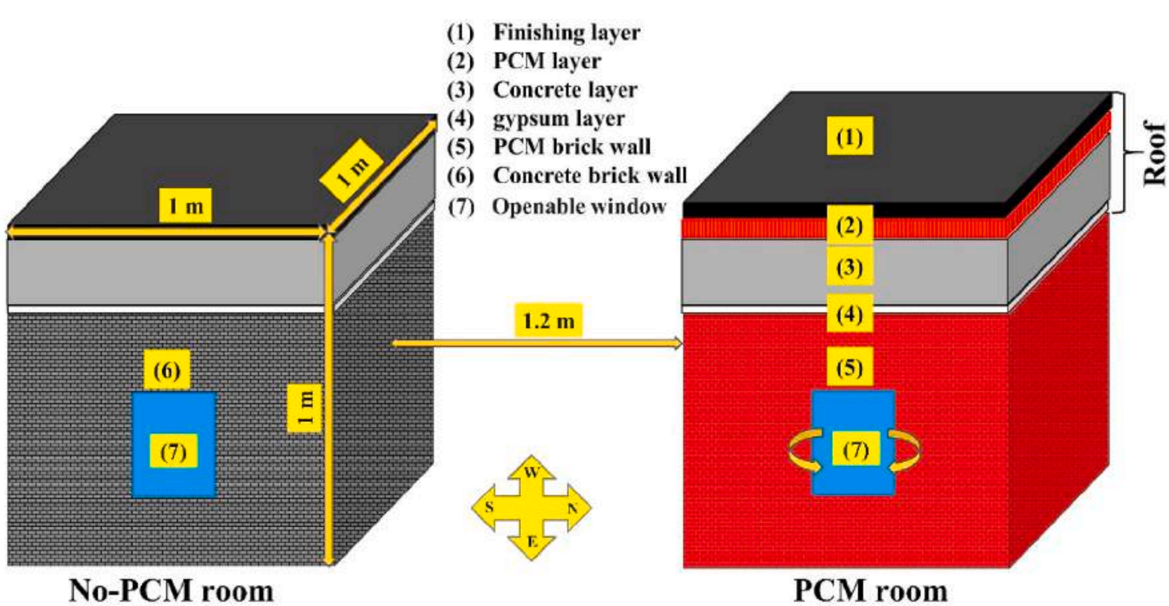

Fig. 1. Schematic view for the experimental rooms.

nanoparticle dispersion (Li et al., 2021), metal foam inclusion (Qureshi et al., 2018), using expanded graphite as a carrier (JianShe et al., 2019) and macroencapsulation with high conductivity materials (Rathore and Shukla, 2019), the method followed in the current research. Table 1 shows the main physical characteristics of the used PCM.

The PCM was macroencapsulated inside the panel and capsules and combined inside the roof and brick walls. In this regard, the panel was made from galvanised steel of 0.5 mm thickness, with dimensions of 100 × 100 × 1.5 cm, holding 7 kg of PCM. On the other hand, aluminium containers of a square cross-sectional area with 1 mm thickness and dimensions of 4 × 4 × 2 cm were used in PCM bricks macroencapsulation. A total of 545 PCM capsules were immersed into the PCM room walls in which every five PCM capsules were dipped inside each concrete brick. Each PCM brick held about 145 g of PCM, making a total PCM quantity of ~16 kg in all walls. Fig. 2 shows photos of the prepared PCM panel/capsules and their position in the tested PCM room.

2.3. Instrumentation

T-type thermocouples from TEMPSENS with a temperature range from −270 °C to 370 °C and an accuracy of ±0.5 °C were installed on the inside element surfaces of PCM and no-PCM rooms to measure the temperature variation continuously. Furthermore, one thermocouple was placed in the centre of each room space to measure the indoor air temperature. Another one was placed outside the rooms to measure outdoor ambient temperature variation. Thermocouples were connected with multi-channel Arduino (type Mega 2560 from Ardonic Co (Ardunic, 2020). and programmed to record the measured temperatures every 10 min throughout the experiment. All recorded data was stored in removable storage memory to easily export and analyse the results at the end of the experiment. The diurnal solar radiation was continuously measured every 30 min using a solar power meter (type SM206) with 0.1 W/m^2 resolution and ±10 W/m^2 accuracy.

2.4. Thermal performance assessment

Several indicators have been presented to quantify the influence of NNV on the thermal performance of a PCM room compared to a no-PCM room. These indicators are presented to assess the thermal comfort and energy-saving earned from PCM incorporation along with the effect of NNV. The average indoor temperature reduction and operative temperature reduction were considered for thermal comfort assessment, whereas the daytime heat gain reduction was considered an effective energy-saving indicator. The average indoor temperature reduction during a specific night period can evaluate the NNV period's effectiveness in maintaining the indoor temperature and ability to reach complete solidification of PCM. Besides, the operative temperature reduction can indicate the interaction of indoor temperature with the inside surface temperature of all room's elements, presenting the actual indoor temperature felt by occupants in actual cases. On the other hand, the heat gain reduction is a good indicator to show the cooling loads that could be reduced, representing vital energy benefits. In the next section, all these indicators will be defined and discussed in detail.

