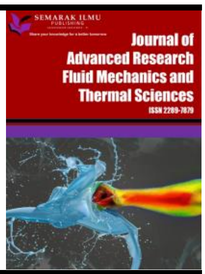
SEMARAK ILMU PUBLISHING

Journal of Advanced Research in Fluid Mechanics and Thermal Sciences

Journal homepage: https://semarakilmu.com.my/journals/index.php/fluid_mechanics_thermal_sciences/index
ISSN: 2289-7879



Effect of Triple Glass Layers on the Thermal Performance of Windows

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ARTICLE INFO

Article history:
Received 17 July 2024
Received in revised form 25 October 2024
Accepted 7 November 2024
Available online 20 November 2024

Keywords:
Thermal performance; multiple glazing layers; numerical simulation; physical properties

ABSTRACT

This study introduces the application of software simulations to evaluate the performance of triple-pane glass windows to meet the requirements for energy-efficient thermal insulation. Using Therm 7.8.55 and Window 7.8.55 software, structural and physical heat transfer models for various single-frame plastic windows were developed. Numerical simulation methods were employed to calculate and analyse the impact of the number of glass layers on the windows' thermal performance, including the heat transfer coefficient and solar heat gain coefficient, to elucidate the energy-saving mechanisms. These simulations examined the physical properties of single-frame triple-glazed plastic windows, such as wind pressure resistance, airtightness, watertightness, and potential condensation on the inner surface. The results indicate that, under identical conditions, the heat transfer coefficient of single-frame triple-glazed plastic windows is reduced by 7.08%, and the solar heat gain coefficient is decreased by 4.18% compared to single-frame double-glazed plastic windows. Additionally, these windows' physical and economic performance meets the necessary standards. Furthermore, incorporating new materials such as Low-E glass can further enhance the thermal performance of the windows, significantly contributing to the reduction of overall building energy consumption.

1. Introduction

In contemporary architecture, the quest for energy efficiency remains paramount, particularly in the design and functionality of building components like windows, which significantly impact the overall energy consumption [1,2]. Research consistently indicates that windows are critical in building energy dynamics due to their role in heat transfer [3]. The traditional approach to enhancing window efficiency has involved improvements to the glass's heat transfer characteristics, as the glass is responsible for more than one-third of a building's heating energy demands [1,2]. The characteristics of the glass itself, the form of glass system construction, and the combination of glass and window frame profiles all affect the heat transfer characteristics of windows [4,5]. Therefore, one of the keys to energy-efficient insulated windows is to use a more energy-efficient glazing system [6].

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https://doi.org/10.37934/arfmts.124.1.183197

This study introduces an innovative glazing system characterised by a single-frame triple-glass window designed to optimise thermal insulation and minimise energy losses. By investigating the effects of increasing the number of glass layers, this paper aims to thoroughly understand their impact on thermal performance, specifically examining heat transfer and solar heat gain coefficients. The exploration extends to the physical and economic attributes of the window system to determine its viability against current standards.

1.1 Research Background

The single-frame triple-glass window uses three layers of glass to form the insulating glass system of windows (combined with the existing types of window frame profiles, this paper chooses to use plastic fibre-reinforced plastic window frame) [5]. Considering the thickness of the window, the carrying capacity of the window frame profile, and other requirements, this paper examines a new insulating glass system by choosing different types of glass with various thicknesses and reasonably distributing the thickness of the glass gas interlayer to meet the higher energy-saving requirements of energy-efficient thermal insulation windows. Figure 1 shows four common types of energy-saving insulated glass windows. The two windows on the left are double-glazed, with heat transfer coefficients of 2.8 W/(m²·K) and 2.3 W/(m²·K). The two windows on the right are triple-glazed with two cavities, where the heat transfer coefficients are significantly lower, at 1.7 W/(m²·K) and 0.9 W/(m²·K).

