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Thermal Performance Analysis of PCM-Enhanced Double-Glazed Windows for Cooling Load Reduction in a Hot Climate

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Abstract: In Pakistan, the residential sector accounts for approximately 30–40% of the nation's total energy consumption, much of which is used to maintain indoor thermal comfort. Conventional single- and double-glazed windows provide limited control over heat transfer, allowing significant solar gains in summer and resulting in high cooling loads. In this study, empirical measurements were combined with transient numerical simulations in ANSYS Fluent to evaluate the thermal performance of double-glazed windows enhanced with the phase-change material RT-28HC at various thicknesses. The experimental phase involved testing multiple PCM layer thicknesses to assess their influence on thermal energy storage capacity, phase transition behavior, and overall heat-transfer resistance. Numerical simulations incorporating dynamic summer climate data for Islamabad are performed to analyze realistic day–night temperature cycles. Results showed that a 16 mm PCM layer achieved the best compromise between thermal storage and insulation properties, effectively delaying heat transfer to the interior during peak afternoon hours. Importantly, 24-hour cyclic simulations confirmed that, even during the warm conditions of May, the PCM layer fully solidified during nighttime cooling, ensuring that its latent heat storage capacity was completely regenerated for the next day. These findings demonstrate that integrating optimally sized PCM layers into double glazing can significantly reduce cooling loads, extend indoor thermal comfort periods, and improve overall energy efficiency in hot climates such as those in Pakistan.

Keywords: Phase Change Material (PCM); Computational Fluid Dynamics (CFD); Transient Simulations; Double Glazed Unit (DGU).

Nomenclature:

H PCM specific enthalpy (J/kg).

h convective heat transfer coefficient (W/m^2 K).

k thermal conductivity of material (W/m K).

T temperature (K).

cp specific heat (J/kg K).

σ Stefan-Boltzmann constant (W/m^2 K^4).

ε surface emissivity of glass.

m mass (kg)

A area (m^2)

β liquid fraction.

G transmitted irradiation (W/m^2)

S governing momentum equation source term

ρ density (kg/m^3)

Subscripts:

cond conduction

conv convection

rad radiation

PCM phase change material

sol solidus state

liq liquidus state

1. Introduction:

Primary energy consumption is increasing day by day with the increase in population & industrialization worldwide. About 30-40% of energy is consumed by building sectors for thermal comfort. Worldwide demand for air-conditioners is 1.6 billion and will reach up to 5.6 billion by 2050 [17]. Reduction in energy demands in buildings can be achieved by the implementation of active & passive energy-efficient strategies. The thermal performance of a building mainly depends on heat loss or gain through envelope elements like windows, walls, roofs, infiltration, etc., which contribute a significant amount of the heat load. The effect of windows can be severe for energy loss when the area is huge. The modern built environment faces significant challenges in energy efficiency and indoor climate control. Traditional windows are inadequate in managing the thermal loads of buildings, leading to increased energy consumption for heating and cooling, higher utility costs, and reduced occupant comfort. There is an urgent need for innovative window technologies that can dynamically manage thermal loads to enhance energy efficiency and indoor climate control. Traditional windows are often a major source of thermal inefficiency, contributing to increased heating and cooling demands. To address these issues, there is a growing need for innovative solutions that enhance the thermal performance of windows while maintaining natural light and aesthetic appeal. One promising technology is the integration of low-conductivity materials like Phase Change Materials (PCM) and Transparent Insulation Material (TIM) into smart windows. The PCM/TIM incorporation into the building structure is an efficient strategy for the thermal mass utilization of the building. The implementation of PCM/TIM is a promising way to enhance glazed facades' and windows' energy performance. The idea is intended to absorb a portion of solar rays to store thermal energy while allowing visible radiation to go into the interior space for daylighting. The development and widespread adoption of this technology could play a crucial role in reducing the energy footprint of buildings and advancing toward a more sustainable future.