Table 1
Characteristics of paraffin wax used in the current work (Akeiber et al., 2017).

Appearance	Melting temperature range (°C)	Thermal conductivity (W/m.K)	Latent heat of fusion (kJ/kg)	Density (kg/m^3)	Specific heat (kJ/kg. K)
White	40–44	0.21	190	930 (solid) 830 (liquid)	2.21 (solid) 2.41 (liquid)

3. Results and discussion

3.1. Analysis of site climate conditions and experimental temperature variation

The experiments were performed on six consecutive days from 18th to September 23, 2021, starting at 6:00 under climate conditions of Al Amarah city (Latitude: 31.84° and Longitude: 47.14°), South of Iraq. September is among the hottest months in Iraq, with nearly equal day and night hours in which the sunshine starts around 5:30 in the morning and sunset around 17:30. Fig. 3 shows historical data on the average maximum and minimum ambient temperatures and monthly sunshine period for the site under study. Besides, the wind speed was in the range of 15–26 km/h during the experimental days (Ministry of Agriculture, 2021).The figure indicates high ambient temperatures exceeding 40 °C during day hours and higher than 25 °C at night in May, June, July, August and September.

The outdoor ambient temperature and solar radiation measured at the site during the experiment period are shown in Fig. 4. Experimental days showed a similar trend regarding the maximum outdoor ambient temperature and solar radiation that exceeded the mark of 45 °C and 1190 W/m^2, respectively, at midday. Recorded data also showed that the ambient temperature was above the mark of 27 °C at night, displaying the importance of cooling and air-conditioning systems in such locations to maintain thermal comfort for occupants.

The temperature variation recorded for the inside surface temperature for PCM and no-PCM rooms' elements are shown in Figs. 5–9.

The figures above showed high inside surface temperatures recorded in the first and last day cycles encountered with high solar radiation. The other four days reported lower solar radiation and outdoor ambient temperatures, resulting in lower inside surface temperatures. In the first day-cycle, the highest inside surface temperature of the roof, east wall, north wall, west wall and south wall of the no-PCM room was 53 °C, 53.75 °C, 54.25 °C, 55 °C and 58.5 °C against 50.25 °C, 52.5 °C, 53.5 °C, 54.5 °C and 57.5 °C of the PCM room elements, respectively. The roofs showed lower inside surface temperature than the walls, although they were exposed to direct incident solar radiation for a long time. This indicates that roofs were built with better thermal resistance materials than walls. In this regard, it is worth mentioning that Isogam and gypsum mortar layers involved in the roof have better thermal resistance than concrete bricks and cement mortar layers of walls, thanks to their low thermal conductivity (Al-Yasiri and Szabó, 2022). Besides, the latter construction materials have high thermal mass, keeping the walls with high surface temperature for a longer time.

The recorded data generally indicated a notable surface temperature difference for the roof of the PCM room against that of the no-PCM room during the daytime. A lower temperature difference was noticed for the east and north walls during day hours, whereas the west and south walls showed a slighter difference during this period. Furthermore, apparent time-shifting of roofs' highest inside surface temperature was noticed against lower time-shifting for walls. However, the east and south walls showed minimal time-shifting than the north and west walls as the latter were exposed to lower direct solar radiation during the day.

All PCM room elements showed negative temperature behaviour during the night due to PCM's uncontrolled heat discharging course. However, walls showed a slight temperature difference during this period against remarkable adverse temperature differences for the roof of the PCM room. This temperature behaviour indicates that the PCM roof stored more heat than any other wall as it was exposed to direct solar radiation all daytime compared with walls that were time-dependent. The negative temperature behaviour of the PCM roof was sustained until the next day-cycle regardless of the period of NNV considered in each day-cycle.

Fig. 2. Installed PCM panel and PCM capsules in the PCM room.

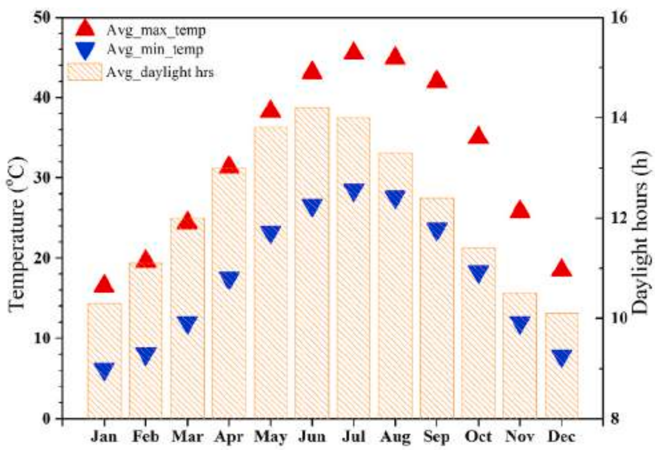

Fig. 3. Climate conditions of Al Amarah city during 2021 (Ministry of Agriculture, 2021).