Fig. 1. Comparison of several types of insulating glass

According to the principle of heat transfer, the indoor hot gas flows through the glass in the layer to exchange heat and cold and then through the glass to the outdoors [7,8]. The gas layer is in a closed state, filled with gas, which is relatively static, and static gas is a highly effective insulation layer, which can make the heat and cold exchange rate relatively low. An increase in the number of glass layers enabled the number of hot and cold airflow exchanges to increase, and the heat transfer time was extended to improve the internal surface temperature of the window, which means reducing heat loss has a very respectable effect [9,10].

1.2 Literature Review

The thermal performance of glazing is a vital element in the overall energy efficiency of buildings [7]. Depending on the season, windows are often the weakest point in a building's thermal envelope, accounting for significant heat loss or gain [6]. This has led to extensive research on improving windows' thermal insulation properties, mainly through multiple glazing layers and advanced materials [11,12]. This review explores various aspects of window design and materials that enhance thermal performance, focusing on using software simulations to evaluate these enhancements.

The primary heat transfer mechanism through windows involves conduction, convection, and radiation [11,13,14]. Adding more glazing layers has significantly reduced heat transfer [15]. Increasing the number of glass layers in a window can effectively lower the heat transfer coefficient (U-value), thus improving the window's insulating properties [12]. The thermal resistance increases with each additional layer of glass, reducing the overall heat transfer through the window assembly [5].

Different glazing systems impact thermal comfort and energy consumption [5]. Thermal and energy performance of high-rise buildings with glazed facades under various climatic conditions [16-18]. Advanced glazing systems, such as triple glazing combined with low-emissivity (Low-E) coatings, substantially improved thermal comfort and energy savings [19,20].

Solar control films (SCFs) are another technology used to augment the thermal performance of glazing [21]. The performance of SCFs in warm climates and found that these films can significantly reduce solar heat gain, thereby enhancing thermal and visual comfort indoors [22]. The study also highlighted that the effectiveness of SCFs depends on various factors, including the type and size of the glass, local weather conditions, and shading devices [23].

Numerical simulations have emerged as a crucial methodology for assessing the thermal performance of window systems [24,25]. Advanced software tools like Therm, Window, and IES(VE) are instrumental in enabling researchers to meticulously model and analyse the dynamics of heat transfer and solar heat gain across various window configurations [26]. These sophisticated programs allow for comprehensive evaluations, which are vital for the development and fine-tuning of innovative window designs prior to the construction of physical prototypes.

By leveraging these simulation tools, researchers can simulate real-world conditions and observe how different window designs perform in terms of insulation and energy efficiency [25,27]. This process involves creating detailed digital models of window systems, including all relevant physical properties and environmental conditions [28-30]. For instance, Therm7.8.55 helps establish structural and physical heat transfer models, while Window7.8.55 focuses on simulating thermal performance parameters such as the heat transfer coefficient (U-value) and the solar heat gain coefficient (SHGC).

The importance of these simulations is underscored by their ability to predict performance improvements accurately [23,31]. These findings underscore the value of numerical simulations in the design and optimisation process [23]. They provide critical insights that can lead to the creation of windows with superior thermal performance, which in turn can contribute to greater energy efficiency in buildings [22]. By relying on these advanced simulation tools, researchers and designers can make informed decisions and innovations that pave the way for more sustainable and energy-efficient architectural solutions [4,14].

Condensation on the interior surface of windows is a common problem in cold climates [32]. The ability of a window to resist condensation is crucial for maintaining indoor air quality and comfort [33]. Using multi-layered glazing and Low-E coatings can raise the inner surface temperature of windows, thus reducing the risk of condensation.

In addition to thermal performance, the physical and economic aspects of window designs are essential considerations [31,34,35]. Windows must withstand wind pressure, provide adequate airtightness and watertightness, and be economically viable [31,36]. The economic performance of advanced glazing systems, such as triple-pane windows, includes the initial installation costs and the long-term energy savings. Studies have shown that despite the higher initial costs, the energy savings over the window's lifespan can make these advanced systems economically advantageous [6,33].

Integrating advanced materials such as phase change materials (PCMs) and aerogels into glazing systems represents a promising direction for future research [34]. They were using PCMs and aerogels in multiple glazing windows and finding significant improvements in energy efficiency. These materials can store and release thermal energy, providing additional insulation and helping to maintain stable indoor temperatures [23].