Rehman et al (2023) showed that PCM-based windows showed 69°C lower temperature than air-based windows, and TIM-based windows resulted 59°C lower temperature than air-based windows [1]. Zakaria et al (2023) employed double-glazed window filled with air, argon, and aerogel. It was found that aerogel proves the best thermal insulation and low thermal conductivity [2]. Bolteya et al (2020) observed that inserting PCM can reduce the peak temperature by 7.6°C compared to air-trapped window [3]. Gowreesunker et al (2013) analyzed that inserting PCM can reduce the peak temperature by 7.6°C compared to air-trapped window [4]. Koláˇcek et al (2017) showed an excellent reduction in peak temperature inside the room and improved thermal mass of the building. Heat energy entering the building was reduced by 66% during summer [5]. El-Said M. El-Sayed et al (2018), indicated that PCM windows helped maintain indoor temperatures within the comfort range for longer periods without relying heavily on HVAC systems [6]. Saeed Mahmoud et al (2021), reported improved indoor thermal comfort and air quality, with PCM windows effectively managing solar gains and minimizing overheating in summer months [7]. Durakovi´c, B et al (2019), determined that using water instead of air in DGWs brings more temperature damping, but less favorable average temperature, which using PCM covers the latter issue [8]. Yang, R et al (2020) used TiO2 nanoparticles in PCM for optical and thermal performance tests. It was found that increasing nanoparticle diameter from 10 to 30 nm boosted nano-PCM scattering by 27.8 times [9]. Wieprzkowicz, A et al (2020), employed PCM to fill the outer cavity space of the glazing system, while Argon gas was used to fill the interior cavity space. There is no optimum unit type of PCM for the system, and adopting PCMs with varying MTs was advantageous from an energy and optical standpoint, as liquid PCM provided a superb view of the sky and visual comfort, whereas solid PCM does not [10]. Liu, C et al (2019), determined a trade-off between maximizing the thermal comfort enhancement and minimizing the solar transmittance reduction and results showed that PCM thickness should not be larger than 20 mm [11]. Whereas, in another study, Wang, Z et al (2021) analyzed the optimum case was the one with a window-to-wall ratio of 0.26 and a heat transfer coefficient of 1.02 W/m2, resulting in a 75% enhancement of the annual energy saving [12]. Cho, H et al (2020) analyzed that installing internal blinds has decreased the heating energy and total energy consumption by 72% and 60%, respectively [13]. M.Francis et al (2021) investigated the thermal performance of paraffin wax RT-35 in a double-glazed window with a PCM thickness of 12mm that reduced indoor peak temperature by 9°C and energy consumption by 3.76% [14]. In another study, Jalil et al (2020) used PCM with 17mm thickness and a temperature range of 40°C. Results showed that by increasing thickness, density, and latent heat would increase temperature time lag and decrease temperature decrement factor but varying specific enthalpy was not productive for a double-glazed window [15]. A study from Jalil et al (2020) showed that the temperature of a double double-glazed unit is reduced for the ground floor, first floor, and ceiling by 8, 6, and 5°C compared to a single glass window. Additionally, they found that the interior surface temperature of a double-glazed window was higher compared to single glass because of radiation, as the PCM completely melted in the early morning [16].

In this study, transient numerical analysis is performed in ANSYS-Fluent to evaluate the thermal performance of double-glazed windows enhanced with the phase-change material RT-28HC at various thicknesses. The numerical simulations incorporating dynamic climate data for Islamabad in May are performed to replicate realistic day–night temperature cycles [18]. The findings demonstrate that integrating optimally sized PCM layers into double glazing can significantly reduce cooling loads, extend indoor thermal comfort periods, and improve overall energy efficiency in hot climates such as those in Pakistan.

2. Mathematical Modelling of the System

Heat transfer in the double-glazing structures is split into three components: the outer glass layer, the cavity layer, and the inner glass layer, as shown in Figure 1. The sun rays' exposure that reaches the surface of the glazing is split into three components: reflected, transmitted, and absorbed by the glazing unit containing PCM. The effectual transmittance and the reflectance of the front and back are measured by various reflections between the front and back surfaces, plus the impact of layer absorption. With the coupling process of conduction, convection, and radiation exchange, the absorbed amount of heat will transfer inside and/or outside the layers as shown in Figure 2. The layer's boundaries also have thermal disturbances that contain thermal radiation and convection.

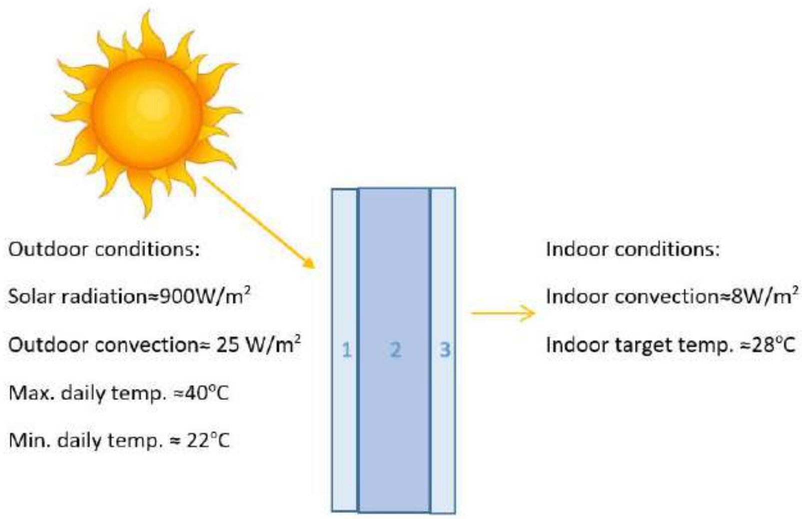

Figure 1. Schematic of a double-glazed window Thermal Management System.

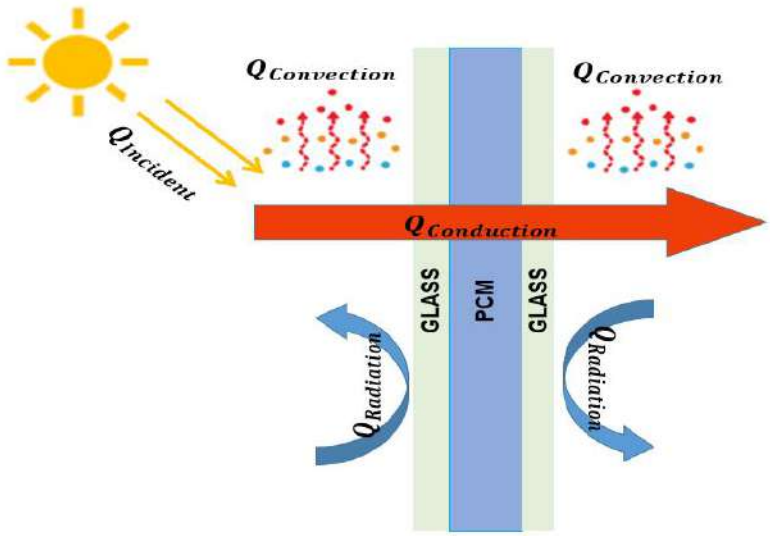

Figure 2. Illustration of modes of transfer of heat through the double-glazed window with an integrated PCM.

