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Experimental Investigation of the Thermal Performance of Triple Glazed Windows Integrated with PCM and Low-e Glass

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ABSTRACT

This study explores the effects of incorporating phase change materials (PCM) and low-emissivity (low-e) glass into triple-glazed windows to enhance thermal insulation in hot summer conditions in Iraq. The objective is to evaluate the effectiveness of four different triple-glazed window (TG) configurations: with two air-filled cavities; with low-e glass and air-filled cavities; with PCM in one cavity and air in the other; and with low-e glass and PCM in separate cavities. The experimental method used solar simulation to replicate high solar radiation (650 W/m²) and measure the internal surface temperatures of each window type. The results showed that configurations of low-e glass and PCM had the highest performance, reducing the inner surface temperature by up to 8.1°C compared to two air-filled cavities and delaying peak heat load by 2 hours. These findings suggest that combining PCM and low-e glass significantly improves thermal comfort and energy efficiency in buildings.

1. INTRODUCTION

In recent years, both synthetic and natural resources have been gradually decreasing. This has led to a crisis that has severely impacted the possible use of these resources [1]. Currently, most classical fossil fuels are not just finite resources but also have significant environmental impact and environmental pollution [2]. Each country has a duty to consistently strive for the growth of innovative and environmentally friendly power sources.

PCM is a highly promising option for saving thermal energy and look like a viable solution for possible energy in the future. This material has the capacity to store or release a big amount of heat when they undergo a phase change. This heat (latent heat) enables them to maintain a consistent temperature and has a duty to consistently strive towards the development of innovative and environmentally friendly energy sources. PCMs are a highly preferred option for storing thermal energy and are considered a viable solution for sustainable energy in the future. This material has the ability to store or release a big amount of heat when it undergoes a phase change.

This heat, known as latent heat, enables them to keep a regular temperature [3]. PCMs are often regarded as very effective cooling technologies due to their affordability, simple design, and special cooling performance [4]. So, investigators in the thermal energy storage's correction have recently begun to focus on PCMs [5, 6]. Thermal energy storage technology enhances the efficiency of using thermal energy [7]. Of the three categories of heat storage - latent heat, chemical energy, and sensible heat - the technology of latent heat storage is particular notable for its high heat storage density and almost isothermal functioning. This technology has great potential for applications in building energy conservation and different other fields [8].

PCM has considerable potential in energy storage techniques. Because of its excellent isothermal properties and high energy storage density [9]. They have the capability to store and discharge an essential quantity of energy during the process of phase transition. Hence, it can be utilized to enhance energy efficiency and simultaneously relieve environmental reflection [10]. PCM heat storage technology falls under the latent heat storage's classification [11].

Furthermore, it can be categorized as solid-liquid, solid-solid, solid-gas, and gas-liquid established on its phase transition properties. Gas storage presents challenges, thus, the main types of PCM used in practical applications are solid-solid PCM and solid-liquid PCM [12]. Previously, studies have first concentrated on solid-liquid PCMs rather than solid-solid PCMs. These investigations have shown conservable drawbacks. Also included is the potential for leakage, corrosiveness, and expensive packaging costs [13]. As a widely recognized latent heat storage material [14], PCM simplifies the storage and release of thermal energy within the phase change operation [15]. PCMs are extensively used in building energy storage, lithium-ion batteries and electronic components because of their temperature stability within a specific range [16, 17].

PCM successfully blocks a range of thermal disaster situations. The PCM's latent heat indicates the amount of heat absorbed or released through the processes of vaporization, sublimation, and dissolution [18-20]. Jalil and Salih [21] examined the thermal efficiency and comfort improvement of a PCM in double-glazed window (DG). The investigation focused on a specific room located in Baghdad. The Navier-Stokes equations, which run the flow in the test chamber, similar solved by the finite volume method.