In a nutshell, despite numerous studies emphasising the thermal performance of double-glazed windows, there is limited research that thoroughly investigates the impact of single-frame triple-glazed systems, particularly in terms of optimising both heat transfer and solar heat gain coefficients. This study aims to bridge this gap by employing advanced numerical simulations to evaluate the thermal insulation properties of triple-glazed windows, comparing their performance with conventional double-glazed alternatives. The research not only contributes new insights into the energy-saving mechanisms of triple-glass configurations but also explores the practical and economic implications of adopting such systems in modern architecture. Ultimately, this work enhances our understanding of how advanced glazing technologies can significantly improve building energy efficiency and supports the development of more sustainable design solutions.

2. Methodology

2.1 Numerical Simulation Tools

In this study, the Therm7.8.55 and Window7.8.55 software developed by the Lawrence Berkeley Laboratory of the University of California (LBNL) were utilised to evaluate the thermal performance of various window configurations. These tools are widely recognised for their ability to model and analyse building components' thermal characteristics accurately. Therm7.8.55 establishes the structural and physical heat transfer models of different single-frame plastic windows, while Window7.8.55 allows for the simulation of thermal performance parameters such as heat transfer coefficients and solar heat gain coefficients.

2.2 Simulation Setup

The simulation process involved several steps to ensure accurate and comprehensive analysis:

1. Model Creation: Detailed models of single-frame double-glass, and triple-glass plastic windows were created. The total thickness of the insulating glass system was maintained at 36 mm for all configurations to ensure comparability.
2. Material Selection: Various types of glass with different thicknesses were selected, and the distribution of the glass gas interlayer was optimised to meet higher energy-saving requirements. For instance, the study chose plastic fibre-reinforced plastic window frames for their superior thermal insulation properties.
3. Boundary Conditions: The indoor and outdoor temperatures were set at 20°C and -20°C, respectively, to simulate winter conditions. This temperature differential is critical for assessing the thermal insulation performance of the windows.
4. Heat Transfer Analysis: The heat transfer coefficient (U) and the solar heat gain coefficient (SHGC) were calculated for each window configuration. The heat transfer coefficient was determined using the inverse sum of all heat transfer thermal resistances, while the SHGC was calculated based on the total solar radiation transmission ratio, window glass area, and other related parameters.

2.3 Data Analysis

The data analysis focused on evaluating the thermal performance of the different window configurations based on the simulation results. The critical parameters analysed included:

i. Heat Transfer Coefficient (U): This parameter measures the amount of heat passing through a unit area of the window per unit time when there is a 1°C temperature difference between the two sides. Lower U-values indicate better insulation performance [13,37].
ii. Solar Heat Gain Coefficient (SHGC): This parameter represents the solar radiation heat gain ratio through the window to the total solar radiation incident on the window exterior [21]. Lower SHGC values are beneficial in reducing unwanted solar heat gain, especially in warmer climates.
iii. Surface Temperature Analysis: The glass's internal and external surface temperatures were monitored to assess the risk of condensation on the inner surface of the window [38,39]. Higher internal surface temperatures help prevent condensation and improve indoor comfort.
iv. Physical Property Evaluation: The physical properties of the windows, such as wind pressure resistance, air and water tightness, and dew performance, were analysed to determine their suitability for various climatic conditions [36]. The wind pressure resistance was evaluated based on the design value of the wind load, while the air and water tightness were assessed based on the construction quality and sealing materials used.
v. Economic Performance: The economic analysis involved calculating the heat consumption of the different window configurations and comparing the energy savings achieved by using single-frame three-glass windows [11,40].

By systematically applying these methodologies, the study aimed to provide a comprehensive understanding of the thermal performance and energy efficiency of single-frame triple-glass windows compared to traditional glass configurations. The results are expected to guide the design and selection of energy-efficient windows for various building applications.

