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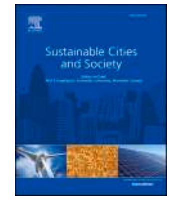

Numerical analysis of thin building envelope-integrated phase change material towards energy-efficient buildings in severe hot location

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ABSTRACT

Phase change materials (PCMs) have a great potential to enhance building thermal comfort and save energy towards energy-efficient buildings. The current study sheds light on employing PCM passively in a thin building envelope under a severely hot location using EnergyPlus software. The thermal contribution of PCM to indoor thermal comfort was evaluated considering the average temperature fluctuation reduction (ATFR), thermal load levelling reduction (TLLR) and operative temperature reduction (OTR). Besides, the total average heat gain reduction (AHGR) and equivalent CO_2 emission and electricity cost saving (ECS) were discussed to quantify the energy-saving. Simulation results demonstrated PCM effectiveness during the hottest summer days. Quantitatively, the PCM contributed to the ATFR by 5 °C- 6 °C, along with TLLR and OTR by an average of 38%-59% and 6 °C, respectively. According to the energy-saving analysis, the daily total AHGR owing to PCM integration ranged between 66.6% and 76.5%, where the roof shared the most. The results also indicated environmental and economic benefits, attaining CO_2 emission reduction by 2 kg/day and ECS by up to 250 IQD/day. Conclusively, the PCM can significantly improve building performance when integrated passively with thin envelope elements in severely hot locations.

1. Introduction

The building sector is the foremost consumer of final energy and is responsible for high CO_2 emissions worldwide (IEA, 2018). The International Energy Agency (IEA) reported that building envelope shares an extraordinary percentage of building energy and responsible for high CO_2 emission ratio by up to 36% and 39%, respectively (IEA & UN Environment Programme, 2019). Consequently, enormous energy-saving could be achieved by improving the thermal performance of building envelope elements (roof, walls, etc.). In recent years, phase change materials (PCMs) have been announced as a sustainable and cost-effective solution to improve building thermal performance, thanks to their remarkable potential to regulate heat energy through the phase change phenomenon. PCMs have the potential to store a huge amount of heat at a nearly constant melting temperature and release it during the freezing/solidification phase, representing a unique thermal energy storage medium (Tunçbilek et al., 2020).

PCMs have been applied for thermal energy storage in different applications, including the building sector (Rathore et al., 2022). In this regard, PCMs were incorporated with building structure to improve its thermal inertia for both cooling and heating applications (Al-Yasiri & Szabó, 2021c), specifically in the following:

i. PCMs have been incorporated into walls with different orientations as a separate layer or mixed within bricks in a micro/macro-encapsulation approach. PCMs have shown remarkable enhancement in walls, achieving temperature time lag and energy-saving by up to 13.3 h and 18%, respectively (Arıcı et al., 2020).
ii. Roofs-enhanced PCM has shown notable improvement in the roof's thermal performance, reducing the inside temperature by about 2.9 °C and decreasing the average heat gain by up to 59% (Meng et al., 2022). Another study (Zhang et al., 2020) stated that the inside surface temperature of the roof could be further decreased by 6.6 °C when the PCM is coupled cool roof.
iii. PCMs have been integrated with windows to minimise summer cooling loads and provide a heating effect in winter for a longer time (Zhang et al., 2020).

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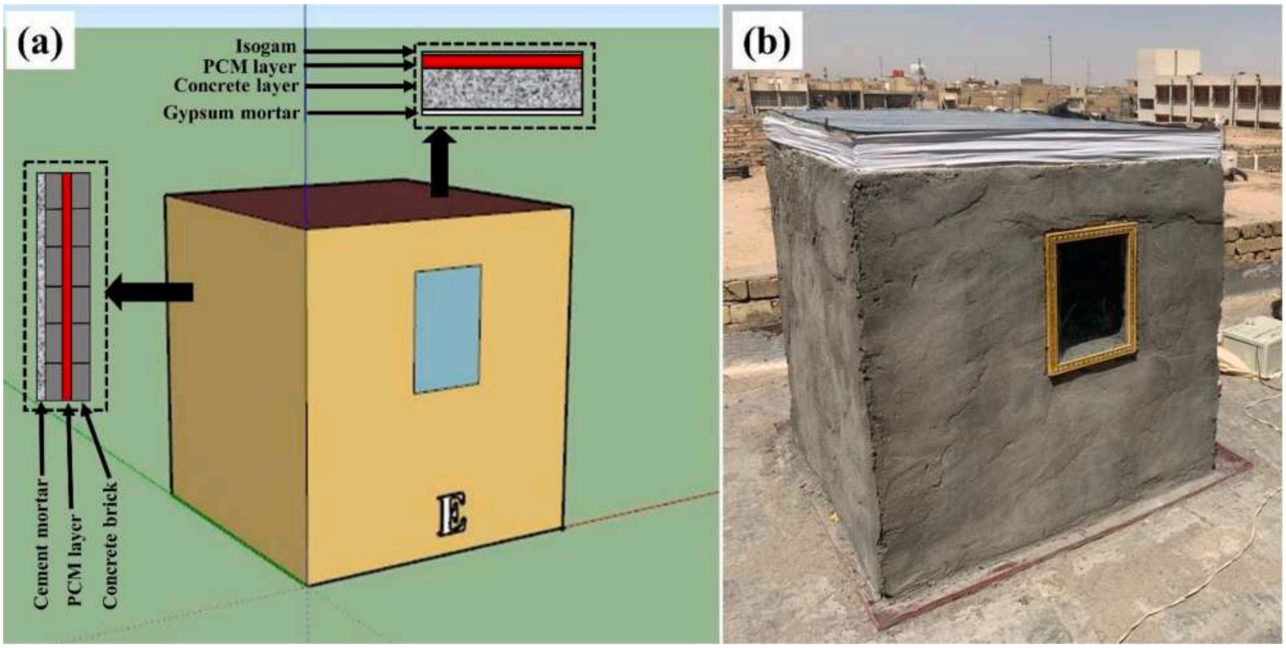

Fig. 1. (a) 3D view of room model in SketchUp, (b) Experimental room from our previous study (Al-Yasiri & Szabó, 2022).

Table 1
Properties of construction materials (Ministry of Construction and Housing-Minstry of Planning, 2013).

Material (from outside to inside)	Layer thickness (mm)	K (W/m.K)	ρ (kg/m^3)	C_p (kJ/kg.K)
Roof:				
Isogam	4	0.35	1400	1100
Concrete	50	1.49	2300	800
Gypsum mortar	2	0.23	980	896
Walls:	10	0.99	2020	1000
Cement mortar	70	1.4	1440	750
Concrete brick (L:230 × W:120)				
Floor:				
Wooden foundation	30	0.18	950	1200
Window:	6	——	——	——
Single glazing (U-Factor=5.48, Solar heat gain coefficient=0.95)				

Table 2
Properties of paraffin wax (PCM).

Property	Unit	Value
PCM appearance	——	Whitish
Chemical composition	%	40 oil + 60 wax
Melting temperature range	°C	40-44
Latent heat	kJ/kg	190
k (solid & liquid)	W/m.K	0.21
ρ (solid/liquid)	kg/m^3	930/830
C_p (solid & liquid)	kJ/kg.K	2.1

iv. Researchers have incorporated different PCM types with plasters and mortars for interior and exterior cladding (Kusama & Ishidoya, 2017). A study conducted by Wi et al. (2021) reported that incorporating PCM with 10 wt% into the cementitious mortar for cladding exterior buildings could shift the peak load by 59.4%, demonstrating extraordinary advances in terms of indoor thermal comfort and energy-saving.

Nonetheless, PCM commercialisation is still limited, and many concerns are open for investigation with no universal agreement in this research scope (Fantini, 2020). Some of these concerns are related to the partial effectiveness of PCM annually (Sharaf et al., 2022). In contrast, others doubted stability over the building lifespan (Fabiani et al., 2020), not to mention the technology infeasibility reported in several locations (Agarwal & Prabhakar, 2022).

Numerous studies have been implemented to investigate the potential of PCM when integrated with building envelopes under different weather conditions, considering the improvement of indoor thermal comfort and energy-saving (Tunçbilek et al., 2020). Some of these studies were performed experimentally under real weather conditions, whereas the others were conducted numerically using advanced simulation tools for long-term investigation. Amongst numerical studies, Mohseni and Tang (Mohseni & Tang, 2021) studied the energy performance and thermal comfort of a residential building integrated with PCMs using EnergyPlus software validated by an experimental model. PCMs of 19 °C- 29 °C melting temperatures were integrated with 5 and 10 mm layer thickness building elements. They investigated the influence of meteorological parameters and cooling/heating loads at the optimal PCM through comprehensive energy analysis. The results indicated that PCM integration could improve indoor comfort, reduce heating and cooling loads, and diminish temperature fluctuations. The study findings revealed that the PCM of 21 °C melting temperature with 10 mm thickness placed in the wall and roof exhibited the best energy conservation and shifting loads from peak to low-peak periods. The study further specified that total CO_2 emission could be reduced by 264 tonnes at the best case over 50 years. Furthermore, the shortest payback period was estimated as 16.6 years for PCM-concrete buildings. Sun et al. (2022) numerically studied four inorganic composite PCM types integrated with a room in an active-passive way to optimise its annual thermal performance. The system incorporated PCM into the wall, ventilation cavity, double-layer radiant floor and increasing PCM thickness. The results showed that the PCM room displayed low annual energy consumption and increased indoor thermal comfort rate by up to 16.58% compared with a reference room with a radiant floor. The results further revealed that increasing PCM thickness has enhanced the thermal comfort rate by 81.58% and saved electricity cost by about 20%.

Under Malaysian weather conditions, Al-Absi et al. (2021) explored the PCM potential for building retrofitting passive cooling and improving indoor thermal comfort. The authors implemented PCM