The issue of conduction was addressed using the finite variation method with the enthalpy method, leading to significant temperature reductions in double-glazed windows compared to single-glass ones—8°C on the ground floor, 6°C on the 1st floor, and 5°C on the roof. Bolteya et al. [22] tested the thermal performance of a PCM (RT28HC) in double-glazed window, finding that the internal peak temperature was delayed by 5 hours compared to air-filled windows. Gao et al. [23] optimized PCM windows for energy-efficient buildings, showing energy savings of 9.4%, 6.7%, and 3.2% across different stories. PCM windows also improved HVAC load redistribution and enhanced grid performance. Ravasio et al. [24] used COMSOL Multi-physics to compare TG windows with PCM to standard TG windows, revealing improved thermal performance, especially in summer, when using different paraffin wax types.

King et al. [25] evaluated the thermal performance of a DG with PCM compared to a standard DG window. Their study showed that PCM integration maintained sufficient light transmittance while improving insulation. Rodriguez-Ake et al. [26] investigated the optimal air gap in a triple-glazed window (TG) for hot climates, finding a 10 mm gap significantly reduced heat transfer compared to DG. Wei et al. [27] demonstrated the energy-saving potential of PCM in multilayer glazing systems, with savings up to 50.71% in fourfold glazing units.

Liu et al. [28] analyzed a PCM and silica aerogel window, identifying an optimal thickness range of 20-30 mm for maximizing thermal efficiency. Kaushik et al. [29] compared a nano-dispersed PCM (NDPCM) DG window to traditional PCM, showing improvements in energy efficiency and temperature reduction. Zhang et al. [30] explored a PCM-low-e glass roof, achieving up to 33.74% energy savings in cold climates. Zhang et al. [31] introduced a dynamic PCM window, which reduced cooling loads by 28.70% in summer, with optimal phase transition temperatures between 19-25°C.

Kamalisarvestani et al. [32] examined thermochromic smart windows, which adjust optical properties to enhance energy efficiency. Cuce et al. [33] highlighted the high insulation performance of solar glass with a pending film, achieving a U-value of 1.10 W/m^{2}K. Jin et al. [34] revealed that thermochromic triple-glazed windows with PCM reduced heat gain by up to 40%. Tao et al. [35] confirmed the accuracy of thermochromic window simulations, showing a 5% average error in predicted temperature data.

Recent research has indicated that conventional glass windows exhibit poor insulation properties, leading to substantial exterior surface temperature increases. This has driven the exploration of integrating PCM and other insulating materials into glazing systems for enhanced thermal performance. Most studies have focused on double-glazed windows in both cold and hot climates, while theoretical studies have extended to PCM integration in triple-glazed windows. However, issues such as heat release during PCM discharge in the summer and the overheating of melted PCM remain challenges that impact insulation performance.

While significant progress has been made in PCM and glazing system research, most work has focused on double-glazed systems or dynamic windows. Few studies have compared the performance of various insulating materials, particularly low-e glass and PCM, in triple-glazed windows, especially in hot climates. Additionally, the issue of heat release during PCM discharge at night and the overheating of melted PCM during the day requires further investigation to optimize performance.

This study addresses these gaps by experimentally investigating four configurations of TG in hot summer climate (Iraq). The configurations tested are:

TG: Regular triple-glazed window.

TG-LW: Triple-glazed windows have low-e glass and air-filled cavities.

TG-PCM: Triple-glazed window with PCM in the outer cavity and air in the inner cavity.

TG-LW-PCM: Triple-glazed window with low-e glass in the outer layer, PCM in one cavity, and air in the other.

The aim is to determine the optimal window configuration for reducing internal surface temperatures and improving insulation performance.