3 Result and Analysis

3.1 Thermal Performance Analysis of Insulating Glass

Leveraging the Window 7.8.55 software developed by LBNL, the performance parameters of three types of insulating glass, namely single-glass, double-glass, and triple-glass, are simulated and compared with those of the other three types of insulating glass in the condition of the same total thickness (36 mm).

The results are shown in Table 1. Among this table, U, SHGC, Tsol, and Tvis refer to thermal transmittance, solar heat gain coefficient, total solar transmittance, and visible light transmittance. It can be seen that, under the condition of the same total thickness, by increasing the number of glass layers appropriately and reasonably distributing the thickness of the interlayer, the heat transfer coefficient of the insulating glass decreases significantly. In contrast, the solar heat gain coefficient decreases to a lesser extent, which is because the glass is ordinary white glass, and the interlayer of the gas is filled with dry air, which has a minor influence on the performance of the solar light penetration.

Table 1
Thermal performance parameters of different types of insulating glass

No.	Type	U	SHGC	Tsol	Tvis
1	Single-glass (36mm thickness glass))	2.962	0.716	0.663	0.799
2	Double-glass (8mm glass+20mm air+8mm glass)	1.993	0.692	0.541	0.725
3	Triple-glass (6mm glass+9mm air+6mm glass+9mm air+6mm glass)	1.854	0.628	0.514	0.665

Note: The glass in the table is ordinary white glass, and the gas layer is dry air.

Table 2 reveals the indoor and outdoor temperatures of 20 and -20 ℃, respectively, under that scenario, and it shows three kinds of insulating glass inside and outside surface temperatures. It can be seen that the internal surface temperature of the triple-layer glass is 3.0 ℃, much higher than the double-layer glass -1.8 ℃, and the single-layer glass -13.6 ℃. It is shown that an appropriate increase in the number of glass layers has a significant effect on blocking heat transfer while increasing the temperature of the inner surface of the glass to fundamentally solve the problem of condensation on the inner surface of the window.

Table 2
Temperature of each glass of different types of insulating glass system

No.	Outside temp	Layer 1		Layer 2		Layer 3		Inside temp
		Out	In	Out	In	Out	In	
1	-20	-14.5	-13.6	-	-	-	-	20
2	-20	-16.1	-15.6	-2.2	-1.8	-	-	20
3	-20	-16.6	-16.2	-6.5	-6.3	2.8	3.0	20

3.2 Window Frame Node Thermal Performance Analysis

Align with the project selected, this study selected the Yunxiwan Project, Dongguan, China, as an example, the 70 series of three-sealed high-resistance PVC alloy profiles with a height of 1,500 mm and a width of 1,200 mm inner flat open plastic steel window was selected as the research object, and the detailed parameters are shown in Figure 2, which shows that this window frame mainly consists of ① fixed window frame, ② opening window frame, and ③ centre stile.

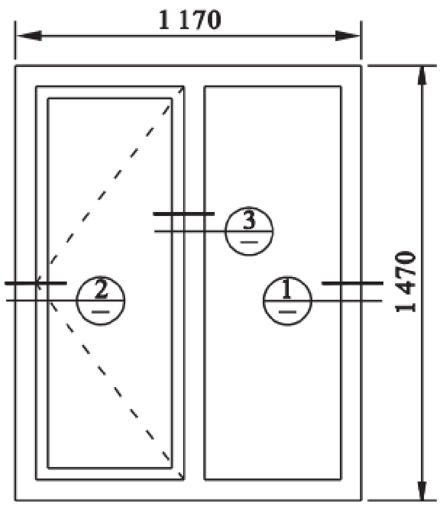

Fig. 2. Facade schematic of window

Therm 7.8.55 software was used to simulate the nodes of the window frame. According to the distribution of isotherms at each node from the outcome of the simulation, the distribution of isotherms in the interlayer of the insulating glass isotherms is very high, and the distribution of isotherms in the layer of air-filled is dense. In contrast, the distribution inside the glass is sparse, which indicates that the integral layer plays an essential role in reducing heat loss. This shows that the gas interlayer has a good effect in reducing heat transfer and has a pronounced heat insulation effect. This shows that the gas interlayer effectively reduces heat transfer, and the heat insulation effect is noticeable.

