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Investigating Energy-Saving Strategies: A Numerical Study of Translucent Insulation and Phase Change Materials in Windows †

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Abstract: In Pakistan, residential energy consumption is predominantly devoted to ensuring thermal comfort, making energy reduction a significant task in building load management. Windows, which are notorious for having poor thermal barriers, contribute considerably to energy losses under harsh weather conditions. Incorporating high thermal inertia materials in windows, such as transparent insulation materials (TIM) and phase change materials (PCM), offers the potential for energy reduction. Using numerical simulations in ANSYS Fluent, this study compares three window types and explores their influence on interior temperature. The findings show that PCM-based windows have a low temperature increase during the melting phase, indicating their great energy-saving potential. Furthermore, PCM absorbs almost 90% of exposed heat, emphasizing its usefulness for energy saving in the Pakistani building industry.

Keywords: PCM; TIM; energy; buildings; fluent; numerical simulation

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1. Introduction

Growing worldwide worries about energy consumption, CO_2 emissions, the effects of climate change, and energy crises have generated a critical need for efficient energy reduction methods in both developed and developing countries. The construction industry stands out as a key contributor to the spectrum of energy-consuming industries, owing to the large energy needs associated with heating and cooling requirements [1]. As a result, it is critical to investigate novel techniques that might handle these energy concerns comprehensively and lead to more sustainable construction practices.

The use of phase change materials (PCMs) in the building envelope is one possible path for improving energy efficiency and lowering dependency on traditional energy sources. PCMs have an extraordinary capacity to absorb and release significant quantities of thermal energy during phase transitions such as melting and solidification while maintaining essentially constant temperatures [2–6]. Buildings can benefit from utilizing the latent heat capabilities of PCMs in a variety of ways, including greater thermal comfort, improved energy performance, lower energy consumption, and a reduction in peak temperature loads.

Traditional coated windows, which have long been used in building construction, have drawbacks such as high total heat transfer coefficients and insufficient thermal insulation [7]. As a result, researchers have concentrated on developing alternative approaches to overcome these flaws and optimize the thermal properties of glazed windows. Various solutions, such as the use of laminated glass, multilayered glass, evacuated glass, intelligent glass, and the insertion of elements, such as gases, aerogels, and phase change materials within window cavities, have been examined [8–13]. Filling the spaces between windowpanes with PCM has emerged as a particularly promising option for improving the thermal efficiency of glazed windows among these approaches. Solar thermal energy may be successfully captured during the day and gradually released at night by using PCM, such as high thermal storage density paraffin wax, effectively managing interior temperature conditions.

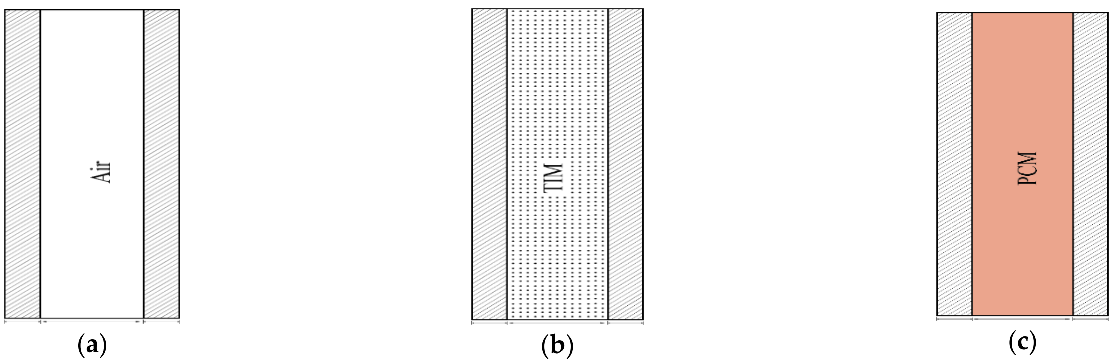
In the context of Pakistan's climatic conditions, especially in Islamabad, this study focuses on rigorous numerical simulations using ANSYS Fluent to investigate the possible advantages and energy-saving implications of adding PCM to double-glazed windows. We intend to assess the usefulness of PCM integration in minimizing excessive heat absorption via windows by analyzing the performance of various window layouts. Previous research in comparable fields has shown that numerical simulations and experimental findings match well, providing confidence in the use of numerical models in analyzing the performance of PCM-based systems [14].