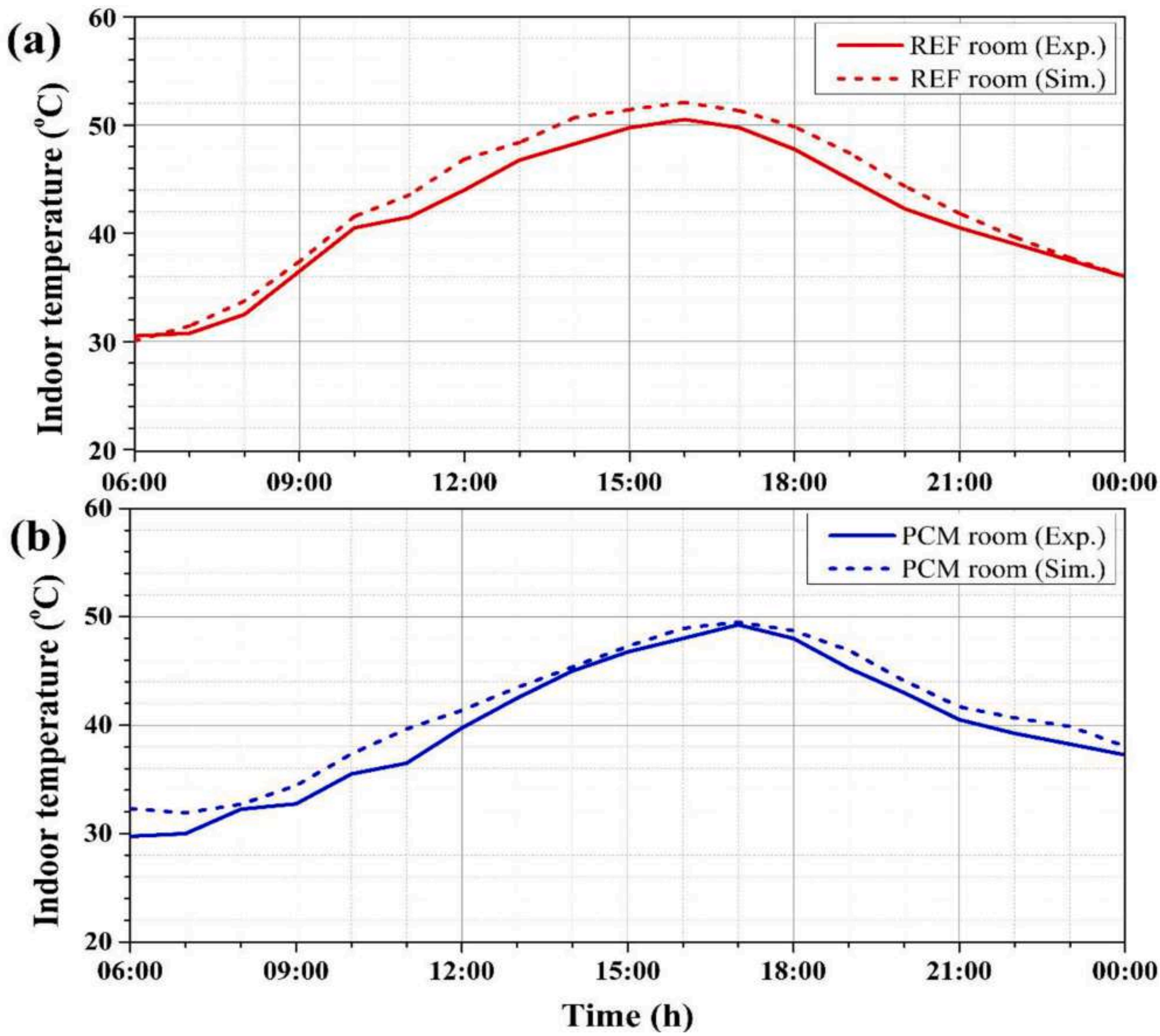

Fig. 2. Validation of the numerical model against experimental results presented in (Al-Yasiri & Szabó, 2022).

sheets placed below the internal finishing of building walls and studied the effect of varying their melting temperature and quantities. The outcomes exhibited noteworthy indoor improvement, particularly when using low PCM melting temperatures with high quantities. In this regard, the optimum thermal performance was attained with PCM of 26 °C- 27 °C and 18 mm thickness, in which the monthly thermal discomfort hours were decreased and thermal comfort was extended by 98%. M'hamdi et al. (2022) integrated PCM with four building envelope types (brick, concrete block, reinforced concrete and earth) under North African climates considering energy, economic and environmental aspects. Numerical results displayed that the maximum energy-saving in the arid and sub-arid climates reached as high as 10.5% for the earth envelope and the lowest rate of 2.57 % in the Mediterranean climate for the concrete block envelope. Moreover, the PCM was more effective for cooling in arid climates for the proposed envelopes, with the highest cooling energy reduction of 7.3%. Besides, the PCM was more effective for heating in the sub-arid and Mediterranean climates, reaching a maximum of 10.7% for the case of the earth envelope. Considering environmental and economic analysis, the PCM under optimal integration conditions has reduced the energy cost and CO_2 emissions by 10% and 707 kg/year, respectively, along with a payback period of 23 years in average. Ismail et al. (2022) studied the effectiveness of incorporating macroencapsulated BioPCMs (25 °C, 27 °C and 29 °C melting temperatures) with different thicknesses into walls and roofs of an educational building. The simulations were verified for a hot climate considering the role of controlled night ventilation with an air change rate of 15 per hour to reduce the indoor temperature. The results indicated that the PCM of 27 °C melting temperature had reduced the indoor temperature by 0.5 °C- 3.3 °C. Besides, the increased PCM layer thickness to about 3.75 cm has affected the indoor temperature slightly, given the incomplete night charging phase of the PCM. Using the same category of PCMs (i.e., BioPCMs), Qu et al. (2021) numerically studied the impact of PCMs on building energy-saving and indoor thermal comfort under Chinese climate conditions considering several key parameters. According to the study findings, PCM integration can effectively decrease indoor fluctuations, and the BioPCMTM23 with 7 cm thickness applied on the inner walls and roof could attain optimal improvement. Moreover, energy-saving of 4.8%- 34.8% can be achieved with proper PCM selection considering the local climatic conditions. The study concluded that building energy-saving could be further maximised using high latent heat PCMs for envelope elements with large surface areas and exposed to longtime solar radiation. Kharboach (Kharbouch, 2022) explored PCM effectiveness in improving buildings' thermal performance under summer conditions in northern Morocco. For three decades, the study

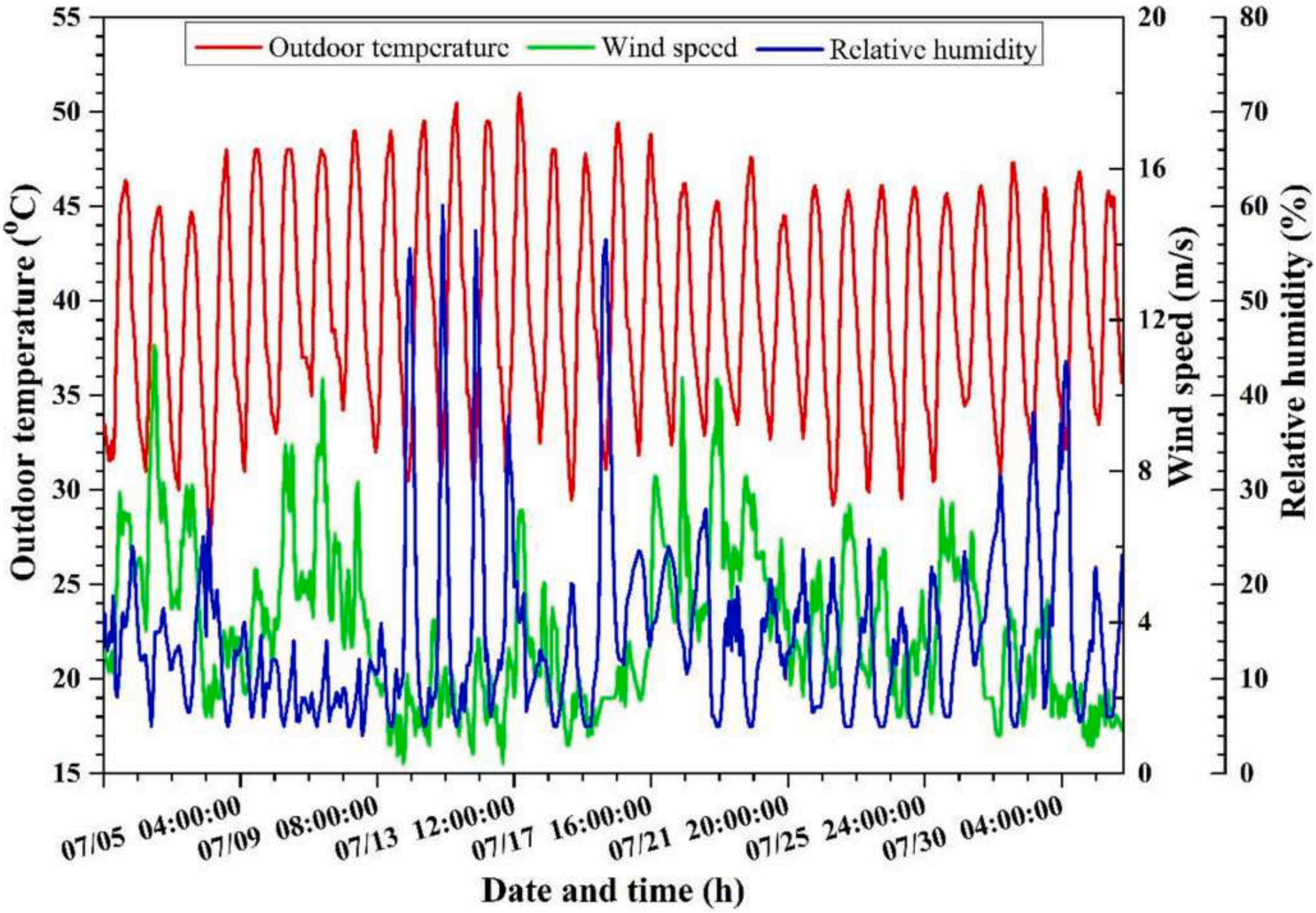

Fig. 3. Average hourly outdoor temperature, wind speed and relative humidity for Al Amarah city during July 2021.

considered two building cases; free-running and air-conditioned office buildings. The simulation findings have shown that the thermal performance of free-running and air-conditioning buildings could be enhanced by 9.87 % and 20.5 %, respectively, for 30 years building lifespan. The results further indicated that the building performance would drop slightly over decade-by-decade at the optimal PCM melting temperature. Sierra and Chejne (Sierra & Chejne, 2022) experimentally examined the effect of microencapsulated coconut oil (as a PCM) incorporated into mortar under weather conditions in Medellín, Colombia. The PCM was impregnated into the mortar with 5 wt%, 15 wt % and 30 wt% and applied with 3, 5, 7 and 10 cm thickness on the inner and outer wall sides. The outcomes showed that applying PCM mortar on the outer walls with 7 cm and 10 cm thickness could reduce the indoor temperature by 10 °C. In contrast, applied PCM mortar on the inner walls kept the room temperature constant for a longer time. Moreover, the best thermal performance was achieved when applying PCM mortar with 15 wt% and 7 cm thickness on two walls, which reduced the cooling requirements by 80%. However, increasing PCM mortar by more than 10 cm resulted in extra cost and slightly enhanced indoor thermal comfort. Wi et al. (2020) experimentally and numerically investigated the role of shape-stabilised PCM (SSPCM) in improving the thermal performance of thick external walls of wooden buildings in Seoul, Korea. The study considered 22 SSPCMs with various melting temperatures, prepared by the vacuum impregnation method, to be installed on the innermost side of walls. Annual energy-saving analysis showed that SSPCMs have largely improved the walls' thermal inertia, decreasing the annual energy consumption by 5% and reducing peak indoor temperature by up to 4.1 °C. Agarwal and Prabhaker (Agarwal & Prabhakar, 2022) recently conducted a thermo-economic analysis on *n*-Eicosane, and OM35 PCMs integrated with constructive clay bricks under Indian composite climate conditions. They studied the best PCM thermal performance considering the wall orientation and brick configuration on annual basis. The results showed that OM35 could reduce the cooling load by 31.1% when integrated with the east-oriented walls, which is equivalent to annual cost saving by USD 1.05/m^2. The study findings also revealed that *n*-Eicosane indicated lower thermal benefits than OM35 especially when incorporated in the north-oriented walls. However, the economic analysis showed that both PCMs were infeasible, exhibiting payback period by 181 years.