3.3 Thermal Performance Analysis of The Whole Window

The window model in Figure 2 is created in Window 7.8.55, and the simulation results of the nodes in section 3.2 are imported into Window 7.8.55, and the performance parameters of the three kinds of plastic windows are obtained, as shown in Table 3.

Table 3
Thermal characteristics of different types of windows

No.	U/[W/(m^2·K)]	SHGC	VT	CR
1	2.304	0.458	0.509	47
2	1.821	0.431	0.432	55
3	1.692	0.413	0.442	60

In this table, serial numbers 1, 2, and 3 represent single-layer, double-layer, and triple-layer glass models. Under the condition of equal thickness, the heat transfer coefficients of the single-frame triple-glass plastic windows are reduced by 26.56% and 7.08% compared with the single-frame single-glass and double-glass plastic windows, the solar heat gain coefficients are reduced by 9.83% and 4.18%, and the visible transmittance ratios (VT), and condensation resistance (CR), are also improved to different extents.

If the 3 mm ordinary white glass in window No. 3 is replaced by 3 mm Low - e glass (coated inside), the U-value is further reduced, and the CR is significantly increased, which is due to the good thermal insulation effect of the Low - e glass coating layer; and the SHGC and VT have been significantly reduced, which is due to the material properties of Low - e glass. This is due to the good thermal insulation effect of the Low-e glass coating layer, while SHGC and VT have a significant decrease due to the material properties of Low-e glass that weaken its solar transmittance to a certain extent compared with ordinary white glass. As a result, the heat transfer characteristics of the window will be significantly improved, while the energy consumption will be significantly reduced.

3.4 Wind Pressure Resistance

Wind pressure resistance refers to the window in the normally closed state; under wind pressure, damage and hardware loosening, opening difficulties, and other dysfunctions [35]. The design value of the wind load acting on the building windows can be calculated according to the Eq. (1) and Eq. (2):

$$\omega = \gamma_w \omega_k \tag{1}$$

$$\omega_k = \beta_{gz} \mu_{sl} \mu_z \omega_o \tag{2}$$

Where ω is the wind load design value of building windows, kPa; ω_k is the standard value of wind load, kPa; γ_w is the wind load component coefficient, take 1.4; β_{gz} is the gust coefficient at height z; μ_{sl} is the wind load local body type coefficient; μ_z is the wind pressure height change coefficient; ω_o is the primary wind pressure, kN/m^2.

Taking the selected city Dongguan as the basis of calculation, check the corresponding standard: β_{gz} is 1.81, μ_{sl} is 1.0, μ_z is 1.10, ω_o is 0.60 kN / m^2, and it is calculated that the standard value of wind load acting on the exterior window of the building at z = 50 m is 1.19 kPa, and the design value of wind load is 1.67 kPa.

The load-bearing capacity limit state and regular use limit state of insulating glass should be calculated according to the wind load assigned to each piece of glass. The distribution coefficient is calculated according to Eq. (3).

$$k_i = \frac{1.25t_i^3}{\sum_{i=1} t_i^3} \tag{3}$$

Where k_i is the wind load distribution coefficient; t_i is the thickness of the number i glass layer, mm.

The calculation shows that the distribution coefficient of each layer of glass is 0.556, 0.069, and 0.556, respectively, and then the wind load is borne by each piece of glass. The wind load of each piece of glass is then calculated. For the calculation of the insulating glass load-bearing limit, only the thickness of the smaller single glass load-bearing is needed. When calculating the load limit of insulating glass, it is only necessary to calculate the load capacity of a single piece of glass with a smaller thickness. The maximum permissible span L can be calculated according to Eq. (4):

$$L = K_1 \times (\omega + K_2) \times K_3 + K_4 \tag{4}$$

Where L is the maximum permissible span of the glass, mm.

k_1, k_2, k_3, k_4 are constants, according to the length-to-width ratio of the glass, the maximum permissible span of 3 mm ordinary white glass is 1,721.4 mm, which is larger than the window model in this paper and the size of standard windows, indicating that this type of insulating glass meets the requirements of wind pressure resistance.

