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# Enhancing Building Envelopes by Looking into the Energy-Saving Methods: A Computational Analysis of Windows' Phase Change Materials and Translucent Insulation

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***Abstract*—Energy reduction is a crucial problem in building load management in Pakistan since residential energy use is mostly focused on providing thermal comfort. Under severe weather, windows, which are infamous for having weak thermal barriers, significantly increase energy losses. Phase change materials (PCM) and transparent insulation materials (TIM), which have high thermal inertia, might potentially reduce energy consumption when used in windows. In this work, three different window designs are compared and examined, and their impact on interior temperature is evaluated using ANSYS Fluent numerical simulations. The study's conclusions highlight the fact that PCM-based windows show very little temperature change during melting, highlighting their significant potential to reduce energy use. Moreover, PCM efficiently absorbs over 90% of incident heat, highlighting its importance in advancing energy efficiency in Pakistan's building industry.**

**Keywords—Load management, energy saving, ANSYS fluent, numerical simulation, TIM, PCM, Building envelope.**

## I. INTRODUCTION

Buildings consume about 40% of the overall energy consumption. Most of the energy consumption is because of heating and cooling loads. Due to this reason, there is an increase in carbon emissions which affects the environment and causes global warming. Active heating and cooling result in a greater amount of energy consumption. With the help of Passive Cooling techniques, we can reduce energy consumption due to heating and cooling loads. The design and analysis of energy-efficient buildings is a challenging problem and various studies are carried out to solve this problem. The NZEBs objectives have raised the bar for building construction standards and various studies are being performed to modify existing building designs as well as construction materials. The primary focus of NZWBs is to reduce overall building energy consumption. The need for effective energy reduction techniques is urgently needed in both wealthy and emerging nations because of growing global concerns about energy consumption, CO2 emissions, the consequences of climate change, and energy crises. Due to the substantial energy requirements connected with heating and cooling demands, the building sector stands out as a significant contributor to the range of energy-consuming businesses [1, 2]. Investigating cutting-edge methods that might fully address these energy issues and result in more environmentally friendly construction methods is therefore crucial.

[3] carried out a review study on Net Zero Energy Efficient Buildings (NZEBs) and discussed various materials to enhance the thermal performance of buildings. The advantages of NZEBs were considered. Studies were conducted on the consequences of NZEBs on the environment and their involvement in the energy crisis. It was determined that by using renewable energy sources like solar, wind, etc. to provide thermal comfort, NZEBs can lower carbon emissions and the energy problem.

Another study [4], discussed the worldwide activities and devolvement trends of NZEBs and policies implemented to assist in the implementation of NZEBs ideas. The study covered the implementation of solar space heating, solar space cooling, renewable source space heating as well as power production through renewable sources which leads to meeting the criterion of NZEBs [5]. A comprehensive study of tools and techniques required for energy balance analysis (EBA) was carried out which explained the use of TRNSYS, ATHENA, ANSYS Fluent, and Design Builder. This study defined a pathway for future research in the implementation of NZEBs. Furthermore, a new idea of implementation of intelligent building is also under consideration to meet NZEBs standards.

The role of phase change materials (PCMs) in reducing the thermal load of buildings was first studied in the early 1970s. [6] proposed the idea of using PCM's heat of fusion as a form of thermal storage medium for heating and cooling buildings. The application of PCMs in buildings as thermal storage units has been under study for decades. The most common practice is the incorporation of PCMs in building envelopes as thermal storage units. The primary aim of previous studies as well as this is to find a suitable PCM to reduce building heating and cooling load for different climate conditions.

Phase change materials (PCMs) can be used in the building envelope to increase energy efficiency and decrease dependency on traditional energy sources. PCMs have remarkable thermal energy-absorbing and -releasing capabilities during phase transitions such as melting and solidification, all while preserving almost constant temperatures [7-12]. Using PCMs' latent heat capabilities can benefit buildings in several ways, including better thermal comfort, lower peak temperature loads, increased energy efficiency, and lower energy usage.

