Analyzing Glass Configurations For Energy Efficiency In Building Envelopes: A Comparative Study

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Received: October 06, 2023; Accepted: November 27, 2023

As the climate of the globe changes, buildings will need to accommodate new standards for typical and extreme weather. Glass configurations may help adapt structures to these changing climates. The most important features of several glass configurations for energy-efficient buildings are compared in this work. Thermal performance, light transmission, solar heat gain coefficient, sound reduction, structural and mechanical strength, and other factors were considered while evaluating glass configurations. The findings show that glass combinations with higher R-values and lower U-values offer excellent thermal insulation and are advised for high thermal requirements. Conversely, those with higher U-values and lower R-values best serve interior applications with low to moderate thermal demands. Considerations like light transmission, solar heat gain coefficient, sound reduction, structural strength, and mechanical strength can help narrow the options for optimum glass configuration for a particular application. Choosing the appropriate glass arrangement requires careful consideration of several factors to produce an indoor atmosphere that is secure, safe, pleasant, and energy efficient.

Keywords: Glass; Energy Efficiency; Thermal Performance; Light Transmission; Sound Reduction; Structural Strength

http://dx.doi.org/10.6180/jase.202502_28(2).0011

1. Introduction

Because of its aesthetic appeal, capacity to let in natural light and allow for views of the outside, glass has held popularity as a building material for many years. Glass may, however, also be a substantial source of energy gain and loss, which can affect a building's energy efficiency and raise heating and cooling expenses. As a result, choosing a suitable glass configuration is essential for accomplishing aesthetic and energy-saving objectives [1].

Buildings must adapt to shifting weather patterns and extreme weather occurrences as the planet's climate changes. Glass arrangements may be necessary for adjusting buildings to these shifting environments. For instance, glass designs with lower solar heat gain coefficients can assist in lowering the amount of heat entering the structure, hence decreasing energy demand for cooling in regions subject to intense heat waves [2]. In places vulnerable to hurricanes or other severe weather events, glass with higher structural and mechanical strength can assist in safeguarding the structure and its inhabitants. Additionally, there can be a demand for glass arrangements that can offer thermal insulation and defense against extreme weather as climate change brings about more frequent and severe weather occurrences. This could include glass arrangements with high structural and mechanical strength levels, thermal insulation, and impact and debris resistance [3, 4]. In general, glass layouts will need to play a crucial part in adapting buildings to these changing conditions as the effects of climate change become more noticeable. It is a complex process that requires the complete attention of façade engineers and architects to determine the best glass configurations for various climate change scenarios and extreme weather events and assess their environmental impact and cost-effectiveness [5].

The thermal performance of the building envelopes significantly influences the energy efficiency and sustainability of a building. Building envelopes must have the right glass combinations since they have an impact on the structure's insulating capabilities and its capacity to control temperature. In the Middle East, where summers are long and hot, the importance of choosing the appropriate glass combinations cannot be overstated. This study compares common glass combinations' thermal efficiency in building envelopes to guide architects and facade engineers toward the most effective glass types and thicknesses for warm regions. Important indicators of thermal performance, such as the U-values and R-values of different glass combinations, are the focus of the research. The results of this investigation on the thermal performance of various glass combinations can improve the efficiency and sustainability of future building designs [6].

The thermal performance of various glass combinations used in building envelopes is evaluated in this study by measuring their U-values and R-values. Single clear, double clear, double low-e (low-emissivity), triple clear, triple low-e, laminated low-e, and insulated glass units with warm edge spacers are just some of the glass types and thicknesses that can be combined [7]. According to the study, the optimum glass combinations for regions with long, hot summers are those with low U-values and high R-values [8]. For their excellent insulating qualities, triple low-e Glass with argon fill, double low-e glass with argon fill, and insulated glass units with warm edge spacers are recommended. When choosing glass combinations, the study underlines the value of considering local construction rules and standards. Architects and facade engineers may use the findings of this study to make knowledgeable choices about the kinds and thicknesses of glass for building envelopes in hot regions [9–12].