3.5 Air and Water Tightness

Airtightness refers to the ability to prevent air infiltration when the window is in a normally closed state. Air infiltration generally occurs in the window frame and sash, frame and glass, sash and glass connection [26,41], and the window frame profiles, the quality of sealing materials and construction technology are closely related to the glass structure having less impact.

Watertight performance refers to the ability to prevent rainwater penetration when the window is in a typical closed state, under the simultaneous action of wind and rain [42]. In addition to the window frame, sealing materials and construction technology, watertight performance is also related to the window frame, window set, the location of drainage holes, the number and size of the opening, and the glass structure is less relevant [8].

3.6 Dew Performance Analysis

In cold and extremely cold regions, windows often face the issue of condensation on their interior surfaces during winter. This phenomenon occurs because the temperature on the indoor side of the window surface drops below the dew point of the surrounding indoor air. Particularly when the outdoor temperature plunges below -20°C and the indoor relative humidity exceeds 30%, the risk of condensation increases significantly. Under these conditions, the window surface becomes colder than the dew point temperature of the nearby air. This temperature discrepancy causes moisture in the warm indoor air to condense upon contact with the cold window surface, leading to the formation of dew or frost.

The occurrence of condensation can have several negative implications. Firstly, it can lead to discomfort for the building occupants as the presence of moisture can make the indoor environment feel colder. Secondly, persistent condensation can result in germs growth, which poses health risks and can damage window frames and surrounding structures. Additionally, frost formation can impair visibility through the windows and reduce their overall performance.

To prevent condensation, it is essential to ensure that the minimum surface temperature on the indoor side of the window remains above the dew point temperature of the indoor air. This can be achieved through various means. One effective strategy is to use insulating glazing systems, such as triple-glazed windows, which are designed to minimise heat transfer and maintain higher surface temperatures on the interior side. Incorporating Low-e (low emissivity) coatings on the glass can also help by reflecting heat into the room, thus raising the surface temperature of the window. Furthermore, filling the space between the glass panes with inert gases like argon or krypton can enhance insulation and further reduce the risk of condensation.

In practical applications, the assessment of potential condensation requires careful consideration of both the indoor and outdoor conditions. Advanced simulation tools and real-world testing can be employed to model the thermal behavior of windows under various scenarios, ensuring that the design meets the necessary criteria to prevent condensation. By maintaining the indoor window surface temperature above the dew point, buildings can achieve better thermal comfort, improved energy efficiency, and enhanced durability of window systems. It can be calculated following the Eq. (5) to determine [43].

$$(T_{min} - T_{out,std}) \cdot \frac{T_{in} - T_{out}}{T_{in,std} - T_{out,std}} + T_{out} \geq T_d \tag{5}$$

Where T_{min} for the window dew performance evaluation index, °C; $T_{in,\,std}$, $T_{out,\,std}$ for the window dew performance calculations corresponding to indoor and outdoor standard temperature, °C; T_{in} and T_{out} are the calculated indoor and outdoor temperatures for the actual project, °C; T_d is the dew point temperature for the indoor design environment, °C.

After calculation, when the indoor and outdoor temperature is 20 °Cand 0°Cand the relative humidity is 50%, 55%, and 60%, the indoor air dew point temperature is 9.3 °C, 10.0 °C, 11.1 °C. The single-frame three-glass plastic window surface temperature of the innermost glass is 12.0 °C, higher than the dew point temperature of the indoor air to meet the requirements of the indoor side of the window surface does not condense.

3.7 Economic Analysis

According to Eq. (6), for calculating the heat consumption of windows, the heat consumption of single-frame single-glazed, double-glazed and triple-glazed plastic steel windows (excluding the heat consumption of cold air infiltration) is calculated.

$$Q_c = U \times F \times (T_{in} - T_{out}) \quad (6)$$

Where Q_c is the heat consumption of the window, W; F is the window area, m^2.
According to the Eq. (9), the calculation results are as follows.