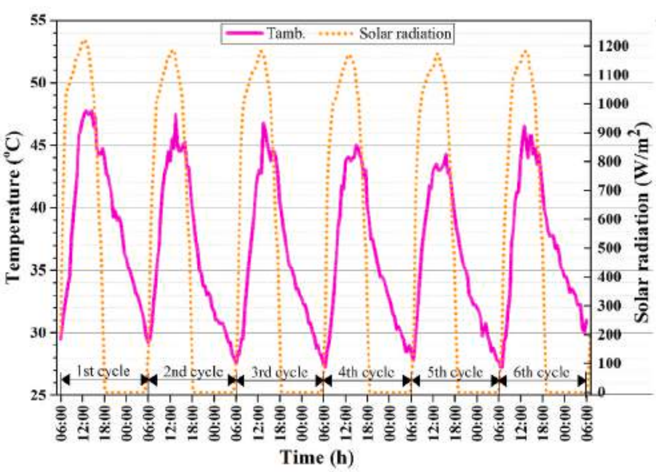

Fig. 4. Ambient temperature and solar radiation in the site during the experiment period.

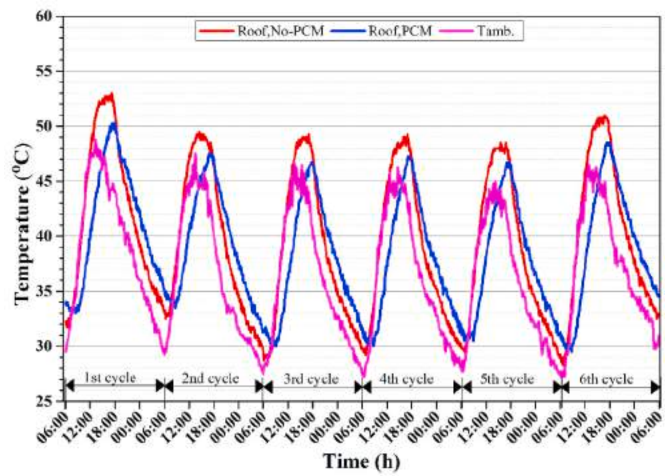

Fig. 5. Roofs' surface temperature and ambient temperature of PCM and no-PCM rooms.

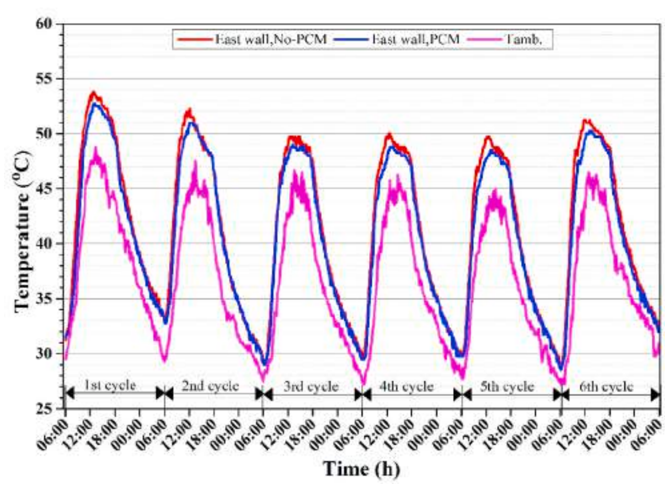

Fig. 6. East walls surface temperature and ambient temperature of PCM and no-PCM rooms.

3.2. Effect of NNV period on the indoor temperature

Buildings with passively integrated PCM suffer from high inside surface temperature of elements when the ambient temperature falls below the operating range of applied PCM (i.e. melting and solidification range). This period is usually designed to be occurred at night by selecting suitable PCM considering the daily ambient temperature variation and the optimal PCM position within the building structure that controls the PCM activation. At night, the relative low outdoor ambient temperature is often employed to remove undesired PCM heat (heat discharging) to enhance the indoor environment and ensure complete PCM solidification for the next day's cycle. For this purpose,

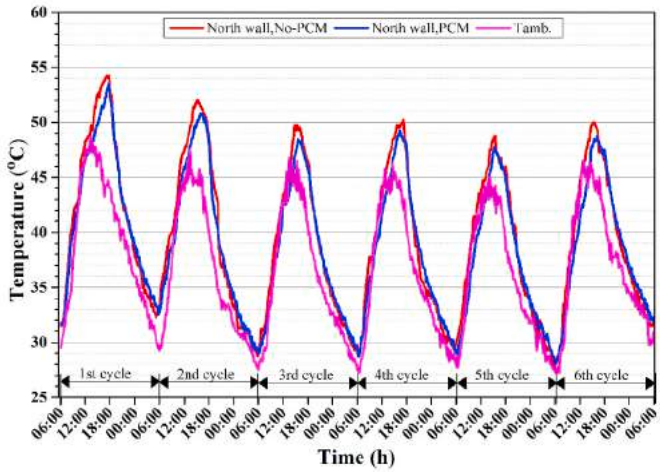

Fig. 7. North walls surface temperature and ambient temperature of PCM and no-PCM rooms.