2. EXPERIMENTAL WORK

Figure 1. Test room model

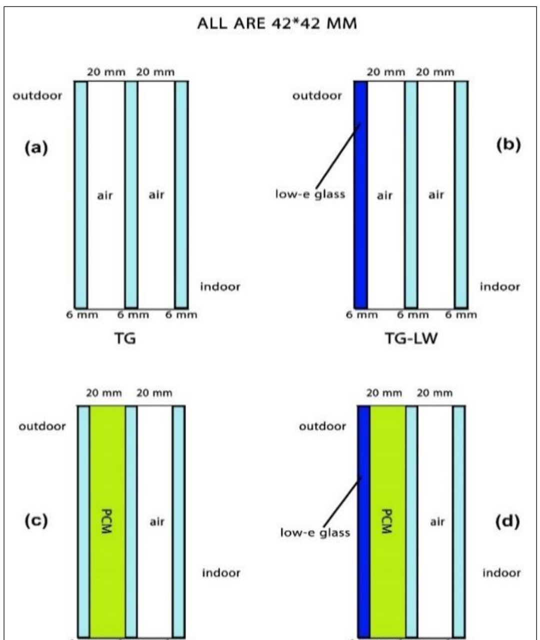

Figure 2. Structure comparison of windows: (a) TG, (b) TG-LW, (c) TG-PCM, and (d) TG-LW-PCM

Table 1. The details of windows (in mm)

Parameters	TG	TG-LW	TG-PCM	TG-LW-PCM
Length	410	410	410	410
Width	410	410	410	410
Glass thickness	6	6	6	6
First cavity thickness	20	20	20	20
First cavity	Air	Air with low e	PCM	PCM with low e
Second cavity thickness	20	20	20	20
Second cavity	Air	Air	Air	Air

Table 2. The PCM's properties [36]

Melting Temperature	Density	Specific Heat	Thermal Conductivity	Latent Heat of Fusion
	Solid Liquid	Solid Liquid		
44	930 830	2.1 2.1	0.21	190
°C	kg. m^{-3}	kJ kg^{-1} K^{-1}	W m^{-1} K^{-1}	J kg−1

Table 3. Measurement apparatus specifications

Measurement	Tool	Model	Range	Accuracy
Temp.	Thermometer	HT-9815	-200 to 1372°C	± 0.15%
	Thermocouple	Type-K	–110 to 1200°C	± 0.3%
radiation	Solar meter	SM206-SOLAR	0.1 to 2000 W/m^2	± 4.8%

Figure 1 displays an experimental setup of the four configurations: TG, TG-LW, TG-PCM, and TG-LW-PCM. A halogen light is utilized to simulate thermal conditions and evaluate the insulation performance of each window configuration. Each of these windows filled with PCM or air and Low e glass as insulation materials depicted in Figure 2. Also, each configuration highlights the differences in insulation materials and glass types for improved thermal performance. Detailed description and dimensions for four windows are provided in Table 1.

A rectangular test room made of sandwich panels with (1.5, 1.5, 1.5) m; 2.5 kg of PCM were used to fill two window cavities with paraffin wax with 44°C melting point.

Table 2 shows the physical properties of PCM. The PCM functions as both a storage unit and an absorbent surface barrier, accumulating thermal energy during the day and releasing it at night.

Thermocouples were distributed as follows: two in each cavity of four windows, one in external surface of each window, one in the internal surface in each window, one inside room.

Figure 3. Solar simulator (halogen lamp)

Figure 4. The phase changes of PCM in TG-PCM

2.1 Measurement devices

Throughout the experiment, it is essential to measure the inner and outer temperature of surfaces and gaps. The necessary data can be collected directly using the measurement instruments. Additionally, radiation was mimicked using 6 halogen lamps (500 W), as illustrated in Figure 3.

Also, Table 3 shows the specifications of measurement apparatus. Physical characteristics of the glass used are presented in Table 4.

Table 4. The physical properties of glass [37]

Thickness (m)	Solar Transmittance	Solar Reflectance	Emissivity
0.006	0.804	0.074	0.84

Figures 4(a)-(h) depict processes of the PCM changing throughout the day. The amount of solar radiation incident on the TG-PCM determines the timing and speed of the melting process; the greater the solar radiation, the earlier and faster the melting occurs.

2.1.1 Thermocouple

To measure the room's temperature distribution, eight type K thermocouples were employed. From the north to the south side of the space as shown in Figure 5.

Figure 5. Thermocouple

2.1.2 Thermometer

The temperature was taken with a thermometer of the HT-9815 model shown in Figure 6. There are four channels on this device. These channels were connected to the thermocouple probes that were placed throughout the room, in each of the four window gaps, and on the outside and inside surfaces of the TG. Manual recording of the data was done.