According to the above literature analysis, PCM applications in building envelopes have been studied in diverse locations worldwide. However, most of these locations have moderate ambient temperatures, and there is still a lack of studies focusing on PCM thermal performance in severely hot conditions, where the ambient temperature reaches the mark of 50 °C and thermal comfort is unreachable easily. Such locations required high PCM melting temperatures with a guaranteed melting phase during the day and full solidification at night. Besides, although PCM passive incorporation is a simple and cost-effective technique, studying its performance under such harsh climates is challenging. Therefore, this study prepared to quantify the PCM thermal performance in terms of indoor thermal comfort improvement and energy-saving potential when passively incorporated into a thin building envelope under severe hot summer days. The thermal performance of a room model integrated with PCM was validated against experimental rooms and investigated numerically by discussing the average temperature fluctuation reduction, thermal load levelling, and operative temperature reduction on the hottest summer day in each month. Besides, energy-saving was also studied by quantifying the average heat gain reduction, equivalent CO2 emission saving, and electrical cost saving. This study is believed to provide detailed insights into PCM thermal

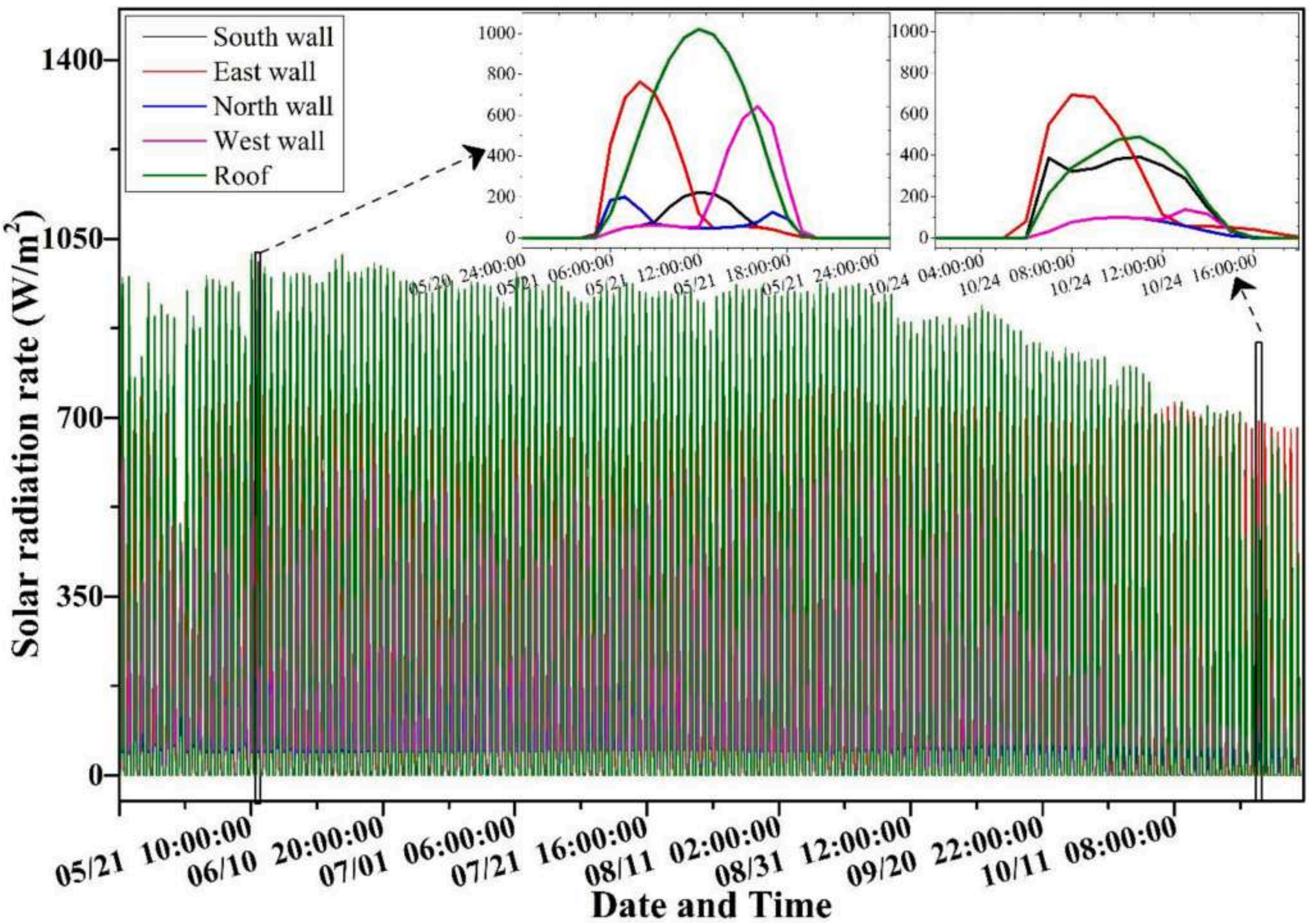

Fig. 4. Solar radiation rate per area incident on room elements.

performance when integrated passively with a thermally-poor building envelope under desert climate conditions.

2. Methodology

2.1. Model description

The simulation was carried out for a detached cubicle room with 3000 mm^3 size (Fig. 1-a) under severe hot weather conditions in Al Amarah city (Latitude: 31.84° and Longitude: 47.14°), Iraq, for six summer months, from 1 May till 30 October 2021. According to the Köppen-Geiger classification, Al Amarah city has a desert climate characterised by severe diurnal ambient temperature exceeding the mark of 50 °C during some days of June and July, making this location among the hottest in Middle East countries (Korosec, 2021).

The room was constructed from thermally-poor construction materials, including concrete brick masonry walls, a flat concrete roof and other finishing and cladding layers. Besides, a single-glazing wooden-framed window was placed on the east wall, whereas the floor was built with a single thick wooden foundation. During the simulations, the floor was set as an adiabatic element, and the window was kept close to study PCM's effect on walls and roofs under non-ventilated conditions. The room integrated with PCM is termed PCM room, whereas the room without PCM used for comparison is termed REF room. The characteristics of construction materials used for the room model are listed in Table 1.

The PCM used in this study is a petroleum-based paraffin wax produced as waste material in large quantities during the dewaxing process in Iraqi governmental petroleum refineries. This product has desired thermo-physical properties (listed in Table 2), making it a good option for thermal energy storage in building applications. It was adopted in the current study thanks to many favourable properties, such as suitable melting temperature for daily temperature variation of the location under study and cost-effectiveness.

The PCM with a 15 mm layer thickness was placed between the Isogam roofing layer and the concrete layer in the roof for the best activation of PCM. Besides, it was placed (with 7 mm thickness) in the middle of brick walls (Fig. 1-a), the optimal locations and thicknesses according to our previous experimental studies (Al-Yasiri & Szabó, 2021b, 2021a, 2021d).

2.2. Simulation method

The room model was simulated using EnergyPlus v9.0.1 software. This software is the most popular in building simulations, established and developed by the US Department of Energy with a high capability of simulating building energetic, economic and environmental aspects (Crawley et al., 2000). The software deals with two input files, namely the EnergyPlus weather file (EPW) and information data file (IDF), which contain all necessary data on the weather of the building location under study and building thermal and physical properties, respectively. Besides, the software output variables are calculated based on advanced heat balance algorithms dealing with heat transfer coefficients related to the surface temperature difference of building elements.

The PCM incorporated into construction elements was investigated using the conduction finite difference (CondFD) algorithm provided within the EnergyPlus to simulate the phase change phenomenon. In this regard, the PCM room elements (walls and roof) are described based on the modified one-dimensional heat conduction shown in Eq. (1) (Deru et al., 2011), as follows:

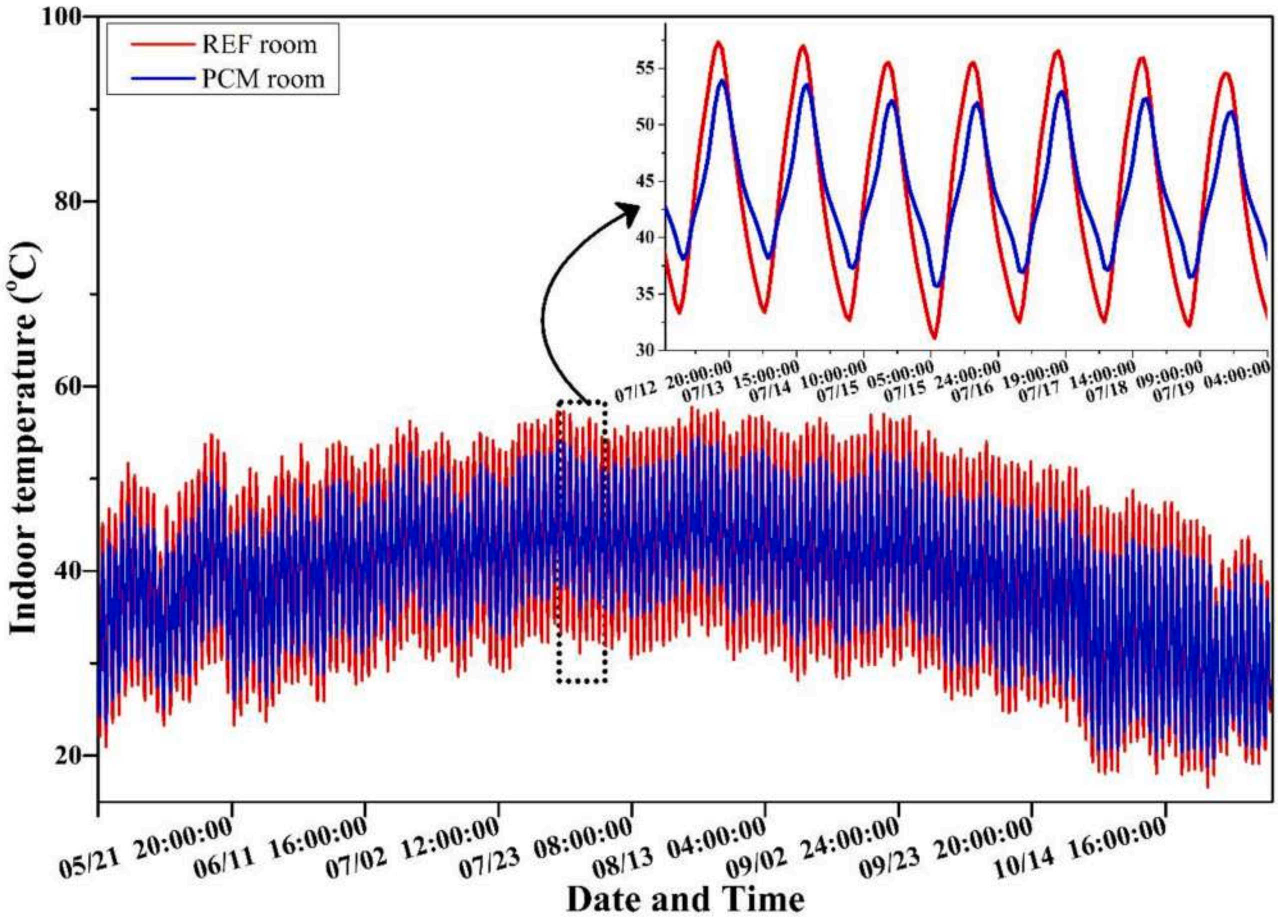

Fig. 5. Hourly indoor temperature variation of REF and PCM rooms with the hottest week of July zoomed out.