Poor thermal insulation and high total heat transfer coefficients are two issues with conventional coated windows, which have been utilized in building construction for a long time [13, 14]. Researchers have thus focused on creating other strategies to get around these shortcomings and enhance the thermal qualities of glazed windows. Many solutions have been investigated [15, 16], including the use of laminated glass, multilayered glass, evacuated glass, intelligent glass, and the introduction of components like gases, aerogels, and phase transition materials. Among these methods, filling the gaps between windowpanes with PCM has emerged as a particularly promising choice for enhancing the thermal performance of glazed windows. With the use of phase change materials, it is possible to successfully absorb solar thermal energy during the day and release it gradually at night.

This research examines the possible advantages and energy-saving implications of adding PCM to double-glazed windows in the context of Pakistan's climate, namely in Islamabad, using rigorous numerical simulations with ANSYS Fluent. Our goal is to ascertain the usefulness of PCM integration in mitigating excessive heat absorption via windows by analyzing the performance of different window layouts. Because other studies in adjacent fields have shown that computational simulations and results agree well, there is confidence in the use of computational models to analyze the performance of systems based on PCM [17].

This study tackles two important issues: First, climates outside of Pakistan have received most of the attention in studies on PCMs and energy-efficient windows. Second, nothing is known about how much energy different passive window variations may save under Pakistan's climate. To analyze several passive window alternatives, particularly for Pakistan's climate, this study uses numerical analysis to evaluate their potential for energy-saving. The creation of a numerical model makes it easier to do further research for subsequent studies.

## II. Research Methodology

The general framework for conducting a numerical and computational study of translucent insulation and phase change materials in Windows is depicted in the schematic diagram in Fig. 1. This involves gathering raw data and using mathematical models to obtain data that will be processed further using a simulation tool. modelling and pre-processing methods for data. Acquired datasets are used in numerical computations for training.

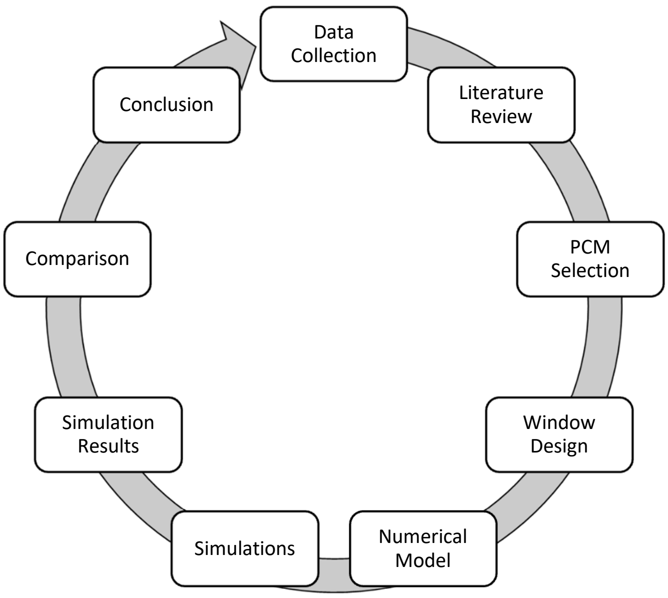



Fig. 1. Schematic diagram

## III. Model Description

This study explores the complex mechanism of heat transmission via windows with a particular emphasis on the use of phase change materials (PCM) and transparent insulation materials (TIM).

Comparing and analyzing the thermal behaviour of three different types of double-glazing windows is the goal. Convection and conduction serve as secondary drivers of heat transmission, with solar radiation serving as the major force. The glass layer in the window prototypes depicted in Fig. 2 is 5 mm thick and is surrounded by an air gap, TIM, and PCM. Notably, RT-25 paraffin wax was selected as the PCM for this investigation because of its exceptional thermal characteristics, whereas silica aerogel, a TIM known for its transparent insulating capabilities, was utilized in this work.