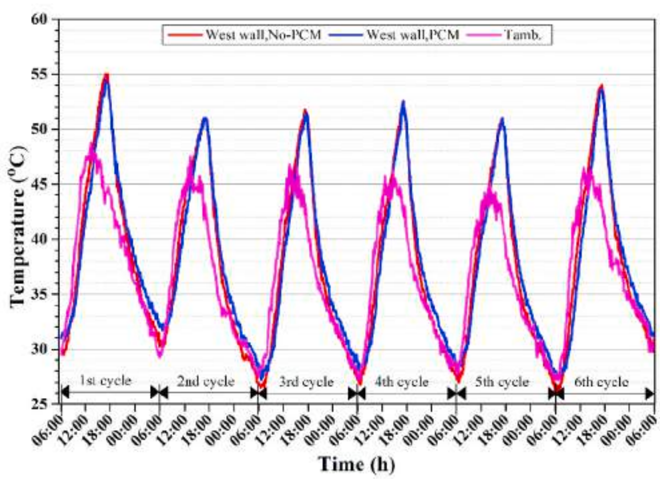

Fig. 8. West walls surface temperature and ambient temperature of PCM and no-PCM rooms.

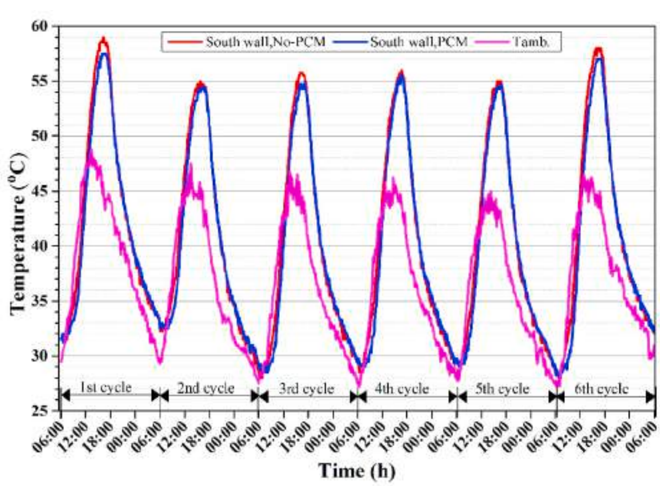

Fig. 9. South walls surface temperatures and ambient temperature of PCM and no-PCM rooms.

passive and active means provide NV through openings (i.e., windows) or using designed air channels considering the amount of air used and time for ventilation. The effect of the NNV period, through the window, on the indoor temperature was investigated in this work to show how much the indoor temperature could be enhanced considering one to 6 h along six consecutive days. Windows were opened for 1 h from 18:00 to 19:00 on September 18, 2021, for 2 h from 18:00 to 20:00 on September 19, 2021, and up to 6 h from 18:00 to 00:00 on September 23, 2021, as indicated in Fig. 10.

The effect of the NNV period was analysed by considering the indoor temperature behaviour in terms of the average indoor temperature reduction and operative temperature reduction.

3.2.1. Average indoor temperature reduction

The average indoor temperature reduction (AITR) shows how the indoor temperature of the PCM room was influenced by the NNV period compared to the no-PCM room indoor temperature. The average indoor temperature variation during the last 6 h of each day cycle (i.e., from 00:00 to 6:00) was considered to study the effect of every NNV period on the temperature variation of the next cycle. Mathematically, AITR was calculated according to Eq. (1), as follows:

$$AITR = \sum_{\tau=00:00}^{\tau=06:00} T_{i,PCM\ room,avg} - \sum_{\tau=00:00}^{\tau=06:00} T_{i,no-PCM\ room,avg} \tag{1}$$

where $T_{i,PCM\ \mathrm{room},avg}$ and $T_{i,no\text{-}PCM\ \mathrm{room},avg}$ are respectively the average indoor air temperature of the PCM and no-PCM rooms (in °C) during the period 00:00 to 6:00 of each cycle.

Fig. 11 shows the AITR in each day cycle considering the PCM and no-PCM rooms.