$$\rho C_p \Delta x \frac{T_i^{j+1} - T_i^j}{\Delta t} = \left(k_W \frac{\left(T_{i+1}^{j+1} - T_i^{j+1}\right)}{\Delta x} + k_E \frac{\left(T_{i-1}^{j+1} - T_i^{j+1}\right)}{\Delta x} \right) \tag{1}$$

where ρ represents the element layer density (kg/m^3), C_p is the specific heat capacity (kJ/kg.K), Δx is the layer thickness (m), and Δt is the calculation time step (s). T denotes the node temperature (K), whereas i denotes the modelled node. Consequently, i+1 and i-1 are the adjacent nodes concerning the inner and outer sides, respectively. j+1 is the instant time step, whereas j is the previous time step. k_W is the thermal conductivity for the interface between i node and i+1 node, whereas k_E is the thermal conductivity for the interface between the i node and the i-1 node (W/m.K).

k_W and k_E are calculated by Eqs. (2) and (3) (Al-Janabi & Kavgic, 2019), respectively, as follows:

$$kw = \frac{\left(k_{i+1}^{j+1} + k_i^{j+1}\right)}{2} \tag{2}$$

$$k_E = \frac{\left(k_{i-1}^{j+1} + k_i^{j+1}\right)}{2} \tag{3}$$

Since the C_p of the PCM layer is a temperature-dependent property each time, its value is calculated by Eq. (4) (Deru et al., 2011) as follows:

$$C_p = \frac{h_i^j - h_i^{j-1}}{T_i^j - T_i^{j-1}} \tag{4}$$

where h is the specific PCM enthalpy (kJ/kg), which can be defined as a function of temperature using Eq. (5) (Deru et al., 2011), as follows:

$$h = h(T) \tag{5}$$

The following assumptions were considered to simplify the fully implicit CondFD algorithm for the transient heat transfer model, as follows:

- The construction materials and PCM are homogeneous and isotropic, with no heat generation within the material.
- The PCM layer is in perfect contact with the other roof and walls construction layers (i.e., negligible contact resistance).
- No hysteresis for the PCM melting and solidification temperatures during the simulation.
- The outer face temperature of walls and roofs was calculated in terms of the sol-air temperature, considering the solar radiation incident on each element and outdoor temperature.

2.3. Model validation

Building models simulated by EnergyPlus software have been validated broadly in the literature by many researchers against experimental and numerical studies (Sharma & Rai, 2020; Tabares-Velasco et al., 2012). In this study, the developed room model was verified by comparing the obtained simulation results with the experimental findings of our previous work conducted under the same weather conditions (Al-Yasiri & Szabó, 2022) (Fig. 1-b). The same construction materials used for experimental rooms were adopted as inputs in the IDF file, and the model simulation was implemented for one day (16 September 2021). The model showed good agreement considering the room indoor air temperature in both the REF and PCM rooms, as presented in Fig. 2. However, a slight difference of a maximum of 6.1% and 7.9% can be observed between the experimental and simulation curves of the REF and PCM rooms, respectively. This divergence can be attributed to the

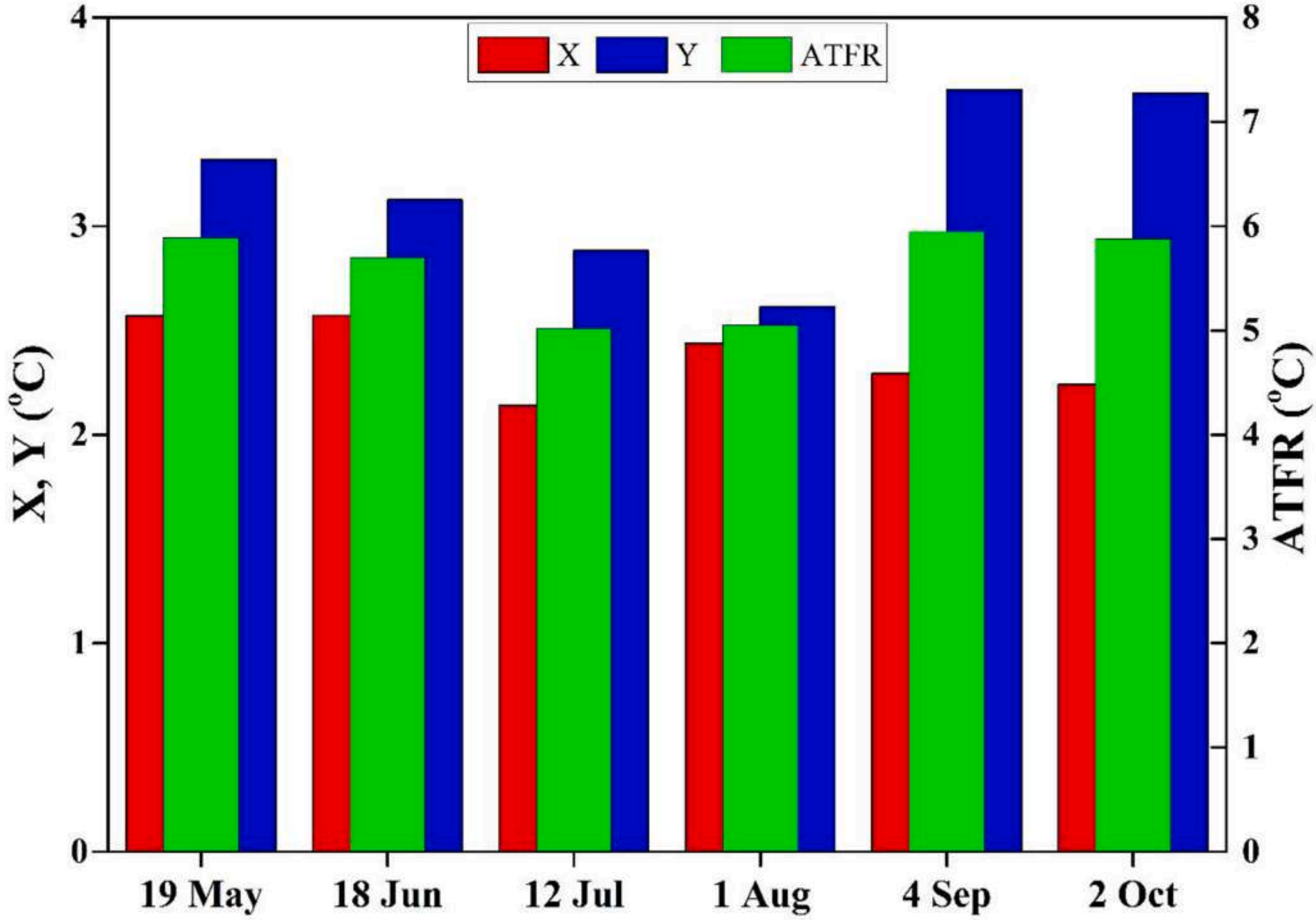

Fig. 6. ATFR of PCM room compared with reference room.

inconsistency of weather data measured during the experimental work compared with that predicted in the weather file used for the simulation. Besides, the thermal and physical properties of construction materials used as inputs in the software do not have the exact values as the room constructed in experimental work, which eventually influences the simulation outcomes.

2.4. Assessment of PCM contribution

EnergyPlus software has many output variables to analyse the building performance, including climatic data summary, envelope summary, zone summary and other energy metrics. The output variables set in this study were the inside and outside face temperatures of walls and roofs in addition to the zone indoor mean temperature and mean radiant temperature. Therefore, several concepts were adopted to quantify the energy contribution of PCM to the room considering the indoor thermal comfort enhancement and stemmed energy-saving at the hottest day of every month, namely 19 May, 18 June, 12 July, 1 August, 4 September and 2 October. The enhancement in thermal comfort was analysed considering the average indoor temperature fluctuation reduction, thermal load levelling reduction and operative temperature reduction. In contrast, the concept of average heat gain reduction and equivalent CO_2 emission saving and electricity cost saving were analysed to quantify the energy-saving.

3. Results and discussion

3.1. Analysis of weather conditions

The outdoor ambient temperature, solar radiation, wind speed and humidity ratio are the exterior boundary conditions of the simulated model and directly impact the performance of PCM-integrated room elements. Fig. 3 shows the outdoor weather conditions of the location under study during July 2021, the hottest month of the year, characterised by high diurnal temperature and long sunshine hours. As designated in the figure, the outdoor ambient temperature is always high, exceeding the mark of 50 °C on some days, whereas the lowest temperatures were normally above 30 °C at night. Besides, the relative humidity mostly ranged between 5% and 45%, except for some days when it increased by around 60%. On the other hand, wind speed also ranged between 0.5- 8 m/s, except a few days reported high values around 12 m/s.

Fig. 4 presents the average hourly solar radiation rate incident on each element of the room model. In July, it can be seen that the roof was receiving higher solar radiation than the walls, exceeding 800 W/m^2. Moreover, the walls were time-dependent concerning direct solar radiation in which the east wall received a high solar radiation rate between 5:30 and 13:00, and the west wall from 12:00 till 19:00. North and south walls received the lowest hourly solar radiation rate (around 200 W/m^2) at the most. All months generally showed a similar trend of solar radiation rate incidents on elements with various values, except for October. The solar radiation trend in October is different. The east wall received higher solar radiation rate than the roof on most days and generally experienced lower ratios than in other months.

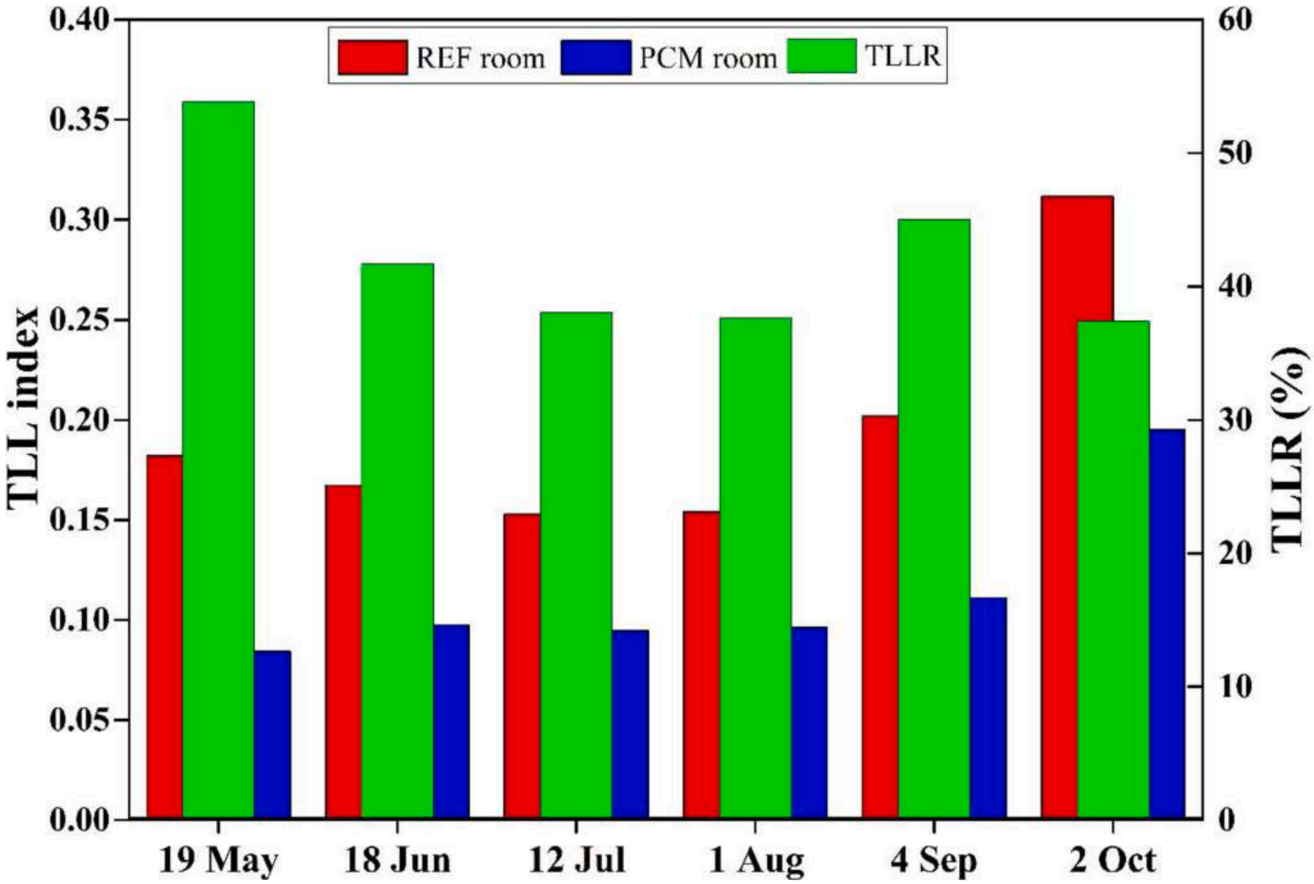

Fig. 7. TLLR of rooms over summer months.