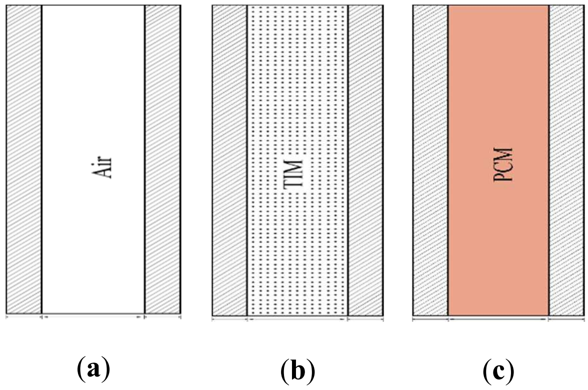



Fig. 2. Schematic of (a) air-based, (b) TIM-based, and (c) PCM-based windows.

The model considers the materials' thermophysical characteristics, including TIM silica aerogel and RT-25 PCM. These elements are necessary to precisely replicate the features of heat transmission and evaluate the thermal performance of the windows. as indicated in Table 1.

TABLE 1. Thermo-physical properties of RT-25 and TIM.

| Parameters | PCM RT-25 | 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 |

## IV. Model Validations and Governing Equations

The Fluent program is used to simulate the melting process within the enclosure (ANSYS 2022). The method of enthalpy-porosity is used to calculate the melt fraction rather than following the melting interface. With the exception of temperature-dependent density fluctuations, this simulation represents laminar and transient flow during PCM melting. Furthermore, density variations during natural convection are handled using Boussinesq approximations. Here are the energy and continuity equations (1) and (2) respectively for this numerical simulation:

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

$$\frac{\partial(\rho H)}{\partial t} + \nabla.(\rho v H) = \nabla.(k\nabla T) + S, \quad (2)$$

where S is the heat produced within PCM, which will be zero, k is the PCM's thermal conductivity V is the fluid's velocity, and ρ is the density of PCM. Equation (3) gives the total enthalpy of the system:

$$H = h + \Delta H, \quad (3)$$

In order to validate the numerical model, the identical problem as published [18] was solved and compared. The results of the new model demonstrated significant agreement with those of [18], as shown in Fig. 3, with variances of less than 5%. This validation demonstrates that the formulation and grid independence of the current model are reliable. The verified model was then used in more simulations.

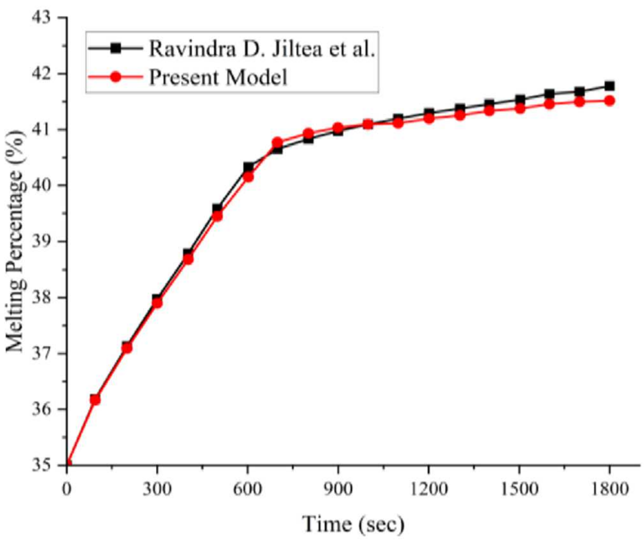
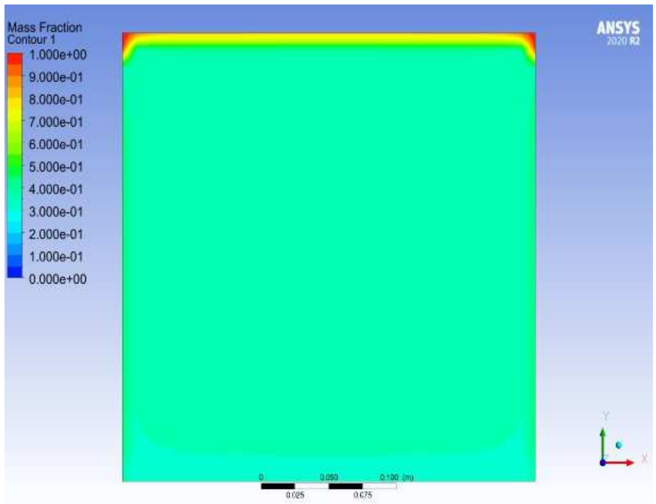