A positive enhancement of the AITR in both rooms can be noticed when NNV is applied. However, this enhancement was relatively slight regardless of the NNV period due to high outside ambient temperature compared with the indoor temperature of the room and the dependency on the buoyancy forces to transfer the heat through the window. The AITR in the 1st, 2nd, 3rd, 4th, 5th and 6th cycle was 0.632 °C, 0.555 °C, 0.493 °C, 0.451 °C, 0.444 °C and 0.438 °C, respectively. These values are equivalent to a temperature reduction of about 12.2%, 21.9%, 28.6%, 29.7% and 30.7%, respectively, when 2 h, 3 h, 4 h, 5 h and 6 h of NNV are applied compared with 1 h NNV. This reveals that applying NNV for 4, 5, and 6 h has nearly the exact indoor temperature enhancement percentages.

Various literature studies have proven the effectiveness of NNV when coupled with PCM applications, agreeing with the findings of the current study. For instance, Alam et al. (2017) studied the effect of NNV applied on PCM models against passive ones under Milbourn (Australia) weather conditions for seven days. The outcomes revealed that the NNV has positively enhanced the indoor peak temperature by up to 2.63 °C compared with only 0.44 °C for passive PCM incorporation. Whereas in another study performed in three Australian cities, Solgi et al. (2019) revealed no effect of NV when coupled with PCM in hot locations. However, their study indicated that the PCM melting temperature, PCM thickness and active NV could be beneficial in other locations. Consequently, Solgi et al. (2017), in another study conducted under Yazd (Iran) conditions, numerically proved that the NNV could reduce the indoor temperature by 0.5 °C compared with when no NNV was used for the office building application depending on the outdoor temperature.

3.2.2. Operative temperature reduction

The operative temperature (OT) defines as the temperature felt by occupants inside the built environment. The OT was calculated in this study considering the indoor air temperature (T_i) inside rooms and the mean radiant temperature ($\overline{T}_{mr}$) of rooms' elements (in °C) according to Eq. (2) (ANSI/ASHRAE Standard 55–2010, 2010), as follows:

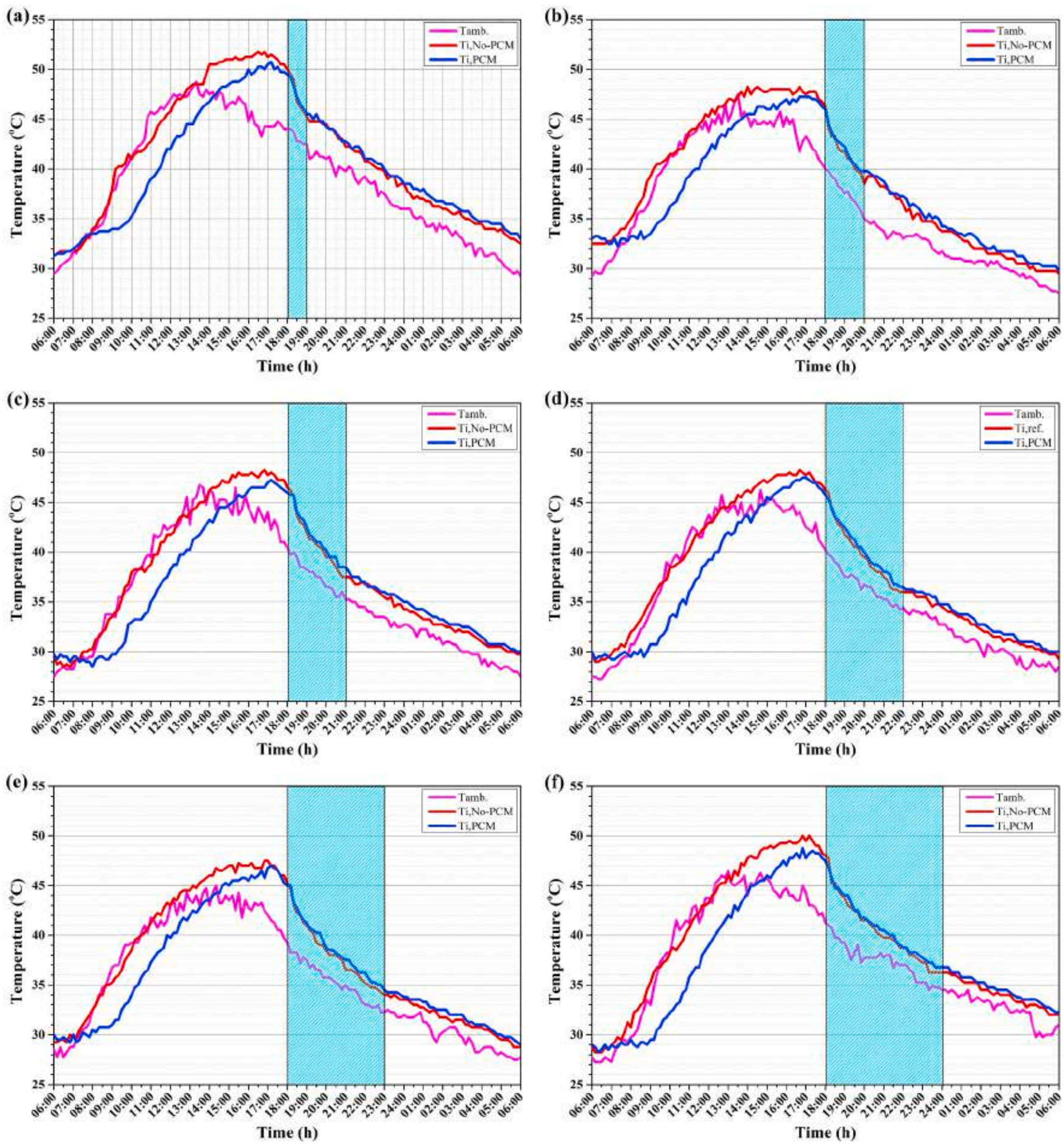

Fig. 10. PCM and No-PCM rooms' indoor and outdoor ambient temperatures with the proposed NNV period.

$$OT = \frac{T_i + \overline{T}_{mr}}{2} \tag{2}$$

$\overline{T}_{mr}$ is calculated considering the inside surface temperature and area of all room elements according to Eq. (3) (Fanger, 1970), as follows:

$$\overline{T}_{mr} = \frac{T_{roof}A_{roof} + T_{east\ wall}A_{east\ wall} + \ldots + T_{south\ wall}A_{south\ wall}}{A_{roof} + A_{east\ wall} + \ldots + A_{south\ wall}} \tag{3}$$

Consequently, the operative temperature reduction (OTR) can be calculated considering the OT of PCM and no-PCM rooms according to Eq. (4), as follows:

$$OTR = \frac{OT_{no-PCM\ room} - OT_{PCM\ room}}{OT_{no-PCM\ Room}} \times 100\% \tag{4}$$

Fig. 12 shows the OT and OTR of rooms during the experimental days.

Fig. 12 shows that the ambient temperature was lower than the OT in the PCM and no-PCM rooms from 12:00 to 6:00 in each day cycle. This occurs because the inside surface temperature of elements affected the OT and heat accumulated inside rooms in the first half of each cycle (i.e. from 6:00 to 12:00). However, the PCM room's OT was consistently lower than that of the no-PCM room from 6:00 to 18:00, resulting from the activated PCM inside the roof and walls. Considering the OT difference between the PCM and no-PCM rooms, a maximum temperature mark of 4.68 °C, 4.23 °C, 3.9 °C, 4 °C, 3.94 °C and 4.8 °C was calculated in the 1st, 2nd, 3rd, 4th, 5th and 6th day-cycle, respectively during the period from 9:20 to 10:10.

Fig. 12 also indicates that OTR values were increased sharply from 6:00 to 12:00. The maximum OTR achieved was about 12.8%, 11.74%, 12%, 12.45%, 11.2% and 15.2%, respectively, in the 1st, 2nd, 3rd, 4th, 5th and 6th day-cycle. OTR values indicate no influence of NNV on the OT of the PCM room in the next cycle, which was affected by the outdoor ambient temperature and solar radiation during the day itself. This is attributed to the relatively high ambient temperature during the night, which cannot be utilised to discharge the entire PCM heat and store

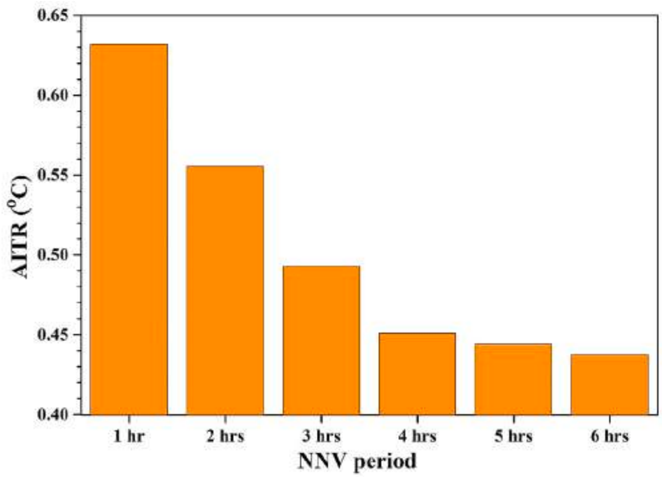

Fig. 11. AITR during each NNV period.