The outdoor weather conditions are essential in this study since the simulation was carried out for a non-conditioned zone. Therefore, the PCM thermal effectiveness relies on the changeable weather conditions during the day and night to passively control heat transfer through the room elements.

3.2. Analysis of indoor thermal comfort

The improvement in indoor thermal comfort is the main purpose of integrating PCMs with building envelope due to increased envelope thermal inertia and enhanced thermal performance (Suresh et al., 2022). Fig. 5 shows the hourly average indoor temperature variation of REF and PCM rooms during the simulation period. As expected, numerical results exhibited low indoor temperatures for the PCM room compared with the REF room during day hours, with obvious time shifting of the highest values by approximately one hour. However, May and October indicated a relatively higher difference in the indoor temperature between the REF and PCM rooms attributed to low outdoor ambient temperatures at night in these two months, compared with June-September. The highest indoor temperature of the REF room was 54.8 °C, 56.3 °C, 57.3 °C, 57.8 °C, 56.7 °C and 49.1 °C in May, June, July, August, September and October, against 50.7 °C, 52.8 °C, 53.9 °C, 54.2 °C, 52.8 °C and 43.7 °C inside the PCM room, respectively.

As mentioned previously, the role of PCM in enhancing indoor thermal comfort can be quantified in terms of several concepts, namely the average temperature fluctuation reduction, thermal load levelling reduction and operative temperature reduction. These concepts are described and analysed in the following sub-sub sections, considering the hottest day in each month.

3.2.1. Average temperature fluctuation reduction

The average temperature fluctuation reduction (ATFR) shows the reduction of average fluctuation in the PCM room indoor temperature compared with that of the REF room during the whole thermal cycle. ATFR can be calculated as the average decrease in the PCM room indoor temperature during the day (PCM charging period) plus the average increase in the PCM room indoor temperature during the night (PCM discharging time). Consequently, the positive ATFR value (> 0 °C) means that the PCM incorporation was advantageous during the thermal cycle, and the higher value indicates better PCM effectiveness. Besides, the negative ATFR value means adverse thermal behaviour of the PCM, while zero ATFR indicates no benefits of PCM integration. Mathematically, the ATFR can be calculated by Eq. (6) considering the sunshine period from 6:00 to 18:00 (symbolised by *X*) in Eq. (7) and the no-sun period from 18:00 to the beginning of the next thermal cycle (symbolised by *Y)* in Eq. (8) (Kenzhekhanov et al., 2020), as follows.

$$ATFR = X + Y \tag{6}$$

$$X = T_{i(av.),REF\ room} - T_{i(av.),\ PCM\ room} \tag{7}$$

$$Y = T_{i(av.),\ PCM\ room} - T_{i(av.),\ REF\ room} \tag{8}$$

where $T_{i(av.),REF\ room}$ represents the average indoor temperature of the REF room, and $T_{i(av.),PCM\ room}$ is the average indoor temperature of the PCM room (°C).

The calculation results of ATFR on the hottest day of each month are presented in Fig. 6.

As designated in Fig. 6, the PCM room showed positive ATFR on all days, indicating PCM effectiveness in all summer months. In general, the PCM showed remarkable contribution regarding the ATFR reaching 5.89 °C in May, 5.70 °C in June, 5.02 °C in July, 5.05 °C in August,

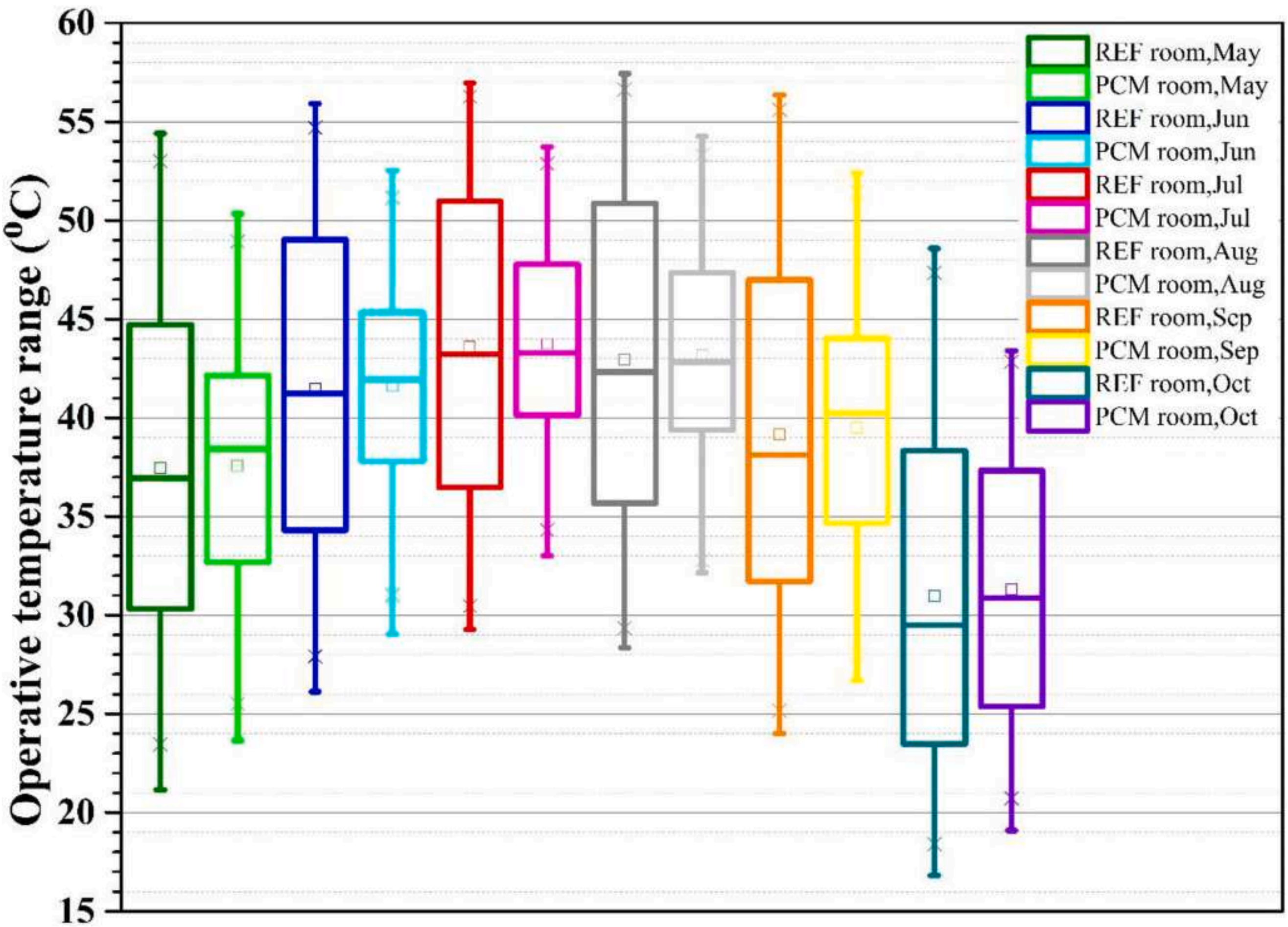

Fig. 8. Operative temperature range of rooms over summer months.

5.95 °C in September and 5.88 °C in October. Besides, it can be observed that Y values were always higher than X values, meaning that the average temperature difference between simulated rooms during no-sun hours (solidification period) was higher than their difference during sun hours (PCM melting period). In this regard, X values ranged from 2.14 °C in July to 2.57 °C in May and June, whereas Y values ranged from 2.61 °C in August to 3.65 °C in September. The main reason behind this behaviour is that rooms were non-ventilated, and the heat accumulated inside zones takes time to be removed at night since the heat transfer rate is associated with the temperature difference between outdoor and indoor environments. Therefore, ATFR could be increased by adopting ventilation means, especially at night, with suitable ventilation air rate (quantity) and temperature level.

3.2.2. *Thermal load levelling reduction*

The thermal load levelling index (TLL) shows the maximum and minimum indoor temperature fluctuation during the thermal cycle. This index directly influences the thermal comfort of occupants in the built environment since it is connected to the high and low temperature limits. Consequently, a lower TLL indicates decent building envelope thermal resistance to attenuate the indoor temperature (Ozel & Pihtili, 2007). Mathematically, the TLL can be calculated according to Eq. (9) and Eq. (10) (Meng et al., 2017) for the REF and PCM rooms as follows:

$$TLL_{REF\ room} = \frac{T_{i,REF\ room,max} - T_{i,REF\ room,min}}{T_{i,REF\ room,max} + T_{i,\ REF\ room,min}} \quad (9)$$

$$TLL_{PCM\ room} = \frac{T_{i,PCM.room,max} - T_{i,PCM.\ room,min}}{T_{i,PCM.room,max} + T_{i,PCM.\ room,min}} \quad (10)$$

The TLL of REF and PCM rooms and TLL reduction (TLLR) during the hottest days of the simulated period are shown in Fig. 7.

Fig. 7 designates remarkable TLL for the PCM room compared with the REF room, meaning that the indoor temperature was diminished in the PCM room more than in the case of the REF room. The TLL of the PCM room was relatively equal for all months, ranging between 0.08 and 0.1, except for October, which showed a high TLL of 0.2. In contrast, the TLL of the REF room ranged from 0.15 and 0.2 in May-September, whereas October showed a higher TLL of 0.31. Considering the TLLR, the hottest day of May showed the highest TLLR of about 58.8%, followed by 45% in August and 41.7% in June. In contrast, July, August and October reported lower TLLR by about 38%, 37.6% and 37.4%, respectively. According to these findings, the PCM was more effective in terms of TLLR during May in dampening the temperature fluctuation inside the zone due to low outdoor temperatures at night. This could be supported by the fact that the PCM reaches melting point quickly on hot days (Wang et al., 2020) due to the high heat charging rate and become less effective when integrated passively till the outdoor temperature drops towards the solidification point. However, October showed a similar TLLR as July, although the TLL was highly different. This could be attributed to the fact that the diurnal outdoor ambient temperature in October was relatively equal to the PCM melting temperature, which partially utilised PCM potential. Therefore, the TLL index was high (see Fig. 7) for both REF and PCM rooms, showing high indoor temperature fluctuations. On the contrary, high outdoor ambient temperature during the thermal cycle in July has kept the PCM in a melting state most of the time while providing a poor cooling medium (at night) due to the low-temperature difference between indoor and outdoor temperatures.