This study addresses two key issues: Firstly, most research on phase change materials and energy-efficient windows has focused on climates outside of Pakistan. Secondly, there is limited knowledge of the energy-saving potential of different passive window variants in Pakistan's climate conditions. Therefore, this study investigates various passive window options specifically for Pakistan's climate, utilizing numerical analysis to assess their energy-saving capabilities. The establishment of a numerical model facilitates further exploration for future research.

2. Model Description

This research study delves into the intricate process of heat transfer through windows, focusing on the utilization of Phase Change Materials (PCM) and Translucent Insulation Materials (TIM). The objective is to compare and analyze the thermal behavior of three distinct types of double-glazing windows.

Solar radiation takes center stage as the primary driver of heat transfer, with conduction and convection playing secondary roles. The window prototypes shown in Figure 1 comprise a 5 mm thick glass layer, accompanied by an air gap, TIM, and PCM. Notably, the PCM utilized in this study is RT25 paraffin wax, chosen for its exceptional thermal properties, while the TIM employed is silica aerogel, renowned for its translucent insulation capabilities.



(a) (b) (c)

Figure 1. Schematic of (**a**) air-based, (**b**) TIM-based, and (**c**) PCM-based windows.

The model incorporates the thermophysical properties of the materials involved, including RT25 PCM and silica aerogel TIM. These properties are essential for accurately simulating the heat transfer characteristics and assessing the thermal performance of the windows as given in Table 1.

Table 1. Thermo-physical properties of RT25 and TIM.

Parameters	PCM RT25	TIM
Solidus Temperature	27 °C	-
Liquidus Temperature	29 °C	-
Latent Heat of Fusion	230 KJ/Kg	-
Specific Heat Capacity	2 KJ/Kg.K	1500
Density Liquid	0.77 Kg/L	-
Density Solid	0.88 Kg/L	0.1 Kg/L
Thermal Conductivity	0.2 W/m.K	0.018 W/m.K

3. Governing Equations and Model Validations

The Fluent software (ANSYS 2022) is used for simulating the melting process within the enclosure. The enthalpy–porosity approach is employed, calculating the melt fraction instead of tracking the melt interface. Assumptions include laminar and transient PCM melting flow, constant thermophysical properties, except for density variations with temperature, and the utilization of Boussinesq approximations for handling density changes during natural convection. In this numerical simulation, the continuity and energy equations are provided as follows:

$$\frac{\partial}{\partial x_i}(\rho u_i) = 0, \tag{1}$$

$$\frac{\partial(\rho H)}{\partial t} + \nabla.\left(\rho \vec{V} H\right) = \nabla.(k \nabla T) + S, \tag{2}$$

where ρ is the density of PCM, $\vec{V}$ is the velocity of the fluid, and S is the heat generated within PCM, which will be zero. k is the thermal conductivity of PCM and H is the total enthalpy of the system given by (Equation (3)):

$$H = h + \Delta H, \tag{3}$$

The numerical model was initially validated by solving and comparing the same problem as reported by Ravindra D. Jilte et al. [15]. The results of the present model demonstrated strong agreement with Ravindra D. Jilte et al. [15] shown in in Figure 2 with variations of less than 5%. This validation confirms the reliability of the present model in terms of formulation and grid independence. Subsequently, the validated model was utilized for additional simulations.

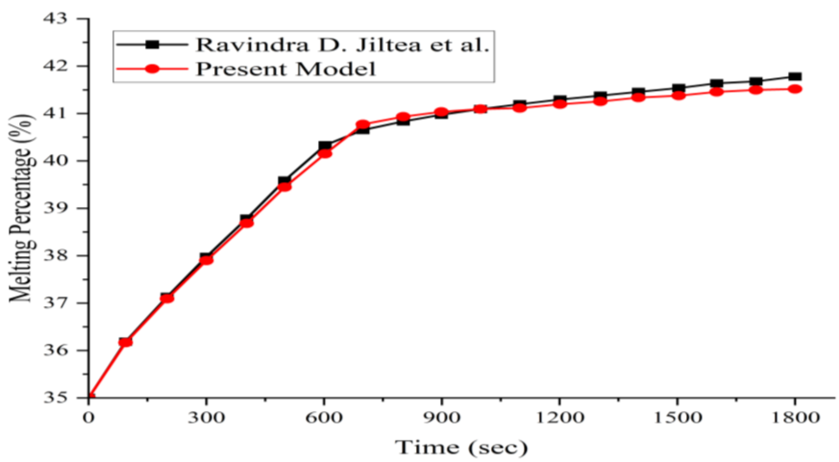


Figure 2. Validation of numerical model [15].