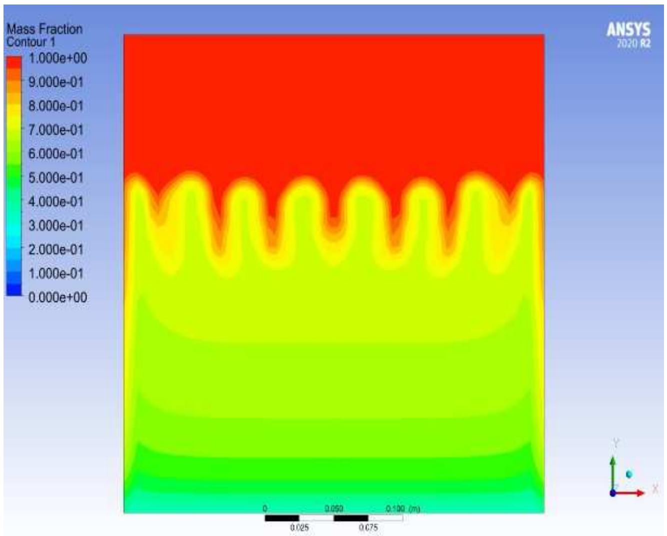

Fig. 3. Validation of numerical model [18]

## V. Results and Discussions

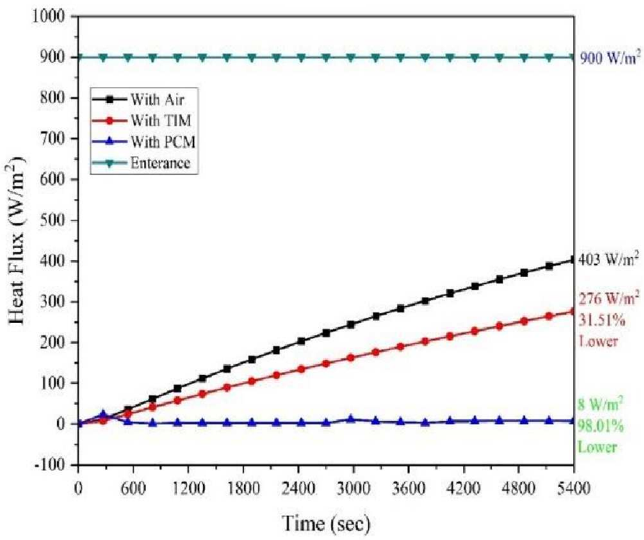
The numerical outcomes of this study provide crucial information on how various types of windows work in regulating room temperature. The phase change material (PCM) was chosen because of the peak ambient temperature in Islamabad being 45 °C and the target room temperature being 26 °C. The behaviour of the PCM during transient circumstances during solidification and melting was modeled using ANSYS Fluent. The outside glass surface of the windows was subjected to a steady heat flow of 900 W/m2. The simulations showed how the PCM could take in heat from the environment, store it, and use it to control the temperature of the space.