Figure 6. Thermometer

2.1.3 Solar power meter

The device measures radiation intensity in the range of 0.1 to 1999 W/m² and responds in one second. Four TGs' surface areas' incident radiation from halogen lamps was measured using the solar power radiation meter with digital LCD model SM206-SOLAR shown in Figure 7.

Figure 7. Solar power meter

2.2 Uncertainty of analysis

The TG's uncertainty can be quantified to improve result accuracy. By accounting for the errors in devices used during practical testing and employing the equations below, the following formula can be utilized to calculate heat uncertainty [38]:

$$\delta Q/Q = [(\delta T / T) 2] 1/2 \quad (1)$$

3. RESULT AND DISCUSSION

This research investigated experimentally the thermal performance of integrated PCM or air and Low e glass with four configurations of TG in summer Iraqi weather: a standard TG has air in both gaps; TG-LW has low-e outer glass and air in both gaps; TG-PCM has a PCM in the outer cavity and air in the inner cavity with glass; and TG-LW-PCM has a PCM in the outer cavity with low-e glass in external and air in the inner cavity. The experimental measurements were carried out throughout the month, especially in July month 2023. Also, the values used in the sun simulation (halogen lights) are similar to the values of solar radiation in the July month.

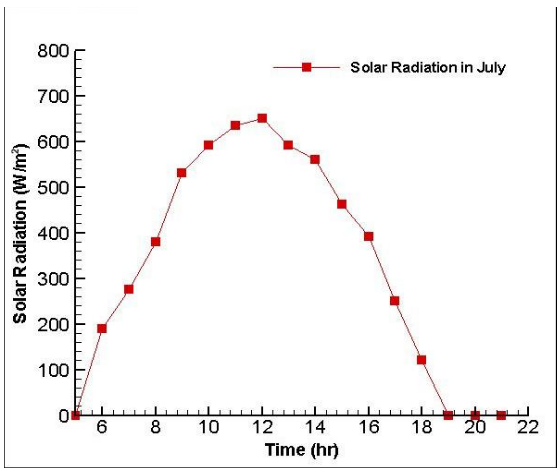

Figure 8. Daytime solar radiation intensity in July 2023

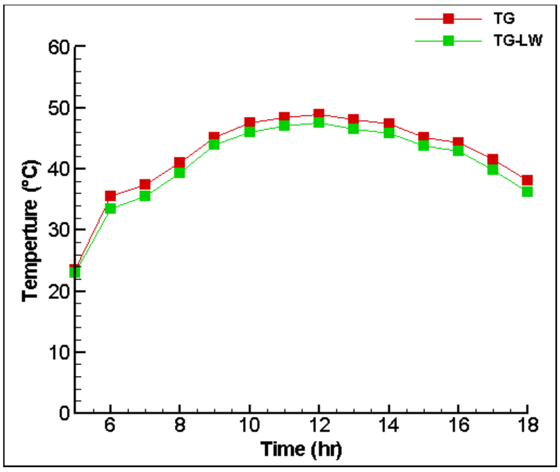

Figure 9. Comparative of the external surface temperature of standard and low-e triple-glazed windows throughout the day in July 2023

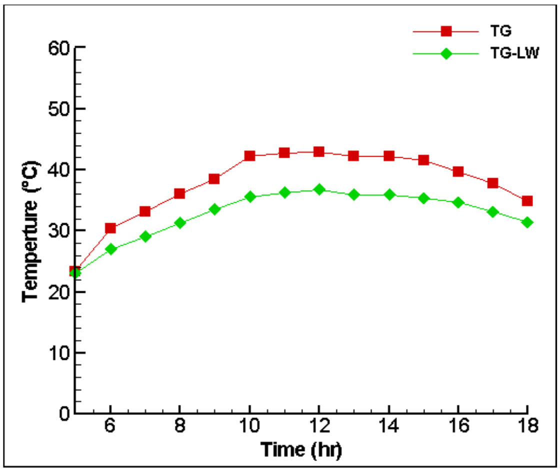

Figure 10. Comparative of the external cavity temperature of standard and low-e triple-glazed windows throughout the day in July 2023

Figure 8 depicts the measured patterns of sun radiation throughout the experimental duration. The maximum radiation measured was 650 W m^{-2} in July at 12:00 PM.