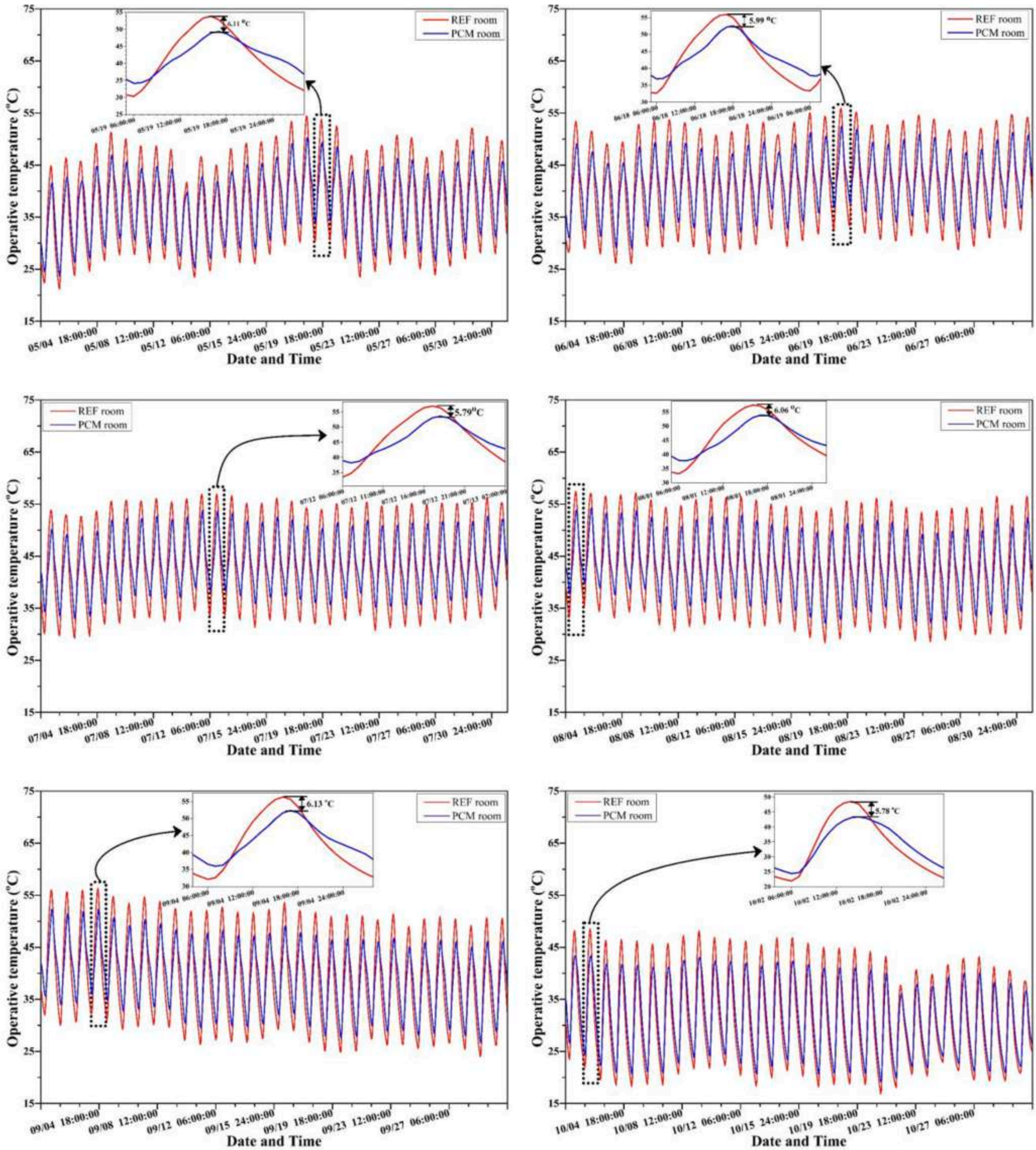

Fig. 9. Operative temperature variation and reduction over simulated period.

3.2.3. *Operative temperature reduction*

Most studies investigating PCM integration into building envelopes frequently focused on energy-saving indicators with little attention to thermal comfort advancements (Vautherot et al., 2015). Therefore, thermal comfort in terms of operative temperature reduction is studied in this sub-subsection.

Operative temperature is the temperature detected by occupants inside the built environment as an average combination of average indoor temperature and mean radiant temperature of surfaces inside the zone (i.e., interior envelope elements such as walls, roof, etc.). Mathematically, the operative temperature can be presented by Eq. (11) (ANSI/ASHRAE Standard 55-2010, 2010) as follows:

$$Operative\ temperature = \frac{T_i + \overline{T}_{mr}}{2} \tag{11}$$

where, $\overline{T}_{mr}$ refers to the mean radiant temperature of a room (in °C), which depends on the surface temperature and area of elements (Fanger, 1970).

Fig. 8 shows the range of operative temperature variation in the REF and PCM rooms during the simulated period. The figure shows that the

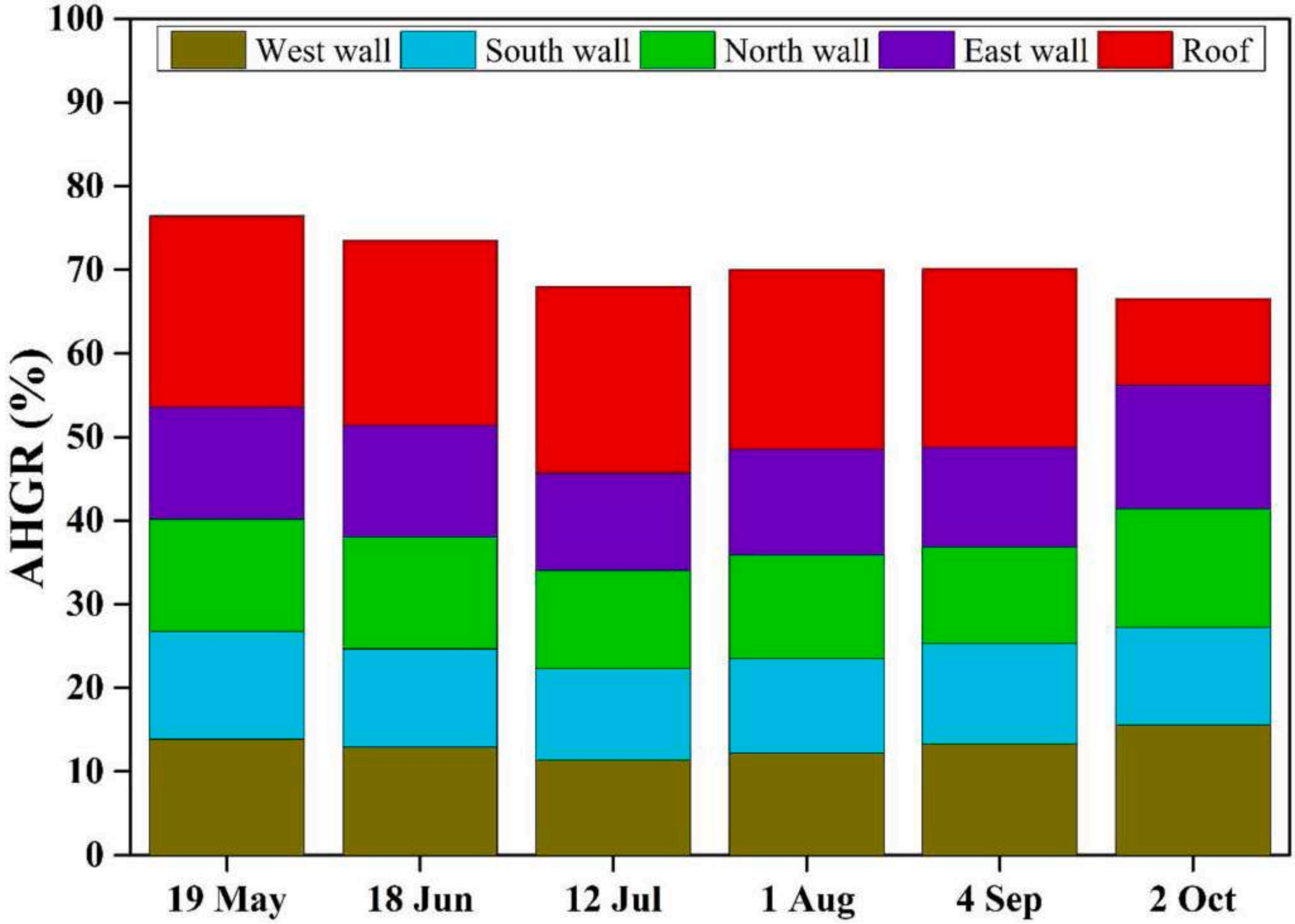

Fig. 10. AHGR of envelope elements on the hottest month day.

PCM room operative temperature variation is apparently lower than that of the REF room in all months, thanks to the PCM potential of damping temperature fluctuation and improved thermal comfort. As expected, June, July, August and September showed high operative temperature variation compared with May and October since the operative temperature was associated with the outside temperature fluctuation throughout the year.

Fig. 8 shows that the minimum/maximum day operative temperature of the REF room was 21 °C/54.5 °C in May, 26 °C/56 °C in June, 29.5 °C/57 °C in July, 28.5 °C/57.5 °C in August, 24 °C/56.5 °C in September and 16.5 °C/49 °C in October, against 23.5 °C/51.5 °C in May, 29 °C/52.5 °C in June, 33 °C/54 °C in July, 32 °C/54.5 °C in August, 26.5 °C/52.5 °C in September and 19 °C/43.5 °C in October inside the PCM room. According to the above temperature limits, the thermal comfort temperature recommended by ASHRAE (American Society of Heating, Refrigeration and Air-conditioning Engineers) Standard 55-2017 (ASHRAE, 2017) cannot be attained by passive PCM incorporation, except in May and October nighttime.

Compared with the REF room, the operative temperature reduction (OTR) in the PCM room could indicate an improvement in the thermal comfort earned from PCM integration. This can be characterised as the thermal comfort temperature difference between the REF and PCM rooms, as presented in Fig. 9. In this regard, the OTR between REF and PCM rooms at the hottest day of May, June, July, August, September and October was 6.11 °C, 5.99 °C, 5.77 °C, 6.06 °C, 6.13 °C and 5.78 °C, respectively.

As observed in Fig. 9, the operative temperature trend showed remarkable enhancement for the PCM room over the REF room during daytime in all months. Nevertheless, this temperature behaviour is reversed during the night time, wherein the operative temperature of the PCM room becomes higher than that of the REF room since it is connected with the indoor temperature variation. This negative behaviour is indorsed to the diurnal heat stored inside PCM elements, dissipating as soon as the outdoor ambient temperature drops below the PCM melting temperature. Besides, due to passive PCM incorporation, the building envelope has discharged heat uncontrollably towards the indoor zone, increasing its temperature and eventually influencing the operative temperature. Since the operative temperature directly impacts occupants' thermal comfort, suitable ventilation methods should be adopted when passively incorporating PCM into the building envelope. This could overcome PCM's negative temperature behaviour during the solidification phase, especially in locations with high outdoor temperatures on summer nights, such as Iraq.