This paper provides the characteristics of the glass configurations considered in this investigation in the forthcoming section. The study's findings as well as an overview of the suggested uses for each glass shape are presented. The consequences of these findings are discussed, and suggestions for choosing the appropriate glass configuration for a given application. The last part of the paper concludes and makes recommendations for further investigation [13–15].

2. Literature review

Glass is a crucial part of building envelopes, and the thermal performance of Glass affects the sustainability and

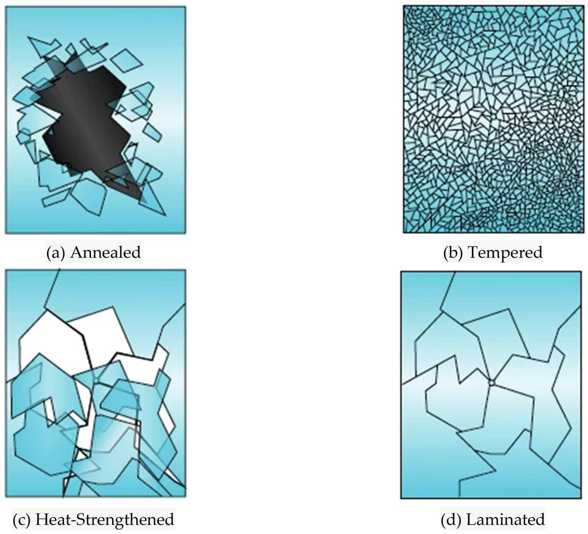

Fig. 1. Types of Glass considered for the current study.

energy efficiency of a building. The choice of glass combinations is essential in hot climates since it impacts a building's capacity to control temperature and lower cooling demands. Experts have conducted comprehensive investigations to examine the thermal performance of various glass combinations. Glass with a higher solar heat gain coefficient (SHGC) is usually recommended for areas where solar heating and lighting are desirable, such as atriums and lobbies, reducing the cooling loads of the building. Glass configurations with lower SHGC, on the other hand, can avoid excessive solar heat gain in offices or rooms with moderate thermal needs. Therefore this reduces the need for active cooling and ensures a pleasant working environment. These illustrate how sustainable building design can benefit from individualized glass configurations based on individual spaces' climatic and functional needs.

Peng et al. [16] examined the thermal performance of several glass kinds and thicknesses in a hot and humid environment. According to the study, laminated and low-e glass offered more thermal insulation than clear glass; thicker glass outperformed thinner glass. The study further shows that using shading devices could significantly reduce cooling loads. Aldawoud et al.'s [17] investigated the thermal performance of various glass assemblages. The study shows that utilizing shading devices and reflective coatings enhances the energy efficiency of building envelopes and that low-e and insulated glass units offered superior thermal insulation than clear glass. Low-Emissivity Materials for Building Applications: A Review and Future Research Perspectives were presented by Jelle et al. [18]. They claimed that low-e materials help buildings use less energy by limiting heat transmission through thermal radiation. However, the aging effects of low-e materials require study because they can significantly affect energy use during a building's lifetime. According to several investigations, laminated and insulated glass units came second to low-e glass with argon fill-in thermal insulation. Reflective coatings and shading mechanisms might lower cooling loads and boost energy effectiveness [19, 20]. Various studies showed that insulated glass units with warm edge spacers and low-e glass with argon fill offered the optimum thermal insulation. Cooling loads could be significantly reduced by shading devices and reflecting coatings [21, 22].

In addition, various researchers have studied glass layouts to determine ideal ways to improve buildings' energy efficiency. A study by Madhaddam et al. examined a wide range of glass, coatings, and glazing systems. They showed that low-e coatings positively affect heat transfer and thermal performance [23]. Do et al., in a study, underlined the value of natural light in creating environment-friendly structures. They investigated how various glass arrangements fared regarding visible light transmission, glare management, and daylight harvesting. Their research showed that smart decisions about glass selection and design can maximize the use of natural light while reducing the need for artificial illumination [24]. Researchers have looked at the effect of glazing systems on energy efficiency and glass types and coatings. The effectiveness of double- and triple-paned windows was analyzed by Michaux et al. They compared the thermal insulation qualities and air leakage rates, finding that triple-glazed windows were more effective at preventing heat loss.