4. Results and Discussions

The numerical results from this study reveal important insights into the performance of different window types in controlling room temperature. With a peak ambient temperature of 45 °C in Islamabad, the desired room temperature was set at 26 °C, which led to the selection of a suitable phase change material (PCM).

Using ANSYS Fluent, the PCM's solidification and melting behavior were simulated under transient conditions. A constant heat flux of 900 W/m^2 was applied to the windows' outer glass surface. The simulations demonstrated the PCM's ability to absorb and store heat, regulating room temperature by capturing excess heat from the environment.

Comparing different window types, the PCM-based window exhibited the lowest heat flow as shown in Figure 3c, 98% lower than the air-based window. The heat flow remained constant over time for the PCM-based window, while it increased for the air-based and translucent insulation material (TIM)-based windows. After 5400 s, the TIM-based window's heat flow was 31.51% lower than the air-based window, indicating the TIM's role in reducing heat transfer.

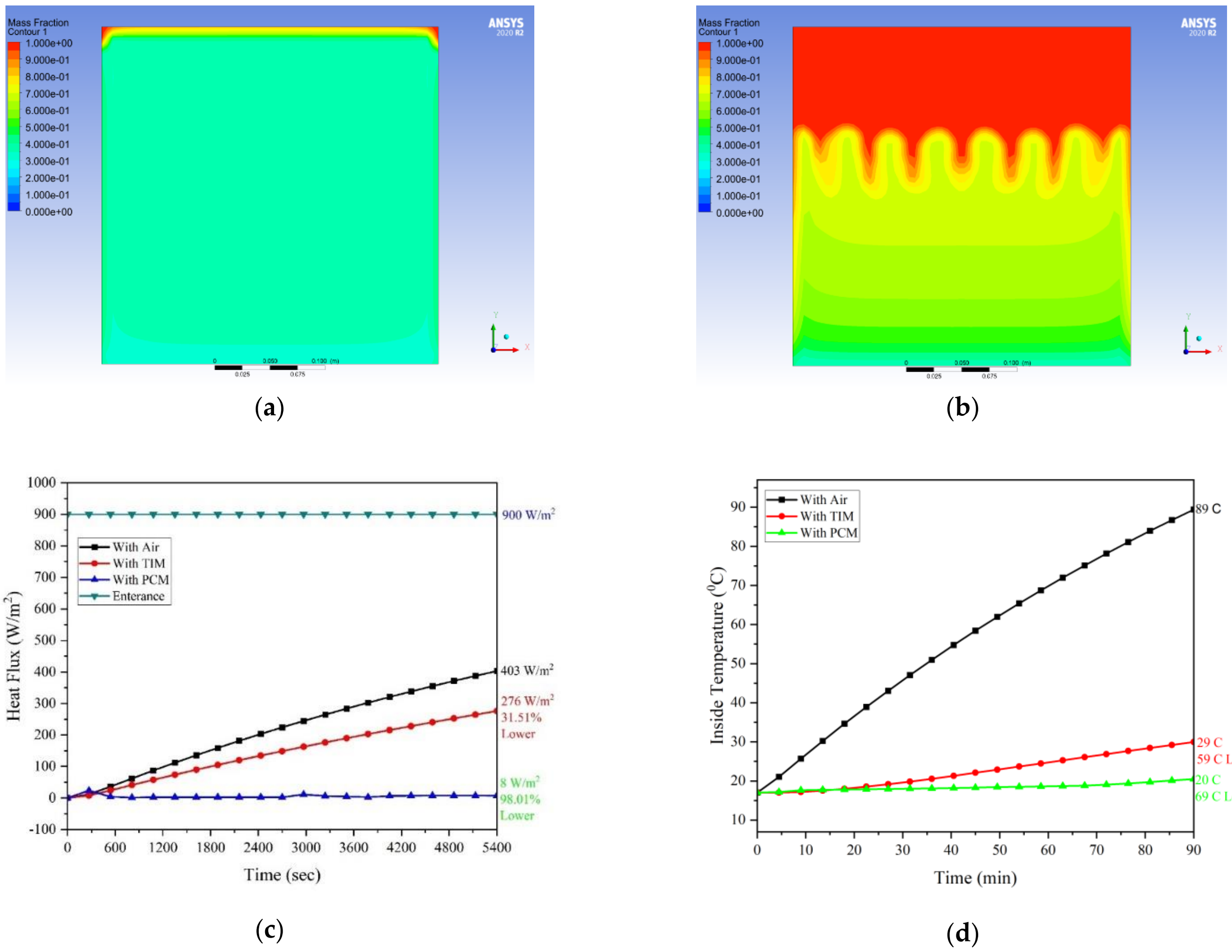


Figure 3. (**a**) Melting contour at 500 s, (**b**) melting contour at 1500 s, (**c**) comparison of heat flux, and (**d**) comparison of indoor temperature.

Regarding indoor temperatures, the PCM-based window maintained the lowest temperature shown in Figure 3d, 69 °C lower than the air-based window. The PCM-based window's indoor temperature remained relatively constant, while it rose rapidly for the air-based window and at a slower rate for the TIM-based window. The TIM-based window showed an indoor temperature 59 °C lower than the air-based window, demonstrating its effectiveness in reducing heat transfer. Additionally, there was a 10 °C temperature difference between the TIM-based and PCM-based windows, highlighting the PCM-based window's superior ability to block solar radiation.

Overall, these findings underscore the significance of window type selection in controlling indoor temperature. The PCM-based window proved to be the most efficient solution, offering potential benefits for energy efficiency and thermal comfort in buildings.

5. Conclusions

This study provides valuable insights into the heat transfer characteristics and performance of different window types in controlling the thermal conditions within a room. By carefully selecting a suitable phase change material (PCM) and employing numerical simulations using the pressure-based solver in ANSYS Fluent, we were able to investigate the solidification and melting behavior of the PCM and analyze its impact on heat transfer.