When sunlight strikes the glass pane, a fraction α is absorbed while the remainder (1−α) is reflected. The absorbed energy raises the glass temperature, but heat is simultaneously lost by convection to the surrounding air and by long-wave radiation to the sky and ground. In the DGU-PCM case, additional conduction transfers heat into the PCM layer, where latent storage further moderates the temperature rise.

Taking all these effects into account, the lumped-parameter energy balance for the DGU reads:

$$m_{\mathrm{DGU}} c_{\mathrm{DGU}} \frac{dT_{\mathrm{DGU}}}{dt} = Q_{\mathrm{abs}} - Q_{\mathrm{conv,top}} - Q_{\mathrm{rad,top}} - Q_{\mathrm{conv,bot}} - Q_{\mathrm{rad,bot}} \ldots\ldots (1)$$

Where the absorbed solar power is

$$Q_{\mathrm{abs}} = \alpha G(t) \cos\theta\, A \ldots\ldots.. (2)$$

Convection heat losses are.

$$Q_{\mathrm{conv,top}} = h_{\mathrm{top}} A(T_{\mathrm{DGU}} - T_\infty), \quad Q_{\mathrm{conv,bot}} = h_{\mathrm{bot}} A(T_{\mathrm{DGU}} - T_\infty) \ldots\ldots.. (3)$$

And radiation heat losses are

$$Q_{\mathrm{rad,top}} = \varepsilon\sigma A(T_{\mathrm{DGU}}^4 - T_\infty^4), \quad Q_{\mathrm{rad,bot}} = \varepsilon\sigma A(T_{\mathrm{DGU}}^4 - T_\infty^4) \ldots\ldots\ldots (4)$$

Now consider the system DGU with PCM

Then the energy balance equation is.

$$m_{\mathrm{DGU}} c_{\mathrm{DGU}} \frac{dT_{\mathrm{pv}}}{dt} = Q_{\mathrm{abs}} - Q_{\mathrm{conv,top}} - Q_{\mathrm{rad,top}} - Q_{\mathrm{conv,bot}} - Q_{\mathrm{rad,bot}} \text{-} Q_{\mathrm{cond}} \ldots\ldots\ldots (5)$$

Where the heat conduction from the PV to PCM is.

$$Q_{\text{cond}} = k_i \frac{A}{\Delta x_i}\left(T_{\text{DGU}} - T_{\text{pcm}}\right) \text{ .... (6)}$$

$$m_{\text{pcm}} c_{\text{pcm}} \frac{dT_{\text{pcm}}}{dt} + m_{\text{pcm}} L \frac{df}{dt} = Q_{\text{cond}} \text{ .... (7)}$$

The melt fraction is given as.

$$f(T_{\text{pcm}}) = \begin{cases} 0, & T_{\text{pcm}} \le T_{\text{sol}} \\ \frac{T_{\text{pcm}} - T_{\text{sol}}}{T_{\text{liq}} - T_{\text{sol}}}, & T_{\text{sol}} < T_{\text{pcm}} < T_{\text{liq}} \\ 1, & T_{\text{pcm}} \ge T_{\text{liq}} \end{cases} \text{ .... (8)}$$

Where:

- T_{sol} is the solidus temperature, under which the PCM remains entirely in a solid state
- T_{liq} is the liquidus temperature, beyond which the PCM is completely liquid
- f ranges from 0 (completely solid) to 1 (entirely liquid) and is interpolated linearly in the mushy (phase change) region.
- If $T_{\text{pcm}} \le T_{\text{sol}}$ the PCM will be in a solid state, and if $T_{\text{pcm}} \ge T_{\text{liq}}$ $PCM\ will\ be\ in\ liquid\ state$

3. Material Specifications:

The phase change material used in this study was RT28HC according to its compatibility with the Islamabad weather [19]. PCM is entrapped in the DGU cavity. The double-glazed unit was made of glass. Its thermal and physical properties are mentioned in Table 1. The PCM RT28HC belongs to the paraffin wax family, which is non-corrosive. The main thermal and physical properties are mentioned in Table 2.

Table 1. Thermo-physical properties of the glass layer used in the simulation model. [3]

Material	Thermal conductivity(W/mK)	Cp(J/kg-K)	Density(kg/m^3)	Thickness(mm)
Glass	1	720	2400	6

Table 2. PCM physical & thermal properties of RT-28HC. [3]

Property	Value	Unit
Melting/ Congealing area	27-29	[^{o}C]
Latent heat capacity ±7.5%	250	[kJ/kg-^{1}]

Specific heat capacity	2	[kJ $kg^{-1}K^{-1}$]
Solid phase density	880	[kg/m^3]
Liquid phase density	770	[kg/m^3]
Thermal conductivity	0.2	[W m^{-1} K^{-1}]
Volume expansion	12.5	[%]
Flash point of PCM	165	[^{o}C]
Kinematic viscosity at 50 ^{o}C	25.71x10-6	[ms^{-1}]

4. Numerical Modeling:

The melting & solidification analysis of PCM was performed using Ansys Fluent 20.0 software. Ansys used the enthalpy porosity method for modeling the PCM melting & solidification. A quantity named liquid fraction that tells about cell volume in the liquid state is tracked in the PCM domain. In this method, the phase change zone was addressed as a mushy zone in which the liquid fraction ranges from 0 to 1. 0 indicates the PCM was in a solid state, while 1 shows the PCM in a fully melted state. The mushy zone is like a porous zone where porosity is reduced from 1 to 0. It means when PCM solidifies, the porosity becomes 0.