Several studies have focused on the need for energy-efficient glass designs over the long run [25]. Piccolo et al. investigated advanced glazing solutions for their potential impact on reducing energy consumption. Their research involves incorporating glass with variable solar heat gain qualities. To achieve adaptive solar management, the authors emphasized the potential of technological glazing systems [26]. While researchers have made significant developments, there are still gaps and constraints regarding glass layouts for energy-efficient buildings. The economic viability and occupant comfort of these combinations the performance of new glass technologies like vacuum-insulated glass and the use of smart glass require more study. In conclusion, past research has demonstrated that the thermal performance of building envelopes in hot regions depends significantly on the choice of glass combinations. Warm edge spacers and low e, laminated, and insulated glass components are suggested for their excellent insulating qualities. Additionally, reflecting coatings and shading devices can dramatically increase energy efficiency [27, 28].

This study attempts to analyze the effects of different glass arrangements on buildings' energy efficiency. Thermal characteristics, solar heat gain coefficients, daylighting efficacy, and viability are assessed in this study. In addition, it highlights how architects, designers, and construction experts can best optimize glass combinations for energy efficiency.

3. Codes and standards for improving building efficiency

Energy codes and standards that are effective in enhancing building energy efficiency are discussed in this section. To ensure that buildings satisfy the minimum energy performance, these codes and standards play a critical role in promoting sustainable and energy-efficient practices. The International Energy Conservation Code (IECC) [29] establishes climate zone-specific requirements for building envelopes, HVAC systems, lighting, and electrical systems. It also addresses critical aspects such as insulation, fenestration, and air leakage control. The Energy Performance of Buildings Directive (EPBD) [30] outlines minimum energy performance requirements, regular inspections, and energy performance certificates for buildings within the European Union. ASHRAE Standards [11, 31–34] cover areas including energy efficiency, ventilation, and thermal comfort. The Leadership in Energy and Environmental Design (LEED) [35–37] certification program sets criteria for energy performance, demand response, renewable energy systems, and commissioning. The Passive House Standard emphasizes high energy efficiency and thermal comfort while emphasizing airtightness and insulation. Table [1] provides an overview of energy codes and standards, their clauses and references related to energy efficiency for buildings.

Architects, engineers, and policymakers may ensure that energy-efficient measures are adequately implemented by adhering to certain norms and standards during the building design and construction. Thanks to these rules and regulations, saving money on energy costs, reducing our environmental impact, and designing livable, long-lasting structures are all possible. It's worth noting that certain conditions and local implementation strategies can cause standards to vary by region.

4. Building systems and technologies

The growing importance of energy-efficient building design is underscored by the increasing efficiency of building systems and technologies in recent years [38, 39]. Considering the rising need for sustainable and energy-saving activities, highlighting the influence and significance of energy-efficient technologies in improving overall building energy performance is crucial. Here, we provide statistical evidence supporting the enormous energy savings that can be realized by installing energy-efficient building systems. We highlight the potential of enhanced glass configurations to contribute to substantial decreases in energy usage and discuss their role in driving energy efficiency. These numbers support our study's claim that glass design can improve buildings' overall energy efficiency and the expanding importance and influence of energy-efficient activities.

- Energy Savings through Energy-Efficient Technologies:

  The U.S. Department of Energy (DOE) found that energy-efficient solutions can reduce building energy use by as much as 30%. Compared to conventional structures, energy-efficient ones often reduce consumption by between 20 and 50% [40].

- Impact of Improved Glass Configurations:

  Research shows that there can be significant energy savings from using energy-efficient glass combinations. Somasundaram et al. demonstrated that by limiting heat transfer and boosting insulating qualities, low-e coated glass can save up to 30% in home energy costs [41].

- Benefits of Daylighting:

  Energy efficiency window layouts make daylighting tactics possible, resulting in significant cost savings. According to the U.S. Green Building Council (USGBC), using daylighting techniques can save a building's lighting energy use by as much as 75% [42].