The results demonstrate that the PCM-based window exhibits the lowest heat flow among the three window types studied. With a reduction of 98% compared to the air-based window, the PCM-based window effectively absorbs and stores heat during the melting process, preventing the majority of it from entering the room. Only a small amount of 8 W/m^2 of heat is transferred to the room, resulting in improved thermal insulation.

Furthermore, the PCM-based window demonstrates temperature stability, maintaining a relatively constant indoor temperature. In contrast, the air-based window experiences a rapid temperature rise, while the TIM-based window shows a slower temperature increase. The TIM-based window also provides a notable temperature reduction of 59 °C compared to the air-based window, indicating the effectiveness of thermal interface materials in reducing heat transfer.

The observed temperature difference of 10 °C between the TIM-based window and the PCM-based window highlights the superior ability of the PCM-based window to block solar radiation. This finding underscores the potential energy efficiency benefits associated with PCM-based windows.

Overall, the findings of this study emphasize the significant impact that different window types have on indoor temperature control. The PCM-based window emerges as a highly effective solution for maintaining lower indoor temperatures and minimizing heat transfer from the external environment. These results contribute to our understanding of energy-efficient building design and highlight the potential advantages of incorporating PCM-based windows in real-world applications.

Future research could further investigate the long-term performance and durability of PCM-based windows, as well as explore the potential for optimizing PCM properties to enhance their heat transfer characteristics. Such advancements would contribute to the development of sustainable and energy-efficient building solutions.

Author Contributions: All authors contributed significantly to the conception, design, and implementation of this research study. U.u.R. played a key role in the conceptualization of the study, conducted the numerical simulations using ANSYS Fluent, and analyzed and interpreted the simulation results. U.M. and M.u.H.A. assisted in the design of the study, conducted literature reviews, contributed to the development of the numerical model, and analyzed the heat transfer dynamics and performance of different window types. M.A.R. provided expertise on the selection and properties of the phase change material (PCM), contributed to the interpretation of the results, and participated in discussions on thermal behavior and indoor temperature control. M.A. and W.J. contributed to the research design, reviewed the methodology and data analysis, and provided guidance throughout the study. This research represents a collaborative effort that draws upon the expertise and insights of all authors. All authors have read and agreed to the published version of the manuscript.

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