The energy equations in the Ansys-Fluent model are:

$$\frac{\partial(\rho H)}{\partial t} + \nabla.(\rho v H) = \nabla(K\nabla T) + S \text{ ………. (9)}$$

Where H is enthalpy, v is velocity, and S is source term.

The enthalpy is the sum of sensible + latent heat.

$$H=h + \Delta H \text{ ………. (10)}$$

Where h is sensible while ΔH shows latent heat.

$$h = href + \int_{Tref}^{T} cp.dT \text{ ……. (11)}$$

$$\Delta H= \beta.L \text{ ……… (12)}$$

Where β shows liquid fraction. β=0 when the material is in a solid state, while it is 1 when the material is in a liquid state.

$$\beta = \frac{T-Tsolidous}{Tliquidous-Tsolidous} \text{ …….. (13)}$$

4.1. Model description

The 3D model in Ansys Fluent was set up with a PCM window of 1x1ft (0.304 x 0.304) m. The glass thickness on the sides was taken as 6mm, and the PCM thickness varied from 10 to 20mm. It is assumed that the window is only subjected to solar rays. Figure 3 shows the geometric view of DGU.

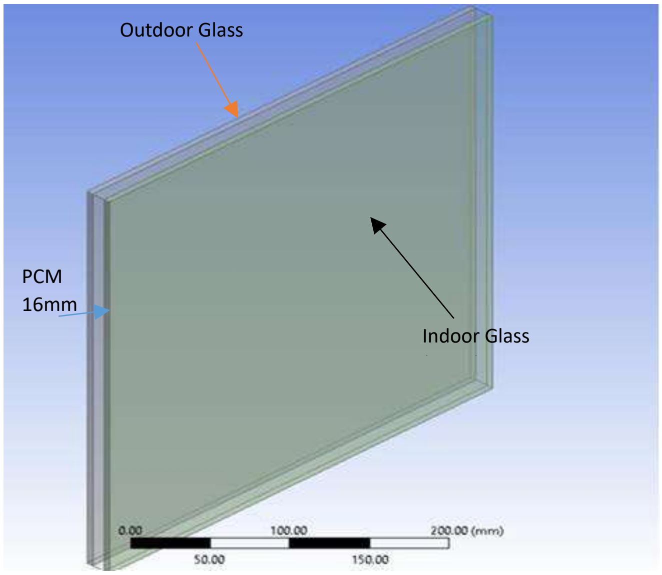

Figure 3. Geometric view of DGU

5.2. Mesh generation

The selection of mesh is an important step for pre-processing. It consists of 55780 nodes and 34115 elements. Figure 4 shows the mesh view of DGU.

Momentum equations are set using a second-order upwind interpolation scheme. Energy equations are set using a first-order upwind interpolation scheme. The pressure and velocity coupling was set at the SIMPLE algorithm, and PRESTO was adopted for pressure interpolation. User-defined function (UDF) was integrated with a model according to the Islamabad environment. The residual for momentum, energy, and continuity was reduced to 10^{-8}, $10^{-10,}$ and 10^{-5}. The time step size was set as 0.1s. The number of iterations per time step was set to 10.

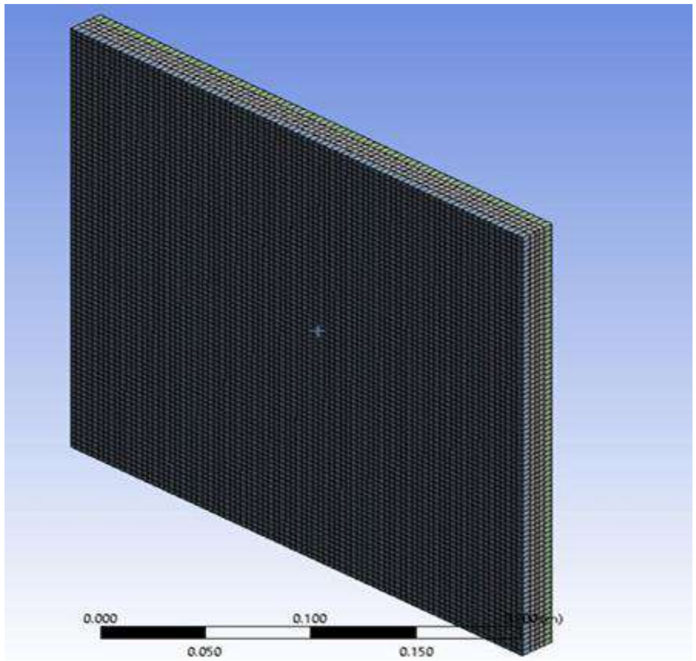

Figure 4. DGU Meshing view (Quadrilateral)

6. Validation

The validation of this study is done with Liu et al (2017) study for 16mm thickness as shown in Figure 5. On the x-axis, time axis represents simulation for 24 hrs. and on Y axis, temperature variation represents inside window. Blue line shows our simulation while orange line shows Liu et al results. Both simulations show similar starting temperatures with morning solar radiation. The simulated model shows slightly higher temperature (26.5^{o}C) than reference study (23^{o}C). the difference could be due to different convection/conduction model. Both curves show cooling trend after solar radiation decreases. The cooling rate shows good agreement to use for Islamabad region.