Figure 9 displays the temperature variation on the external surface of TG configurations. Compared to the external temperature of TG, the figure indicates a reduction in temperature of TG-LW compared with TG during the day from 6:00 AM to 6:00 PM, due to the property of low-e glass, which reduces the transfer of heat through windows while allowing visible light to pass through and making it an effective insulator in buildings.

Figures 10 and 11 show the temperature of the interior and exterior cavities in the two TG along the timeline in July 2023. The TG configuration shows higher temperatures throughout the day, while the TG-LW configuration demonstrates improved thermal insulation, maintaining lower temperatures. From 6:00 AM to 6:00 PM, the external gap's peak temperatures in TG and TG-LW were 49 and 44°C, respectively. Also, in the inner cavity for two windows the peak temperatures were 43 and 36.8°C, respectively.

Figure 12 depicts the inside temperature of the two types of windows with glazing TG and TG-LW. The TG configuration shows consistently higher internal temperatures, while the TG-LW configuration demonstrates better insulation by maintaining lower internal surface temperatures throughout the day. The maximum glass temperature at maximum solar 650 W m^{-2} at 12:00 PM was observed as 36.4°C for a window triple glazing window with normal glass TG whereas it was only 32.4°C in a window triple glazing window with low-e glass TG-LW.

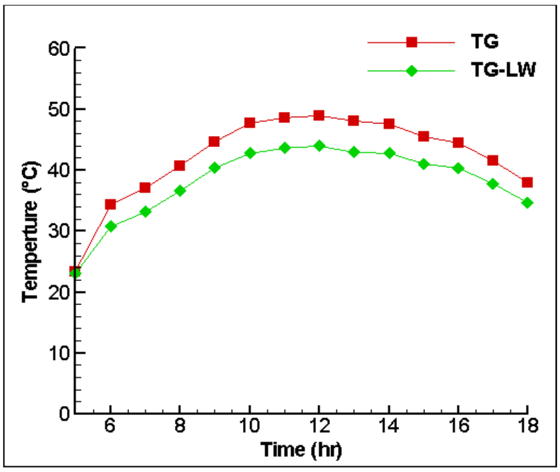

Figure 11. Comparative of the internal cavity temperature of standard and low-e triple-glazed windows throughout the day in July 2023

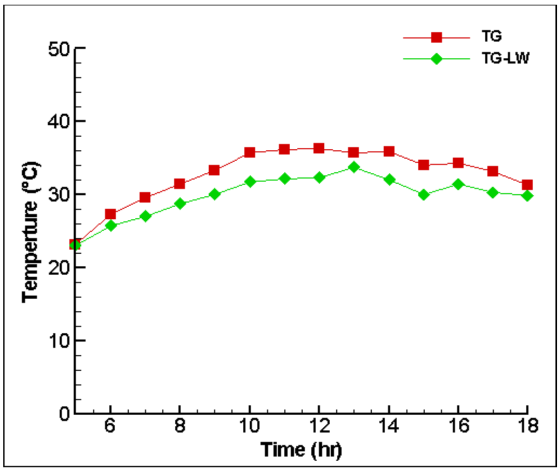

Figure 12. Comparative of the internal surface temperature of standard and low-e triple-glazed windows throughout the day in July 2023

Both types of glazing show an increase in temperature as the day progresses from morning 6:00 AM to 12:00 PM and begin to cool down as evening approaches. Due to the daily solar radiation cycle, where the intensity peaks around midday, the low-e glass was showing a slower temperature than that of the normal glass, which could indicate that the low-e glass, while preventing heat from entering, also retains heat for a longer period. Therefore, the use of low-e glass in windows reduces approximately 4°C compared to the TG.