3.3. *Energy performance analysis*

In numerical studies, building energy-saving accomplished by integrating PCM with envelope elements is essential to evaluate its performance on a seasonal/annual basis (Tunçbilek, Arıcı, Bouadila, et al., 2020). This mainly discusses the reduction of cooling/heating load and associated environmental and economic analysis. Since we deal with the building envelope alone in this study, the energy-saving in terms of solar heat gain reduction and associated CO_2 emissions and electricity cost reduction were considered, as discussed in the following sub-subsections.

3.3.1. *Heat gain reduction*

The solar heat gain crossing the building envelope from the outdoor

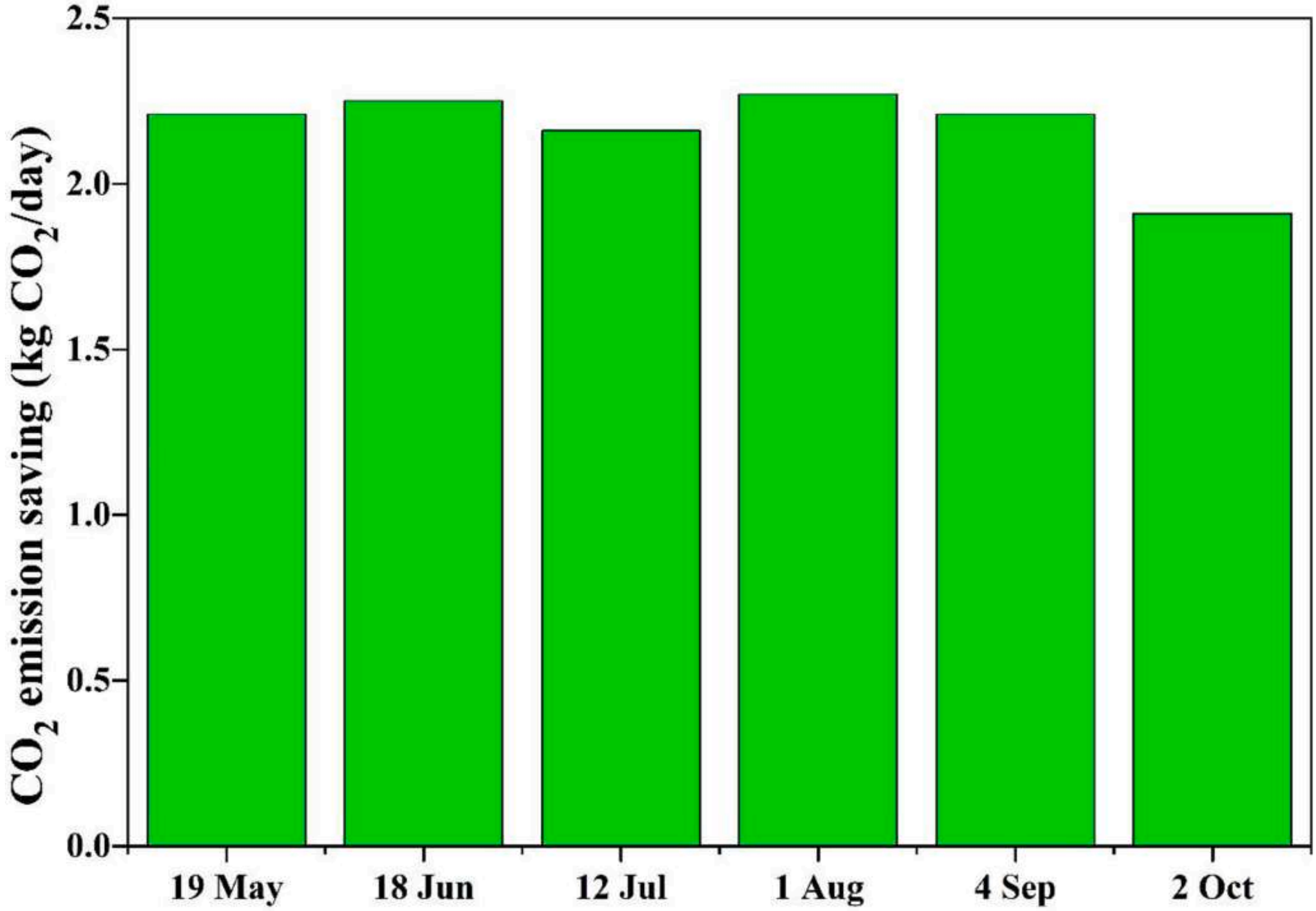

Fig. 11. Daily CO_2 emission saving.

towards the indoor environment is essential to quantify the building's thermal performance as it determines the cooling load together with the internal heat gain sources (i.e., occupants, devices, lighting, etc.) (Sharma & Sengar, 2019). The heat gain of envelope elements can be calculated according to Eq. (10) (Al-Rashed et al., 2021) in terms of the convective-radiative heat transfer coefficient of the element inside the surface and indoor room temperature (h_i, in W/m^2.K), element area (A, in m^2) and the difference between the inside surface temperature (inside face surface temperature, T_s) and indoor temperature (T_i both in °C), as follows:

$$Heat\ gain = h_i\ A\ (T_s - T_i) \tag{10}$$

The values of h_i proposed by ASHRAE as 8.29 W/m^2. °C for vertical elements (walls) and 6.13 W/m^2. °C for horizontal elements (roofs) are adopted in this study (ASHRAE, 1997). Subsequently, the average heat gain reduction (AHGR) can be presented as the reduced average heat gain between the REF room elements compared with those of the PCM room during day hours from 6:00 to 18:00, according to Eq. (11) (Fateh et al., 2018), as follows:

$$AHGR = \frac{\sum_{6:00}^{18:00} Heat\ gain_{REF\ room} - \sum_{6:00}^{18:00} Heat\ gain_{PCM\ room}}{\sum_{6:00}^{18:00} Heat\ gain_{REF\ room}} \times\ 100\% \tag{11}$$

Fig. 10 shows the AHGR attained over the simulation period.

As shown in Fig. 10, the roof achieved the highest AHGR every month, except in October, compared with the walls. In this regard, the roof shared about 22.9% in May, 22.1% in June, 22.3% in July, 21.5% in August, and 21.4% in September. This high share indicates the effectiveness of PCM in the roof more than with walls, which is mainly attributed to the high PCM thickness incorporated into the roof (15 mm) compared with walls (~7 mm). Besides, since the roof was receiving a high solar radiation rate for a longer time, it was the hottest element in the room (Fig. 4). This led to an increase in the PCM effectiveness in the PCM room compared with the REF room roof, which was at a high surface temperature. However, the roof showed a different trend in October, where the AHGR reached a slight reduction of only 10.4%, which is relatively lower than that of walls. This is attributed to the fact that the roof received lower solar radiation in October than in other months, as shown in Fig. 4, which affected the PCM melting phase.

Although the walls were constructed from a thin combination, they showed good AHGR for the PCM room compared with the REF room. In general, all PCM room walls showed relatively similar AHGR during the simulated period, with a higher share for the east and west walls, followed by the south wall. This behaviour has the same attribution as the PCM roof since the east and west walls received higher solar radiation rates than the south and north walls (as indicated in Fig. 4). The east wall was more effective in June, July and August than the west wall, whereas the latter was better in May, September and October.

The total AHGR of the PCM room compared with the REF room reached 76.5%, 73.5%, 68.2%, 70.1%, 70.2% and 66.6% on the hottest day of May, June, July, August, September and October, respectively. May showed the highest total AHGR, followed by June. In contrast, October achieved the lowest, indicating that the outdoor ambient temperature variation during the day and night was the main factor behind PCM effectiveness. However, these outcomes eventually indicate a decent contribution of PCM to building energy saving, resulting from effective melting temperature, and can significantly reduce the cooling loads in hot climate buildings.

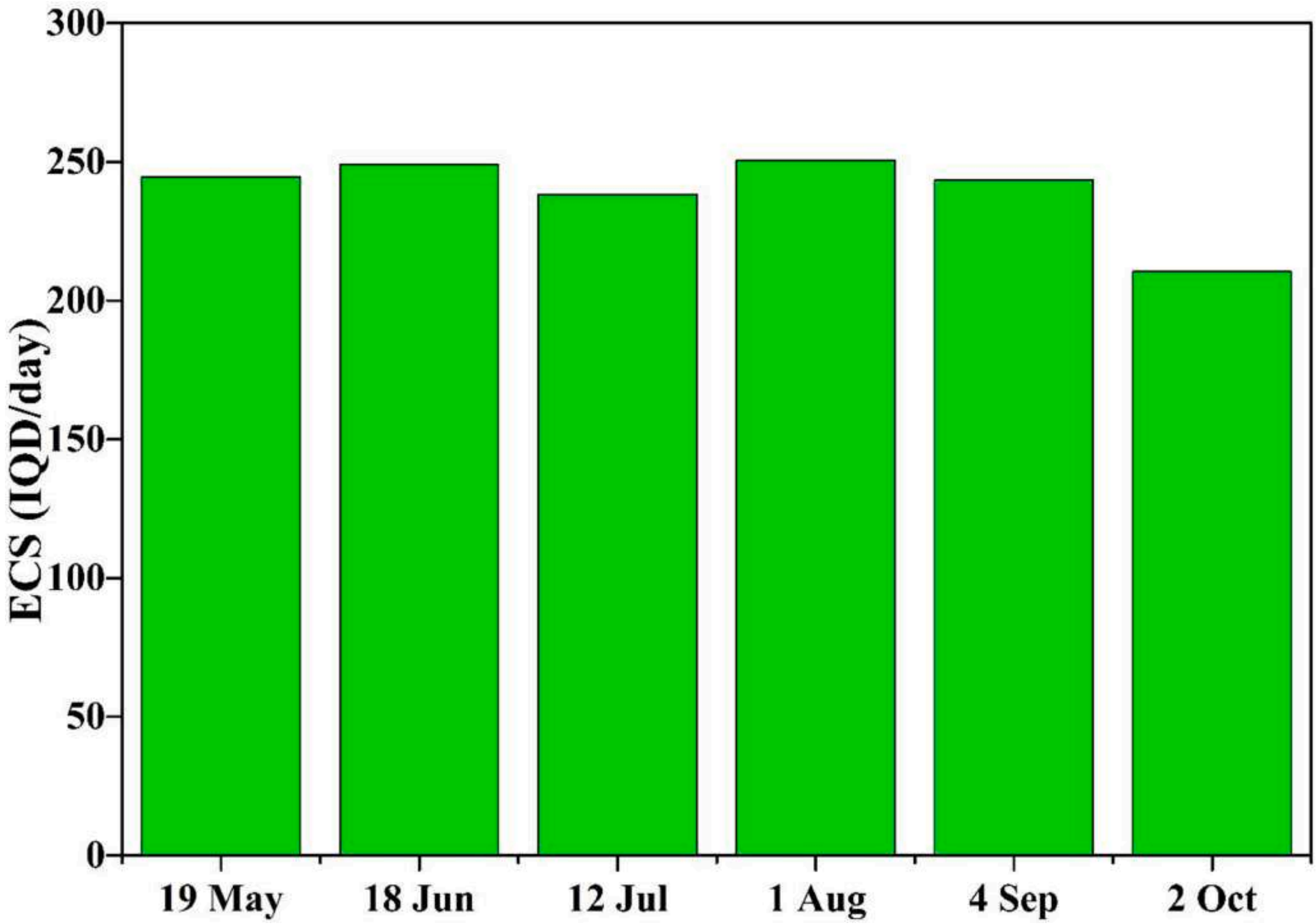

Fig. 12. Daily ECS on hottest summer days.