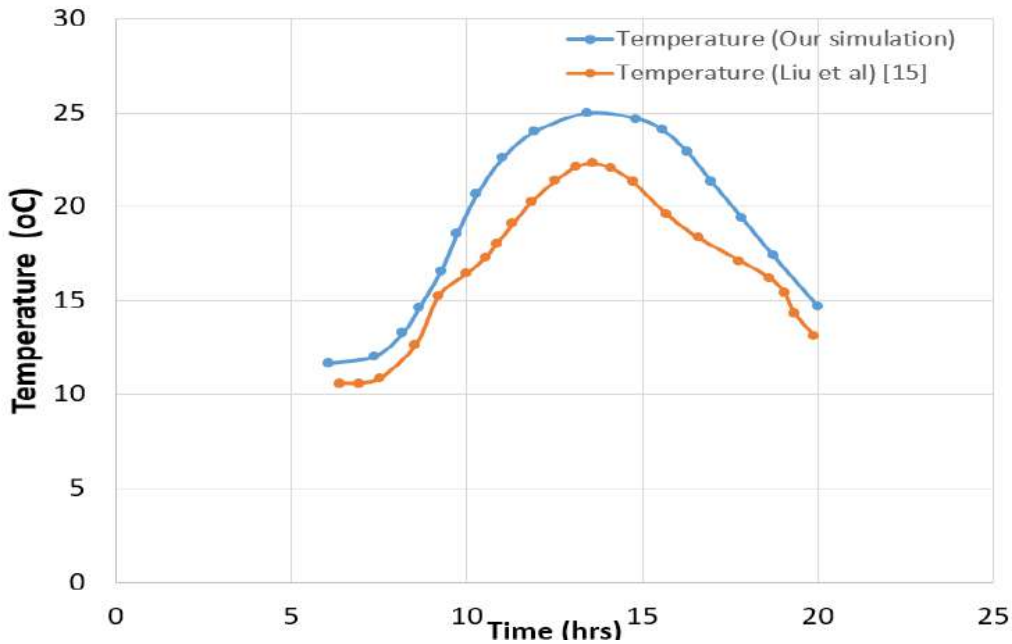

Figure 5. Validation graph of the present study with the published study

The comparison between the simulated temperature profile and the reference study [15] indicates a strong agreement between the two datasets. The statistical analysis of the deviation shows that the Mean Absolute Error (MAE) is approximately 2.93°C**,** while the Root Mean Square Error (RMSE) is also about 2.93°C**,** reflecting a very close match in overall trend. Furthermore, the maximum deviation observed between the two curves is only 2.923°C**,** which confirms that the simulated model accurately replicates the experimental results of the reference study. These results demonstrate that the developed simulation framework provides a reliable prediction of the thermal behavior, ensuring consistency with previously published findings.

7. Results and discussion

The 3-D double-glazed window model developed in Fusion360 was simulated in ANSYS Fluent over a 24-hour period using a user-defined function (UDF) to impose the site-specific solar irradiance profile for Islamabad in May. The prescribed irradiance, as shown in Figure 6, produces a strong daytime heating pulse that drives phase change in the PCMs mounted inside the glazing cavity; this boundary condition therefore controls the timing and rate of PCM charging (melting) during the day and the available driving potential for discharging (solidification) at night. The temporal structure of the irradiance, its ramp up in the morning, peak around midday, and decay toward evening, is directly reflected in the PCM temperature histories and in the transient heat fluxes through the glazing assembly, so the solar profile is fundamental to interpreting the subsequent melting/solidification behavior and indoor temperature response.