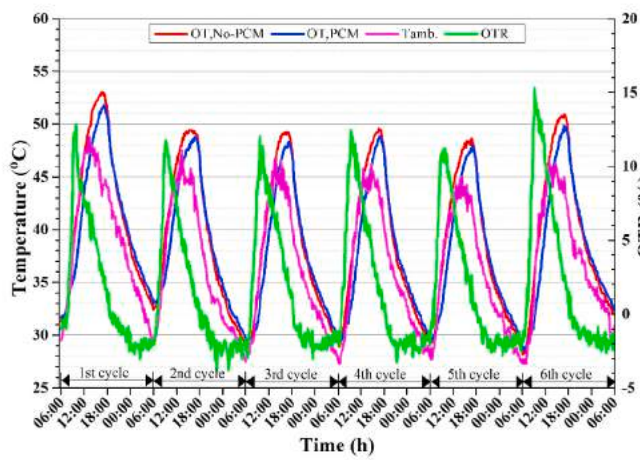

Fig. 12. OT and OTR of PCM and no-PCM rooms.

coolness for the next cycle. Therefore, the PCM room still shows a negative indoor temperature behaviour during the nighttime regardless of the NNV period applied. The research works verified under other locations worldwide indicated similar findings regarding the benefits of NV when coupled with the PCM elements. For instance, Liu et al. (2020) explored the OT earned from coupling PCM with NV under ten Chinese cities compared to the potential of NV alone. Numerical results showed that the NV was more effective with PCM-integrated buildings than the NV alone, reaching OTR by 1 °C–2 °C. In another study, Ramakrishnan et al. (2017) numerically showed that NV could effectively decrease the heatwaves during the day and maintain lower indoor OT at night under Australian weather conditions. The main findings indicated that employing NV with PCM can reach OTR by up to 4 °C, providing better PCM thermal performance.

3.3. Analysis of energy-saving

Energy analysis of PCM integrated building envelopes is often studied in the literature to show the benefits of PCMs in terms of heating/cooling reduction (Rathore and Shukla, 2020). This can be achieved by analysing the heat transfer reduction in terms of the average heat gain difference. The average heat gain difference (AHGD) was presented as the reduction of average heat gain (HG) in the PCM room compared with that of the no-PCM room (in watt, W), according to Eq. (5), as follows:

$$AHGD = 1 - \frac{HG_{PCM}}{HG_{no-PCM}} \times 100\% \quad (5)$$

where HG_{PCM} and $HG_{no\text{-}PCM}$ were calculated individually for roofs and walls from 6:00 to 18:00, according to Eq. (6) (Al-Rashed et al., 2021), as follows:

$$HG = h_i\, A\, \Delta T \quad (6)$$

where h_i signifies the combined convective-radiative heat transfer coefficient for inside room elements and indoor air temperature (it was considered as 8.29 and 6.13 W/m$^{2\circ}$C for walls and roofs, respectively (ASHRAE, 1997)). A is the element area and is considered equal to 1 m^2 for all elements, including the east wall, to simplify the calculations. ΔT refers to the difference between the element inside surface temperature and the indoor temperature.

Fig. 13 shows the AHGD of PCM and no-PCM rooms during experimental day cycles.

It can be seen that the AHGD of the roof was always higher than that of other walls. Moreover, the roof contributed to 44.9%, 45.1%, 45.9%, 46.7%, 43.9%, and 44.4% of total AHGD in the 1st, 2nd, 3rd, 4th, 5th and 6th cycles. This is attributed mainly to two reasons: firstly, the PCM quantity loaded in the roof per unit area was higher than that loaded inside each wall (i.e., around 7 kg in the roof compared to 4 kg in every single wall). Secondly, the roof was exposed to direct solar radiation for a longer time than walls, which increased the benefits of PCM in the roof.

The north wall showed higher AHGD than other walls, although it received direct solar radiation during the early hours only in each cycle, limiting the PCM utilisation. On the contrary, the west wall showed the lowest AHGD as it was exposed to low solar radiation in the late afternoon, making partial utilisation of PCM storage capacity similar to the west wall of the no-PCM room (as highlighted in Fig. 8). The east and south walls indicated relatively similar AHGD due to their activated PCM during the high solar radiation and ambient temperature period that utilised the PCM potential for a certain period till it reached the entire melting state. The total AHGD in the 1st, 2nd, 3rd, 4th, 5th and 6th cycle was respectively 78.7 W, 63.1 W, 68.6 W, 69.7 W, 71.6 W and 87.9 W. These AHGD values indicate that NNV does not affect the AHGD in the next day-cycle, which is influenced by the solar radiation and ambient temperature of the day itself. However, it is worth mentioning that the recorded temperatures of all elements were affected by each other. In other words, thermocouples are expected to be influenced by the accumulated heat coming from all elements inside rooms and the inside surface temperature of elements.

The energy-saving results obtained from the current work (in terms

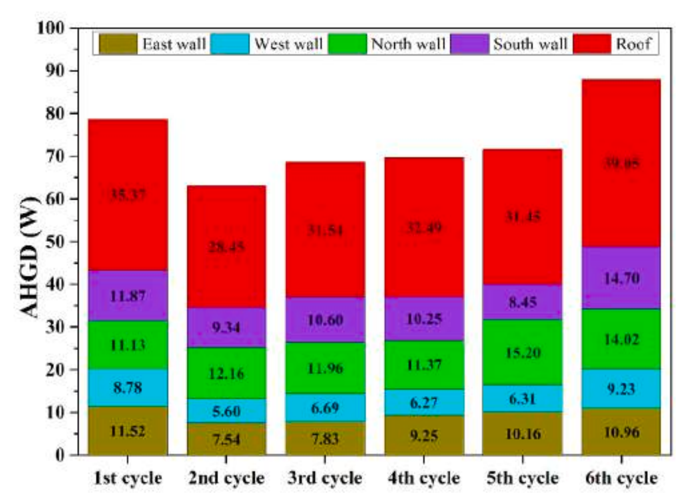

Fig. 13. AHGD in each experimental day.