Figure 13 depicts the inside temperature of the two types of windows with glazing TG-PCM and TG-LW-PCM. The TG-PCM configuration exhibits higher internal temperatures, while the TG-LW-PCM demonstrates better insulation performance by maintaining slightly lower temperatures throughout the day. The comparison was conducted from 6:00 AM to 9:00 PM. under consistent conditions. The maximum glass temperature at maximum solar 650 W/m^2 at 12:00 PM was observed as 30.2°C for a window triple glazing window with normal glass with PCM TG (PCM-Air), whereas it was only 28.3°C in a window triple glazing window with low-e glass with PCM TG-LW-PCM.

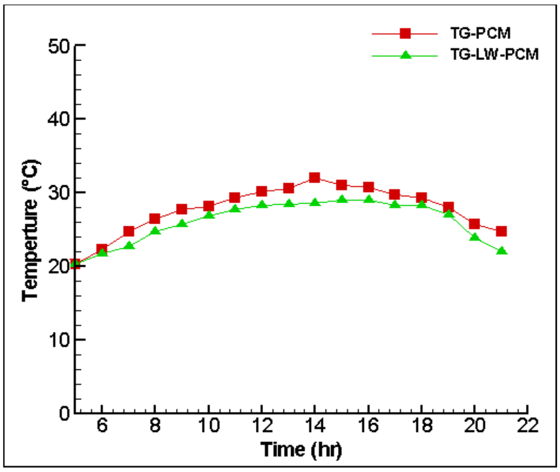

Figure 13. Comparative of the internal surface temperature of standard and low-e triple-glazed windows with PCM throughout the day in July 2023

Figure 14 depicts the inside temperature of the four types of windows with glazing TG, TG-LW, TG-PCM and TG-LW-PCM. TG shows the highest temperatures, while TG-LW-PCM demonstrates the best insulation with the lowest internal surface temperatures. The configurations with PCM (TG-PCM and TG-LW-PCM) perform better in thermal regulation compared to their counterparts without PCM. The maximum glass temperature at maximum solar 650 W m^{-2} at 12:00 PM was observed as 30.2°C for a window triple glazing window with normal glass and PCM (TG-PCM), whereas it was only 28.3°C in a window triple glazing window with low-e glass and PCM (TG-LW-PCM).

At 12:00 PM, under high solar radiation (650 W/m^2), the inner surface temperatures of TG, TG-LW, TG-PCM, and TG-LW-PCM were 36.4, 32.4, 30.2, and 28.3°C, respectively. This reflects a decrease of 4, 6.2, and 8.1°C, respectively, compared to the TG. Additionally, the TG-LW-PCM window extended the time lag by 2 hours, shifting the peak load.

These findings suggest that the Low-E glass with PCM TG-LW-PCM is more efficient in minimizing heat gain in comparison to other windows TG, TG-LW, TG-PCM because of the heat-absorbing and heat-releasing capabilities of PCM, which help stabilize temperature variations. The effectiveness of PCM can be easily determined by observing the gradual rise and fall of the temperature curve, indicating a sluggish transition between solid and liquid phases. This behavior signifies the latent heat's absorption and release by the PCM. The decreased in peak internal surface temperature of TG-LW-PCM indicates that the Low-e coating effectively blocks a significant portion of infrared radiation, hence reducing the thermal load on the interior surfaces.

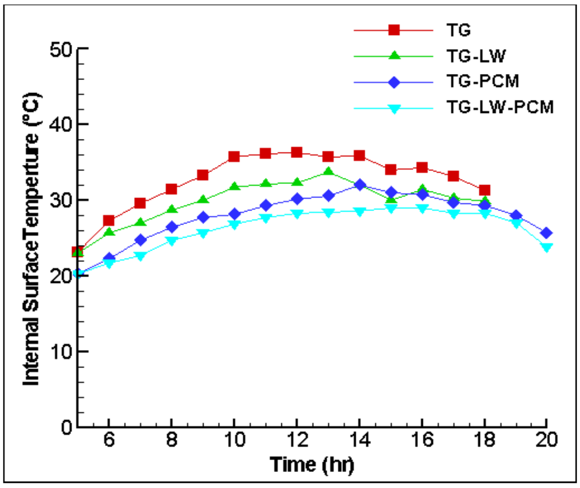

Figure 14. The internal surface's temperature variation for four TG in July 2023

3.1 Comparison with previous studies

Table 5 presents a comparison of the internal surface of this study with that of previous papers.