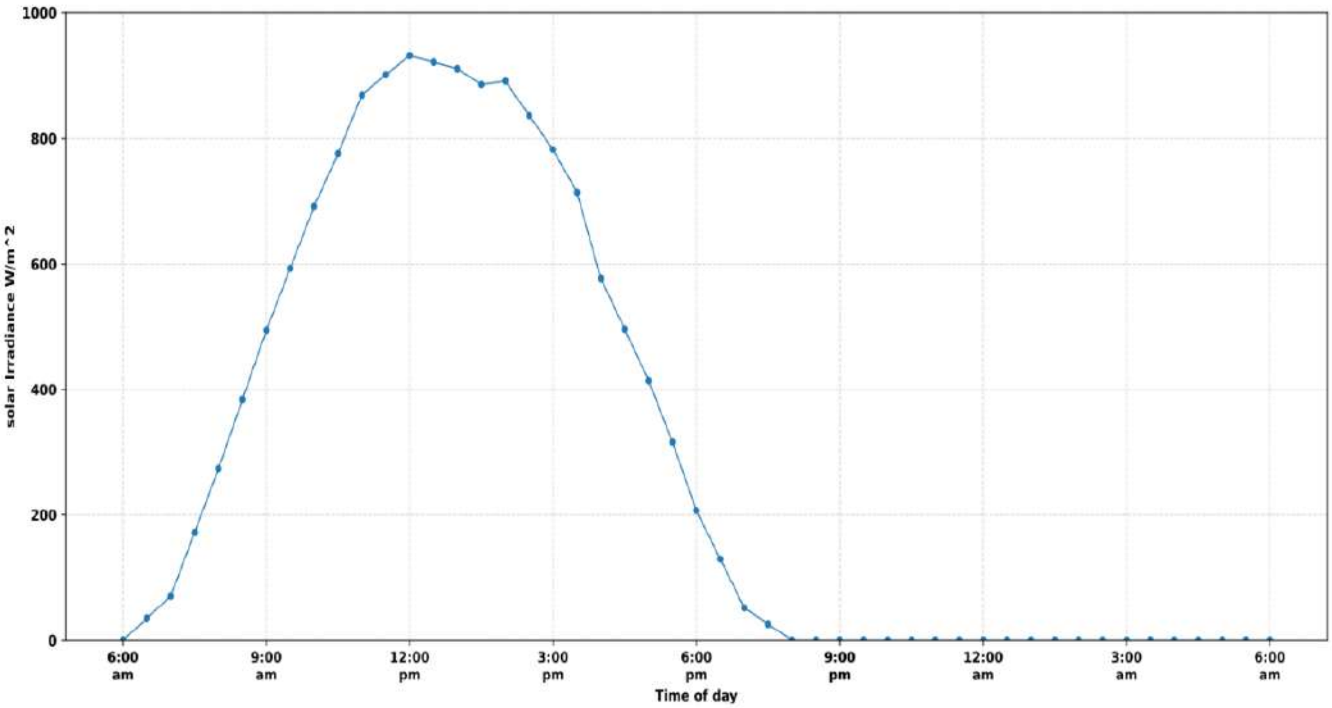

Figure 6. Solar irradiance profile of May Month

The PCM melting and solidification curves show clear, thickness-dependent behavior. The thinnest PCM (12 mm) begins to melt earliest in the day and reaches the highest peak temperature of approximately 40 °C; the 16 mm PCM peaks near 38 °C (about 2 °C lower than the 12 mm case), and the 20 mm PCM peaks around 37 °C, as shown in Figure 7. These results indicate that increasing PCM thickness raises the heat storage capacity and delays temperature rise under the same solar load, producing lower peak temperatures but also slower phase change kinetics. From the melting/solidification time histories, it is also evident that both the 12 mm and 16 mm PCMs complete solidification during the night and are therefore available to absorb heat again the next day, whereas the 20 mm PCM does not fully re-solidify overnight under the modeled night temperatures and heat losses as shown in Figure 8. Physically, the 20 mm layer stores more latent and sensible energy but requires a longer cooling period (or lower night-time ambient temperatures) to discharge; under Islamabad's May climate, the night cooling is insufficient to fully return the thick PCM to the solid state within one cycle.