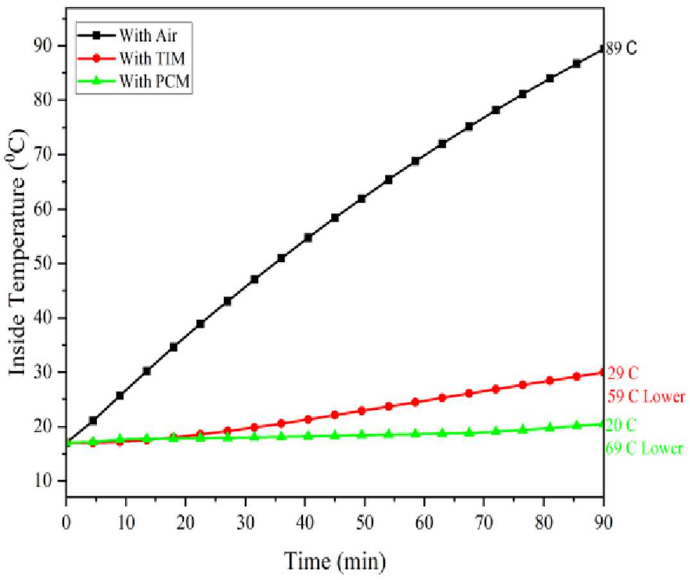

(a)




(b)




(c)




(d)

Fig. 4. (a) Melting contour at 500 s, (b) melting contour at 1500 s, (c) comparison of heat flux, and (d) comparison of indoor temperature.

As shown in Fig. 4c, the window based on phase change materials had the lowest transfer of heat of all the given types of windows; it was 98% lower than the air-based window. The heat flow through the windows based on PCM increased with time, in contrast to the air-based and transparent insulation material (TIM)-based windows. The role of the TIM in decreasing heat transfer was demonstrated by the fact that after 5400 seconds, the heat flow via the TIM-based window was 31.51% less than via the air-based window.

As shown in Fig. 4(d), the windows based on PCM maintained the lowest interior temperature, 69 °C below that of the windows based on air. For the air-based window, the inside temperature rose dramatically; for the TIM-based window, it grew more slowly; and for the PCM-based window, it remained essentially constant. The inside temperature of the TIM-based window was 59 °C lower than that of the air-based window, demonstrating its effectiveness in preventing heat transmission. The TIM-based and PCM-based windows differed in temperature by 10 °C as well, demonstrating the PCM-based window's improved capacity to block solar radiation.

These findings demonstrate, in general, how crucial window type selection is for controlling interior temperature. The best choice, which may increase a building's thermal comfort and energy efficiency, is the PCM-based window.

## VI. Conclusions

This study offers insightful information on the properties of heat transfer and the effectiveness of various window choices in controlling the interior temperature.

- Using computational models or simulations and the ANSYS Fluent’s pressure-based solver, we successfully delved into the solidification and melting characteristics of the phase change material (PCM) and examined how these properties impact transmission of heat.
- The findings show that the PCM-based window has the least amount of heat transmission out of the three window types under investigation. In contrast to the air-based window, the PCM-based window reduces heat absorption and retention during the melting process by 98%. This is achieved by efficiently blocking a major percentage of heat from entering the room. The meagre 8 W/m2 of heat being released into space is indicative of this improved thermal insulation.
- By maintaining a somewhat constant interior temperature, the PCM-based window also demonstrates temperature stability. The air-based window's temperature rises faster than the TIM-based window's, which rises more slowly.
- In comparison to the air-based window, the TIM-based window exhibits a notable 59 °C temperature reduction, suggesting the efficacy of thermal interface materials (TIMs) in mitigating heat transmission.
- The PCM-based window's improved capacity to filter solar radiation is highlighted by the temperature difference of 10 °C that was detected between it and the TIM-based window during testing. This result emphasizes the potential advantages of PCM-based windows for energy efficiency.
- Overall, the study's findings highlight the important influence that various window types have on maintaining a comfortable interior temperature. A particularly efficient method for preventing heat transmission from the outside environment and maintaining lower internal temperatures is the PCM-based window.
- The previously described results underscore the possible benefits of applying PCM-based windows in practical situations, therefore improving our understanding of energy-efficient building architecture.

Subsequent studies ought to examine the resilience and efficiency of windows that integrate phase change materials (PCMs), alongside investigating strategies to modify PCM characteristics to augment their capacity for heat transmission. These developments may aid in the creation of environmentally and energy-conscious building solutions.

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