While this study focuses on a hot climate, the effectiveness of PCM and low-e glass varies with different environmental conditions. In colder climates, where the primary concern is retaining heat inside the building rather than preventing it from entering, PCM would function differently. Instead of storing excess heat from solar radiation, PCM in cold climates would absorb heat during the daylight and then release the heat at night to help stabilize room temperatures. Studies in colder regions have demonstrated that PCM can significantly reduce heating energy consumption by storing solar heat during daylight hours and releasing it when temperatures drop. For example, Zhang et al. [30] reported energy savings of up to 33.74% in winter when PCM and low-e glass were used together.

In moderate or temperate climates, the performance of PCM and low-e glass would be less pronounced but still beneficial. Here, the PCM's key function would be to regulate temperature fluctuations by absorbing heat on warmer days and releasing it during cooler nights. Low-e glass would continue to provide year-round benefits by reflecting infrared radiation, reducing both heating and cooling demands.

In humid tropical climates, where the combination of high temperatures and humidity creates additional challenges, PCM would help reduce cooling loads by absorbing excess heat. Nonetheless, the melting point of the PCM would need to be carefully selected to ensure it transitions effectively at the typical temperature range of these environments. The inclusion of low-e glass would still provide benefits by minimizing heat gain through infrared reflection.

Table 5. Comparison of the internal surface temperature with previous studies

Author	Experimental Work	Reduction in the Indoor Surface Peak Temperature
Present work	TG-LW, TG-PCM and TG-LW-PCM compared with standard TG	4, 6.2 and 8.1°C
Li et al. [39]	This study investigates the thermal performance of PCM in TW throughout the summer season	5.5°C compared with standard TW
Abbas et al. [40]	PCM capsules used as insulation material in hollow bricks	4.7°C compared to the wall without PCM

These comparisons show that while PCM and low-e glass are highly effective in hot, dry climates like Iraq, their application can be tailored to provide energy efficiency in a variety of climates. By selecting the appropriate PCM material and window configuration, the benefits can be extended to colder, temperate, or tropical environments.

4. CONCLUSION

This work experimentally explored the thermal performance of four triple-glazed window configurations (TG, TG-LW, TG-PCM, TG-LW-PCM) in the hot summer climate of Iraq. The using of PCM and low-e glass as insulating materials significantly improved the thermal insulation of the windows. Among the tested configurations, the TG-LW-PCM window exhibited the best performance, reducing the inner surface temperature by up to 8.1℃ compared to the standard TG window. Additionally, the TG-LW-PCM configuration increased the thermal time lag by 2 hours, delaying the load of peak heat and enhancing thermal comfort.

Key findings indicate that combining PCM and low-e glass offers superior insulation because of the PCM's ability to absorb and release heat during phase transitions and low-e glass's capacity to reflect infrared radiation, thereby reducing heat transfer. This highlights the potential for PCM and low-e glass to improve energy efficiency and thermal comfort in rooms, particularly in hot climates.

For future research, it would be valuable to explore the performance of PCM and low-e glass under different climate conditions, such as cold or humid environments, and to investigate the long-term durability of these materials. Additionally, practical applications of this research could include optimizing window designs for residential and commercial buildings in various regions to reduce energy consumption and enhance sustainability.

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NOMENCLATURE

PCM	Phase Change Materials
TG	A normal glass in triple-glazed window with air in both cavities.
TG-LW	Same TG window but the external glass is a

	low-e glass type.
TG-PCM	A triple-glazed window with normal glass, the outer gap includes PCM while the inner cavity contains air.
TG-LW-PCM	Same TG-PCM window, but the external glass is a low-e glass type.
DGU	Double-Glazing Window
TTL	Temperature Time Lag
HVAC	Heating, Ventilation, and Air Conditioning
DG	Double Glass
SG	Single Glass
NDPCM	Nano-Dispersed PCM
SiO_2	Nano Silica
DPCMW	Rotating Dynamic Phase Change Material
VO_2	Vanadium Dioxide
HISG	High-Insulation Sustainable Glass
TC	Thermochromic