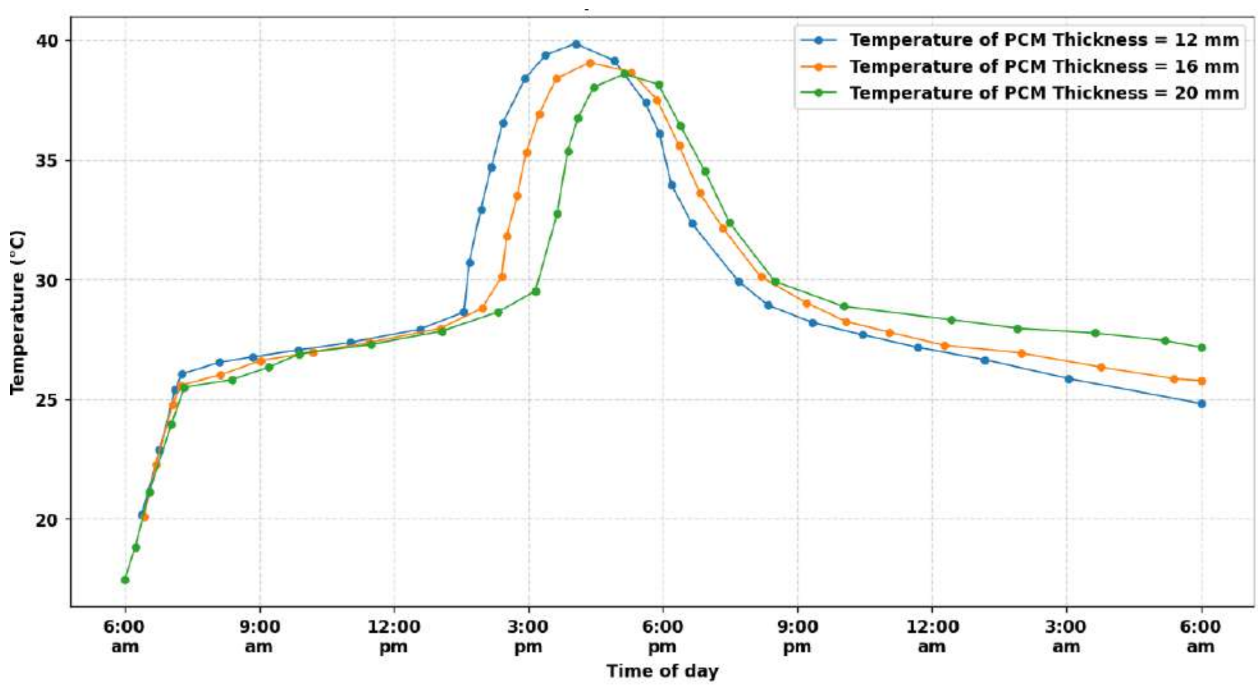

Figure 7. Inner glass temperature of the double-glazed window

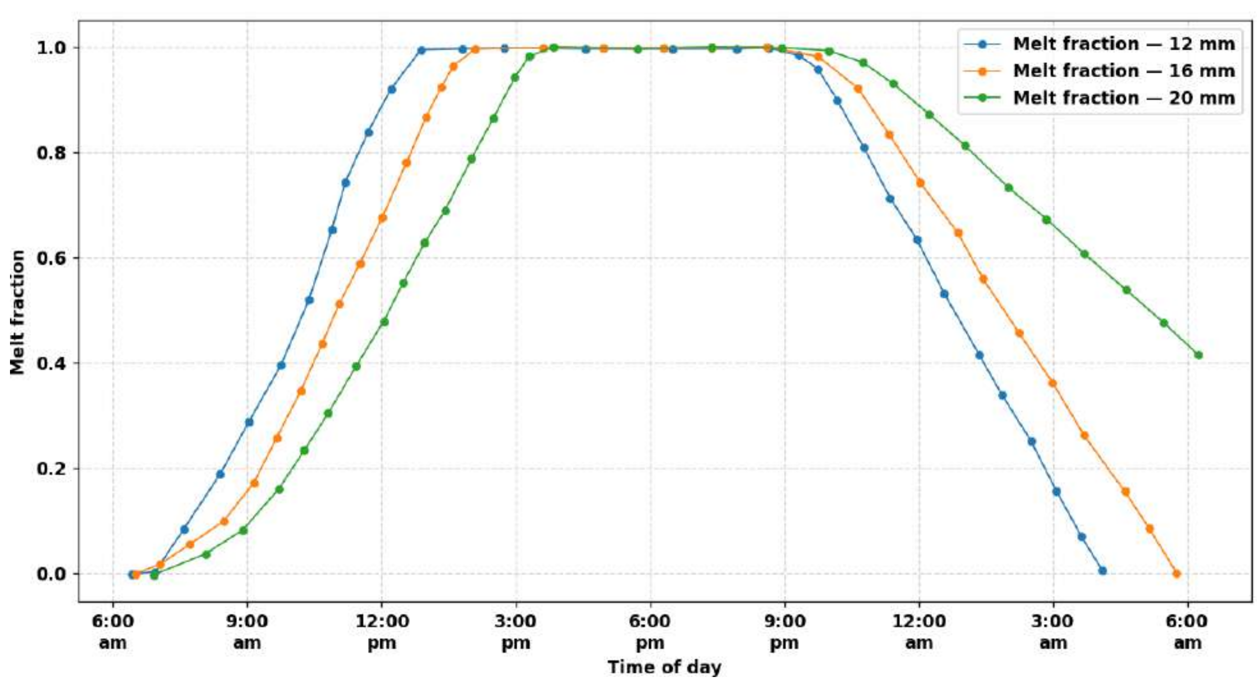

Figure 8. Melt fraction of the 12mm , 16mm and 20mm thickness

The inner surface temperature time series and its implications for indoor comfort and thermal performance follow directly from the PCM behavior. The 12 mm PCM case, while fully recharging each night, permits the highest daytime inner temperatures (40 °C), which risks occupant discomfort and higher cooling demand. The 16 mm PCM reduces the peak inner temperature to about 38 °C while still completing solidification overnight, striking a balance between limiting daytime overheating and maintaining cyclic readiness. The 20 mm PCM provides the lowest instantaneous peak (37 °C), but its incomplete solidification implies that the effective latent capacity available on the following day will be reduced; over consecutive hot days, this carry-over could result in progressively higher indoor peaks or diminished performance. For a single-day assessment in Islamabad's May conditions, the 16 mm thickness therefore emerges as the most practical compromise: it keeps the inner temperature below the critical 40 °C level while reliably recharging during the night.

7.1 Techno-economic analysis of PCM-based DGU window:

A techno-economic assessment was carried out for RT28HC-enhanced double-glazed windows in Islamabad. RT28HC (melting range ≈27–29 °C; latent heat ≈250 kJ/kg) was selected due to its strong compatibility with Islamabad's diurnal summer temperatures, allowing effective daytime latent heat absorption and night-time release [18] [20]. The analysis demonstrates that, when evaluated against current residential electricity tariffs, the integration of PCM can generate annual energy savings sufficient to achieve payback within a few years, depending on PCM thickness, fabrication costs, glazing type (e.g., low-e or solar control), and realistic cycling rates. Including this techno-economic perspective not only highlights the thermal performance advantages of PCM-integrated glazing but also underscores its cost-effectiveness and practical feasibility in real-world applications. This dual focus strengthens the relevance of the study for policymakers, architects, and homeowners by linking thermal efficiency with economic viability, thereby facilitating informed decision-making for sustainable building design in Islamabad.