Heat consumption of single-frame single-glazed plasticised steel window: Q1 = 87.31 W; Heat consumption of single-frame triple-glazed plasticised steel window: Q2 = 71.91 W; Heat consumption of single-frame triple-glazed plastic windows: Q3 = 61.18 W.

After comparison, the heating heat consumption of single-frame triple-glazed windows (Q3, 61.18W) is 29.93% lower than that of single-frame double-glazed windows (Q1, 87.31W). It can be deduced that if single-frame three-glass windows are used in a building, the energy-saving benefit is very significant.

4. Limitations and Future Directions

The limitations and future directions of the study on the thermal performance of triple-glass windows present a multi-faceted exploration into the current constraints and the potential advancements that could be achieved in the field of energy-efficient building materials. This section delves into various aspects of the study, highlighting both the challenges encountered and the promising avenues for future research and development.

One significant limitation of the study is the selection of materials used in the simulations. While the study demonstrates the improved thermal performance of single-frame triple-glass windows using standard materials, it suggests the potential for even more significant improvements through the use of advanced materials such as Low-E (low emissivity) glass. Low-E glass has a microscopically thin coating that reflects heat while allowing light to pass through, significantly enhancing the insulating properties of the windows. The incorporation of such materials could lead to substantial energy savings, yet the study does not fully explore their impact, thus leaving room for further research into optimising material combinations.

The reliance on specific numerical simulation tools, namely Therm 7.8.55 and Window 7.8.55, represents another limitation. While these tools are robust and widely recognised in the field, they may not capture all real-world variables and conditions. The assumptions and constraints inherent in these simulations could lead to discrepancies between predicted and actual performance. Future studies should consider integrating more comprehensive simulation models that can incorporate a broader range of environmental and operational conditions. These advanced models could provide a more nuanced understanding of window performance across different climates and building types.

The physical property analysis conducted in the study covers crucial aspects such as wind pressure resistance, airtightness, and watertightness. However, the testing conditions and methodologies used may not fully represent the diverse environmental conditions that windows will face in real-world applications. Variations in temperature, humidity, and other climatic factors can significantly affect these properties. Therefore, real-world testing and validation of the simulation results are essential. Pilot installations in actual buildings would provide invaluable data on performance under practical conditions, offering insights that simulations alone cannot provide.

The economic analysis in the study primarily focuses on heat consumption and the associated energy savings. While this is a critical factor, it does not encompass the complete economic picture. Initial installation costs, maintenance expenses, and the potential savings over different climatic conditions or building types are also important considerations. Future studies should broaden the economic analysis to include comprehensive lifecycle cost assessments. This approach would provide a more accurate understanding of the financial benefits and trade-offs associated with the adoption of triple-glass window systems.

Advancements in materials technology present exciting opportunities for future research. The integration of phase change materials (PCMs) and aerogels into glazing systems is a promising direction. PCMs can store and release thermal energy, providing additional insulation and helping to maintain stable indoor temperatures. Aerogels, known for their low thermal conductivity, can significantly reduce heat transfer. Research into these and other advanced materials could lead to the development of window systems with unprecedented thermal performance.

Another future direction involves the development of multifunctional windows that go beyond thermal insulation. For instance, windows that incorporate photovoltaic cells could generate electricity while also providing insulation. Similarly, smart windows with dynamic tinting capabilities can adjust their transparency based on the intensity of sunlight, thereby reducing cooling loads in the summer and allowing passive solar heating in the winter. Such innovations could transform windows from passive elements into active contributors to a building's energy management system.

Sustainability is an increasingly important consideration in building materials research. Future studies should explore the environmental impact of manufacturing, installing, and disposing of triple-glass window systems. Life cycle assessments (LCAs) could provide insights into the overall sustainability of these systems, considering factors such as energy consumption, carbon emissions, and the use of non-renewable resources. This holistic approach would ensure that advancements in thermal performance do not come at the expense of environmental sustainability.