3.3.2. CO_2 emission saving

Diminishing CO_2 emissions is a fundamental objective in modern society when dealing with building technologies since it is associated with global warming and climate change anxieties (Uludaş et al., 2022). In this study, the CO_2 emission saving was quantified for the hottest day of each month considering the total average heat gain difference (AHGD) in each room (in kW) and the equivalent quantity of CO_2 produced from each kWh of electricity generated in Iraq, according to Eq. (12) (Al-Rashed et al., 2021), as follows:

$$CO_2 emission\ saving = total\ AHGD \times \frac{kgCO_2}{kWh\ electricity} \times day\ hours \quad (12)$$

According to IEA, the magnitude of 1.00284 kg CO_2 per each kWh of electricity was considered in this study as a typical value for calculations since Iraq still heavily employs natural gas and petroleum resources for powering governmental power plants and generating electricity (IEA, 2020). Fig. 11 shows the calculation results of CO_2 emission saving attained from PCM integration.

The results indicated remarkable CO_2 emission saving by about 2.21, 2.25, 2.16, 2.27, 2.21 and 1.91 kg CO_2/day in May, June, July, August, September and October, respectively. Such values have a huge environmental impact on the building sector, considering the performance of PCM over a building lifespan of about 50 years. The average CO_2 emission could be saved more when incorporating PCM for larger building envelope areas. However, optimisation for PCM position and quantity could be investigated to make useful PCM incorporation with building elements and balance the thermal, environmental and economic concerns.

3.3.3. Electrical cost saving

Cost saving of electricity is another necessity of modern technologies and the immediate requirement of their commercialisation, especially in Iraq, which still suffers from electricity shortage, especially during the summer months. The electricity cost saving (ECS) achieved from PCM incorporation into envelope elements of the simulated model was calculated taking into account the total AHGR (in kW) and the electricity cost (C) on a daily basis, as presented in Eq. (13) (Rathore & Shukla, 2020), as follows:

$$ECS = Total\ AHGR \times \frac{C}{kWh} \times day\ hours \quad (13)$$

The value of C was considered equal to 60 IQD per kWh of electricity based on the newest Iraqi tariff for each kWh of electricity supplied for buildings (Iraq Electricity Prices, 2021). The calculation results of ECS in each selected day of the simulated period are presented in Fig. 12. The ECS reached in May, June, July, August, September, and October was respectively about 245, 249, 238, 250, 244 and 210 IQD/day. Although this contribution is relatively slight considering the PCM incorporation initial cost, it would be more effective considering a large building area and long-term service. Regardless of what ECS attained, integrating PCMs with buildings contributes to the revolutionary steps towards energy-efficient buildings and nearly zero-energy buildings adopted by modern society (Wang et al., 2022).

In summary, Table 3 lists the main findings obtained in this work compared to those achieved in similar studies conducted worldwide for the full building envelope.

Table 3
Summary of main findings of recent literature studies in comparison with the results of the current study.

Location (country, city)	PCM type (melting temperature, °C)	Building element/ PCM layer thickness (mm)	Investigated parameters/indicators	Main findings	Reference
Iraq (Kut city)	Paraffin wax (44)	Roof and walls/ 10 and 20	Indoor temperature reduction, cooling load reduction and ECS	• Maximum indoor temperature reduced by 2.18 °C. • Maximum cooling load reduction by 20.9% was reached at 1 cm PCM thickness. • Maximum ECS by 1.35 USD/day.m^3 was attained at 1 cm PCM thickness combined with walls.	(Hasan et al., 2018)
Denmark	17 PCM types (18 °C- 26 °C)	Roof and walls/ 5-100	Annual energy consumption reduction and average indoor temperature reduction	• The PCM of 24 °C melting temperature performed best than other PCMs. • Annual energy consumption reduction by 7 %- 15 % and average indoor air temperature reduction by 3.4 °C - 4.2 °C was achieved.	(Hagenau & Jradi, 2020)
Australia (Melbourne)	15 BioPCM types (18-32)	Roof and walls/ 5-25	Discomfort hours reduction, energy consumption reduction, peak cooling demand reduction,	• PCM of 25 °C melting temperature and 2.5 cm thickness was optimal. • The discomfort hours were reduced by 82%. • Reduction of energy use, peak cooling demand, CO_2 emissions, and energy cost by about 40%, 65%, 64%, and 35%, respectively.	(Kumar et al., 2021)
Kuwait (Kuwait City)	RT-31 (27–33), RT-35 (29–36) and RT-42 (38–43)	Roof and walls / 20	Heat gain reduction, energy-saving and CO_2 emission saving	• Heat gain reduction was reached by 15.25% for RT-31, 15% for RT-35 and 14.21% for RT-42 in July. • The energy-saving attained was 34.68 kWh/m^2 for RT-31, 34.12 kWh/m^2 for RT-35 and 32.32 kWh/m^2 for RT-42 in July. • In July, the CO_2 emission saving reached 14.32% for RT-31, 14.1 for RT-35, and 13.34% for RT-42. However, RT-31 reached a maximum annual CO_2 saving of 198.65 kgCO2/m^2.	(Al-Rashed et al., 2021)
Morocco (Benguerir city)	RT-18 HC (17–19 °C), RT-21 HC (20–23 °C), RT-25 HC (22–26 °C), RT-28 HC (27–29 °C) and RT-35 HC (34–36 °C)	Roof/ 5-30	ATFR and annual energy-saving	• The PCM RT-28 HC is optimal for the location under study. • The highest annual ATFR and energy saving of 1.91 °C and 13.77% were attained at 15 mm thickness.	(Salihi et al., 2022)
Egypt (Cairo and Aswan)	PCM-21 (19-23), PCM-23 (21-25), PCM-25 (23-27), PCM-27 (25-29), PCM-29 (26-31) and PCM-31 (28-33)	Roof and walls/ 10-40	Discomfort hours reduction and cooling energy reduction	• The PCM of 29 °C melting temperature and 2 cm thickness performed the best. • The discomfort hours reduced from 52.8% to 9.24%. • The cooling energy was reduced from 16.83% to 14.25%	(Abd El-Raheim et al., 2022)
Pakistan (Islamabad, Karachi, Lahore, Peshawar and Quetta)	SP21EK (22), SP24E (24), SP25E2 (25), A22H (22), A25H (25), RT21HC (21), RT22HC (22), RT25HC (25), PureTemp18 (18), PureTemp20 (20), PureTemp23 (23), CrodaTherm19 (19), CrodaTherm21 (21), CrodaTherm24W (23) and CrodaTherm24 (24)	Roof and walls/ 10-100	Monthly energy saving and payback period	• CrodaTherm24 was the optimal PCM. • An average monthly energy saving of 44.9%, 35%, 32%, 35%, and 49.6% is achieved in Islamabad, Karachi, Lahore, Peshawar, and Quetta, respectively. • The payback period was between 20-23 years in Lahore, and 22-27 years in Karachi, while it was not feasible in the rest cities.	(Khan et al., 2022)
Saudi Arabia (NEOM smart city)	PCM-24 (22-24)	Roof and walls/ 5, 10 and 20	Heat transfer reduction	• The heat transfer was reduced by 63.5%, 73.6%, and 78.7% using 5, 10, and 20 cm, respectively.	(Fagehi & Hadidi, 2022)
Iraq (Al Amarah city)	Paraffin wax (40-44)	Roof and walls/ 15 (roof) and 7 (walls)	ATFR, TLLR, OTR, AHGR, CO_2 emission saving and ECS	• ATFR by 5 °C- 6 °C, TLLR of 38%-59%, OTR by 6 °C were achieved. • Total daily AHGR by 66.6%- 76.5% was reached, with equivalent CO_2 emission saving by an average of 2 kg/day and ECS of 210-250 IQD/day.	Current study

4. Conclusion

The current study numerically investigated the thermal performance of PCM when passively integrated with a thin building envelope considering the thermal comfort enhancement and potential energy-saving under Iraqi severe hot summer months. The PCM thermal contribution was evaluated by considering several variables of indoor thermal comfort (average temperature fluctuation reduction, thermal load levelling reduction and operative temperature reduction) and energy-saving (average heat gain reduction, CO_2 emission and electricity cost saving) in the hottest day of each month. According to simulation results, the PCM was effective in all summer months, even during the hottest days, displaying remarkable enhancement of indoor thermal comfort and notable energy-saving. Besides, the following conclusions can be drawn from the study, mixed with the opinion of authors for future insights:

- Generally speaking, the outdoor ambient conditions during the thermal cycle (day and night) were the sole controller of PCM effectiveness since the study was verified in a non-ventilated room.
- The average temperature fluctuation was reduced by about 5 °C- 6 °C in the PCM room compared with the REF room, indicating a more stable indoor temperature during the thermal cycle. However, the average temperature difference between rooms during the night period (indicated as Y) was greater than the difference during day hours, indicating the poor thermal performance of PCM during the solidification phase. Accordingly, adopting methods to tackle this issue will be the main target of future research work.
- The PCM has reduced the thermal load levelling reduction during the thermal cycle by 38% to 59%, with superior performance during May. However, the thermal load levelling index was high in October, according to Fig. 7, indicating poor effectiveness of PCM during this month. This is expected since the PCM melting point was higher than the ambient temperature of October during most hours which limits the PCM thermal storage potential.
- The operative temperature in the PCM room was reduced by an average of 6 °C compared with the REF room, attaining better thermal comfort for the built zone. However, the thermal resistance of envelope materials and envelope area may influence indoor thermal comfort since the mean radiant temperature is associated with the indoor surface temperature and element area.
- Considering the energy-saving owed to PCM integration, a noteworthy average heat gain reduction was achieved in all investigated hot days, ranging between 66.6%- 76.5%, where the roof contributed utmost than the walls, except in October. The solar radiation rate incident on the elements is the main parameter influencing the PCM effectiveness. Researchers and building designers should pay attention to the PCM quantity involved in the building element considering their direction/orientation towards the sun.
- The CO_2 emissions were saved by an average of 2 kg CO_2 per day, demonstrating enormous positive environmental impact considering the limited room volume. Further studies to investigate the annual environmental impact of PCM-enhanced full building scale are recommended for interested researchers.
- The electricity cost could be saved by an average of 210-250 IQD/day, which is economically viable considering the long lifespan of buildings and the summer period in Iraq. However, October showed the lowest contribution of PCM, indicating poorer PCM effectiveness compared with other months due to dropped outdoor air temperature near PCM melting temperature. Besides, the PCM contributed mostly in May and September, considering the indoor thermal comfort enhancement, while it showed better energy-saving potential in August.

The results presented in this study are believed to highlight the thermal contribution of high melting temperature PCM under severe hot climates when integrated passively. However, the PCM thermal performance could be improved further by considering other techniques to increase PCM effectiveness throughout the thermal cycles, such as employing day and night ventilation and investigating the combined use of thermal insulation and PCM.

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.

Data availability

Data will be made available on request.

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