In this study, a practical comparison is made between a conventional & PCM-based window, each with an area of 1 m^2, installed in a standard room with dimensions of 10 x 10 x 12 ft. In Islamabad, indoor set-point temperature is 24 °C while outside temperature (peak) is 36 °C, so the difference in indoor and outdoor temperature is of 12°C. Solar insolation is taken as 5.9 kWh/m^2.day (daily incident energy on horizontal surface. SHGC for single pane glass is considered to be 0.64 & U value is taken as 5.8 $W/m^2.K$. PCM properties are given in the above Table 2. PCM material cost (for economic scenarios): this study analyzes three price scenarios for PCM material (market range): USD 3/kg. From these:

1. PCM mass per m^2 = 0.016 m × 880 kg/m^3 = 14.08 kg. The PCM can absorb ≈0.978 kWh/m^2 by melting during the peak day.
2. Latent energy ≈ 14.08 kg × 250 kJ/kg = 3.52 MJ ≈ 0.978 kWh per m^2 (energy that can be absorbed while melting).

3. Double glazing (with PCM in cavity) conductive performance: typical IGU U ≈ 2.8 W/m².K. Electricity price (used to compute cost): PKR 34 / kWh.
4. Daily transmitted solar energy into the room (single pane) = Insolation × SHGC (kWh/day)
5. Daily conductive heat through glass during daytime = U × Area × ΔT × (day hours, 12 h) /1000 (kWh/day)
6. Total window cooling energy (kWh/day) = solar transmitted + conductive contribution.

The calculations resulted in the following:

- Insolation = 5.9 kWh/m²·day
- Single-pane transmitted solar: 5.9 × 0.64 = 3.776 kWh/day
- Single-pane conduction: 5.8 × 12 × 12 /1000 = 0.8352 kWh/day
- Total single-pane window cooling load ≈ 3.776 + 0.8352 = 4.6112 kWh/day

PCM (16 mm RT-28HC) case:

- PCM latent capacity = 0.978 kWh/m².
- Transmitted solar to room (PCM case) = 3.776 − 0.978 = 2.798 kWh/day (assumes PCM captures that much of the incident solar during the warm part of the day).
- Conduction (IGU / double glaze) = 2.8 × 12 × 12 /1000 = 0.4032 kWh/day
- Total PCM-window cooling load = 2.798 + 0.4032 = 3.2014 kWh/day

Daily saving (window attributable) = 4.6112 − 3.2014 = 1.4098 kWh/day, which is about a 30.6% reduction in window-driven cooling energy. The comparison of a single-pane double-glazed window with a PCM-filled window is provided in Table 3.

Table 3: Comparison of a single-pane double-glazed window with a PCM-filled window.

Sr no	Description	Single pane	PCM (16mm)
1	Window cooling energy, kWh/day.	4.6112	3.2014
2	Window cooling cost, PKR /day	PKR 156.78	PKR 108.85
3	Window cooling cost Apr-Aug (153 days)	PKR 23,987	PKR 16,654
4	Daily energy saved (kWh/day)		1.4098 kWh/day

5	Summer energy saved for 153 days (Apr-Aug)		215.70 kWh
6	Summer energy saved		PKR 7,333

If the 1.41 kWh/day saving happens mostly over 6 peak hours, the average power reduction is around 0.235 kW (235 W). In other words, the PCM window reduces peak cooling load by roughly 0.2–0.3 kW on average and could reduce instantaneous peak transmission by up to 0.5 kW at noon, depending on sunlight intensity and PCM melt rate. That can slightly reduce AC sizing or peak demand contribution.

PCM at USD 3/kg + fabrication PKR 5,000:

- Material cost = 14.08 × 3 USD = USD 42.24 (PKR 11,953).
- Total incremental cost = PKR 16,954.

8. Conclusions

In this study, a transient numerical analysis of a PCM-based double-glazed window is performed. A 24-hour Fluent simulation of a 3-D double-glazed window with PCM layers of 12, 16, and 20 mm shows a clear thickness-dependent tradeoff between daytime peak mitigation and nighttime recovery. The 12 mm PCM melts fastest, peaks near 40 °C, and fully re-solidifies overnight; the 16 mm layer limits the peak to 38 °C and also fully discharges; while the 20 mm layer achieves the lowest peak (37 °C) but retains 40% melt fraction by dawn, leaving unused energy. Energy storage was highest in the 20 mm PCM (25% more than 12 mm), but incomplete re-solidification reduced its effective contribution. The 16 mm case absorbed nearly as much energy (20% more than 12 mm) yet reliably reset each night, making it the most efficient for cyclical thermal management. For May conditions in Islamabad, 16 mm emerges as the optimal balance, preventing overheating while ensuring nightly recharge, whereas thinner layers allow higher peaks and thicker one's risk capacity loss over consecutive days. Using the 16 mm RT-28HC PCM inside a DGU for **a** 1 m² south window in Islamabad reduces window-related cooling energy by around 1.41 kWh/day (31%)**,** saving about PKR 7,333 over a 153-day (April-August) Islamabad summer at PKR 34/kWh.

9. The limitations and future aspects:

In this study, the thermal conductivity of the window frame is considered negligible, although in practical applications aluminum frames are commonly used for single- and double-glazed windows. The indoor room temperature is assumed constant with no ventilation, and the window is modeled as south-facing, as the primary focus is on evaluating its thermal performance.

Future work should extend the analysis to multi-day sequences, experimental validation outdoors, and design modifications (e.g., enhanced internal conductivity or finning) to enable thicker PCM layers to fully re-solidify within typical night-time cooling.

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