In addition to improving the thermal performance of windows, future research should also address the aesthetic and functional aspects. The design and appearance of windows are important to architects and building occupants. Innovations in window technology should aim to enhance not only energy efficiency but also the visual and functional qualities of windows. For example, advancements in transparent insulation materials could provide high levels of insulation without compromising on transparency and aesthetics.

The integration of digital technologies into window systems is another promising avenue for future research. Smart sensors and IoT (Internet of Things) technologies could be used to monitor and optimise the performance of window systems in real time. These technologies could provide data on factors such as temperature, humidity, and light levels, enabling dynamic adjustments to optimise energy efficiency and indoor comfort. Such smart window systems could play a key role in the development of intelligent buildings that adapt to changing environmental conditions.

The study also highlights the importance of understanding and mitigating the risk of condensation on the interior surface of windows, particularly in cold climates. Condensation can lead to the growth of germs and damage to building materials, posing health risks and compromising the integrity of the building. Future research should focus on developing window systems that can effectively manage moisture and prevent condensation. This could involve the use of materials and coatings that enhance the thermal performance of the inner surface of the window, keeping it above the dew point temperature even in cold conditions.

Another area for future research is the development of standardised testing and evaluation methods for advanced window systems. The lack of standardised methods can make it difficult to compare the performance of different window systems and validate simulation results. Developing and adopting standardised testing protocols would facilitate the assessment and comparison of new technologies, helping to accelerate their adoption in the market.

In conclusion, while the study provides valuable insights into the thermal performance of single-frame triple-glass windows, it also highlights several limitations and areas for future research. Advances in materials technology, comprehensive simulation models, real-world testing, and a holistic approach to economic and environmental analysis are essential for further improving the performance and sustainability of window systems. The integration of digital technologies, aesthetic considerations, and standardised testing methods will also play a crucial role in the development of next-generation windows. These future directions promise to drive significant advancements in building energy efficiency, contributing to more sustainable and comfortable built environments.

5. Conclusions

In summary, the development of energy-efficient thermal insulation windows, specifically single-frame triple-glass plastic steel windows, represents a significant improvement over existing energy-saving windows in terms of both the heat transfer coefficient (U-value) and the solar heat gain coefficient (SHGC). Based on the detailed analysis provided in this study, the following conclusions can be drawn.

The integra's layer within the insulating glass system plays a crucial role in minimising the heat transfer coefficient of the window. By carefully optimising the thickness distribution of this layer, it is possible to design a glazing system that offers superior thermal performance. This optimisation can lead to significant reductions in energy loss, contributing to enhanced insulation efficiency. Under the same total thickness of 36 mm, single-frame triple-glazed plastic steel windows exhibit marked improvements in key performance parameters compared to their double-glazed counterparts. The heat transfer coefficient of single-frame triple-glazed windows is reduced by 7.08%, and the solar heat gain coefficient is decreased by 4.18% compared to single-frame double-glazed plastic windows.

The thermal performance of these windows can be further enhanced by incorporating additional technologies and materials. For example, filling the glazing system with inert gases like argon or krypton and utilising Low-e (low emissivity) glass can significantly improve the insulation properties. Moreover, redesigning the window frames with a focus on deeper energy-saving measures can lead to even greater reductions in heat transfer and solar heat gain, ultimately reducing the overall energy consumption of buildings. If the 3 mm ordinary white glass in window No. 3 is replaced by 3 mm Low-e glass, the U-value is further reduced and the condensation resistance (CR) is significantly increased, demonstrating the superior thermal insulation effect of Low-e coatings.

The advancements in single-frame triple-glazed windows highlight their potential to contribute significantly to energy conservation in buildings. The detailed findings and recommendations from this study underscore the importance of continued research and development in this area, aiming to achieve even higher standards of energy efficiency and environmental sustainability in building design. These improvements are crucial for reducing the overall building energy consumption, making single-frame triple-glazed windows a vital component in the pursuit of sustainable architecture.

Acknowledgement
This research was not funded by any grant, but we still thank Universiti Sains Malaysia (USM) and the School of Housing, Building and Planning (HBP) for their support and guidance.

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