of HG) are remarkable compared with the literature studies, showing an advantageous application of PCM. For instance, Lei et al. (2016) numerically studied a 10 mm PCM layer (28 °C melting temperature) incorporated into the exterior walls in Singapore, showing HG reduction of 21%–32% on an annual basis. Under Indian weather conditions, Rai (2021) numerically investigated various masonry wall configurations integrated with PCM in different locations within the walls. He has shown that the PCM can reduce the daily HG in all studied cases, reaching up to 45.2% at the best configuration results. Hasan et al. (2016) experimentally revealed that the HG could be reduced by up to 44% when incorporating concrete blocks under hot weather in the United Arab Emirates. They concluded that the mechanical NV is more applicable than NNV in hot locations due to high outdoor temperature and low wind speed.

Generally speaking, investigating the total HG is essential in the current study to quantify the energy saved by implementing PCM into building structures. This method represents a clean strategy that can remarkably reduce CO_2 emissions and limits the reliance on cooling and air-conditioning systems, which are heavily used in hot climate countries. Subsequently, PCMs and their remarkable benefits are expected to be among the cleaner schemes adopted in future building installations.

4. Study limitations and future recommendations

The findings are limited to the location and period of experimentations specified in the current study. The thermal performance of PCM elements could be expected alike under other hot months (i.e., May to October) where the diurnal temperature exceeds the PCM melting temperature. Consequently, the PCM thermal performance will not be the same under lower outdoor temperatures, such as the winter season, due to the lack of PCM melting phase. On the other hand, limited dimensions of used experimental rooms may influence the indoor temperature due to the continuous accumulation of heat through the room's elements.

There are some remarks and recommendations which can be highlighted for future studies, considering the scope of this work, such as:

- The PCM quantity involved in walls could be reconsidered depending on the solar radiation received by each wall. More PCM can be loaded into walls exposed to high direct solar radiation for a more extended period, such as the southern and western walls.
- Extending the experimental work through simulation tools to study the effectivity of the proposed model on lower temperature days during the spring and autumn seasons, along with economic analysis. This study could help optimise the PCM melting temperature towards better thermal performance and viable economic aspects.
- The results showed that the NV was worthless in the studied location due to high outdoor temperature at night; alternative cooling mediums could be employed to maintain a better thermal performance of PCM. These alternatives could be evaporative cooling means or any other free cooling source.

5. Conclusion

PCMs integrated building envelopes have shown excellent benefits in terms of energy and environmental aspects to reach cleaner production in the construction industry. In hot regions, PCMs are beneficial for reducing the building thermal energy demand and maintaining better thermal comfort, the core of future smart cities. However, some limitations regarding the adverse thermal performance of PCMs during the night period and adopting the best strategies to minimise such effects are significant in recent literature studies. The present work aimed to experimentally analyse the NNV effect on the AITR and the OTR, taking into account different periods of 1 h–6 h for six consecutive days. The work extended to analyse the energy benefits of PCM incorporated building roofs and walls in the hot climate considering the AHGD. The results indicated temperature stability of elements' surface temperature at the beginning of the next day cycle regardless of the NNV period, indicating the beneficial use of PCM for the studied location. Increasing the NNV period has decreased the temperature difference between the indoor environment of PCM and no-PCM rooms considering the AITR period. Although the temperature was decreased slightly due to high outdoor ambient temperature, NNV of 4 h was enough to reduce the PCM room indoor temperature acceptably. No considerable reduction occurred with more NNV period. During this period, AITR of 28.6% was reached against 12.2% when 2 h NNV was applied compared with 1 h NNV period. Besides, only 29.7% and 30.7% were achieved with NNV of 5 and 6 h, respectively, compared with 1 h NNV. Regardless of the NNV period, a slight influence on the OTR during the night was realised. Moreover, the solar radiation and ambient temperature influence the OTR during each cycle. The AHGD was higher under hot outdoor conditions due to the high melting temperature of the used PCM. Furthermore, the roof contributed more than 44% to the total AHGD of each cycle compared with the AHGD of all walls. Besides, the north wall contributed the most to the total AHGD compared with the other walls.

CRediT authorship contribution statement

Qudama Al-Yasiri: Conceptualization, Methodology, Data curation, Formal analysis, Investigation, Writing – original draft, Writing – review & editing. **Márta Szabó:** Conceptualization, Formal analysis, Writing – review & editing, Supervision, Funding acquisition.

Declaration of competing interest

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

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