- Energy-efficient solutions in commercial buildings:

  Energy-efficient solutions have also been successful in the commercial sector at lowering energy usage. Commercial buildings can lower their energy consumption by as much as 80% if they install energy-saving technologies such as advanced glass systems, lighting controls, and efficient HVAC systems, according to the International Energy Agency (IEA) [43].

- Market Growth of Energy-Efficient Building Technologies:

  The demand for greener construction methods is increasing. The global market for energy-efficient building systems is expected to reach $361.6 billion by 2026, according to a report by MarketsandMarkets. This

Table 1. Information about Glass or insulation based on energy codes.

Energy Code/Standard	Description	Key Clauses	References	Glass/Insulation Information
Leadership in Energy and Environmental Design (LEED)	Green building certification program promoting energy efficiency and sustainability in building design, construction, operation, and maintenance.	Energy and Atmosphere category requirements, including minimum energy performance, demand response, and renewable energy systems.	EAc1, EAc2) (LEED v4, EAp2,	Requirements for building envelopes, lighting systems, and HVAC efficiency. (LEED v4, EA prerequisite, and credit requirements)
Energy Performance of Buildings Directive (EPBD)	European Union directive setting requirements for the energy performance of buildings within member states.	Minimum energy performance requirements for new buildings and major renovations.	(EPBD, Article 4)	Energy performance certificates for buildings. (EPBD, Article 11)
Passive House Standard	The international standard for energy-efficient building design focuses on achieving high energy efficiency and thermal comfort.	Requirements for space heating and cooling demand, primary energy demand, and air leakage.	(Passive House Passivhaus Planning Package)	Thermal bridge-free design and high-quality insulation. (Passive House Institute, Passivhaus Planning Package)
International Energy Conservation Code (IECC)	Model energy code with climate zone-specific requirements for building envelope, HVAC, lighting, and electrical systems.	Climate zone-specific requirements for building envelope, HVAC systems, lighting, and electrical systems.	(IECC, Chapter 5-8)	Building thermal envelope requirements include insulation, fenestration, and air leakage control. (IECC, Chapter 11)
ASHRAE Standards	Standards developed by ASHRAE related to energy efficiency, ventilation, and thermal comfort in buildings.	Energy Standard for Buildings Except Low-Rise Residential Buildings.	ASHRAE Standard 90.1	ASHRAE Standard 90.1 provides requirements for building envelope insulation and fenestration.
		ASHRAE Standard 62.1 : Ventilation for Acceptable Indoor Air Quality.	ASHRAE Standard 62.1	ASHRAE Standard 62.1 includes requirements for insulation and air barrier systems.
		Thermal Environmental Conditions for Human Occupancy.	ASHRAE Standard 55	ASHRAE Standard 55 addresses thermal comfort and thermal insulation in buildings.

represents a compound yearly growth rate (CAGR) of 12.3% from 2018 to 2026 [44].

5. Analytical assessments

This study examined the thermal performance of several glass combinations, as shown in Table 2 that are often used in building envelopes. These include single clear, double clear, double low-e, triple clear, triple low-e, laminated low-e, and insulated glass units with warm edge spacers.

Fig. 2 depicts several possible combinations of glass lamination that can be used as single, double, or triple-glazed. A material's thermal resistance is gauged by its R-value. Using Eq. (1), the R-value for each glass combination was determined.

$$R-\text{ value } = \frac{\text{thickness (m)}}{\text{thermal conductivity (W/mK)}} \quad (1)$$

The calculations' thermal conductivity data are from reliable sources utilized in the industry. The reciprocal of the R-value, the U-value, gauges a material's heat transfer coefficient. Using Eq. (2), the U-value for each glass combination was determined [46].

$$U-\text{ value } = \frac{1}{(R1+R2+R3+\ldots)} + \left(\frac{0.04}{A}\right) \quad (2)$$

R-value, U-value, thickness, thermal conductivity, and total area are a few metrics that may be used to assess the thermal performance of glass combinations.

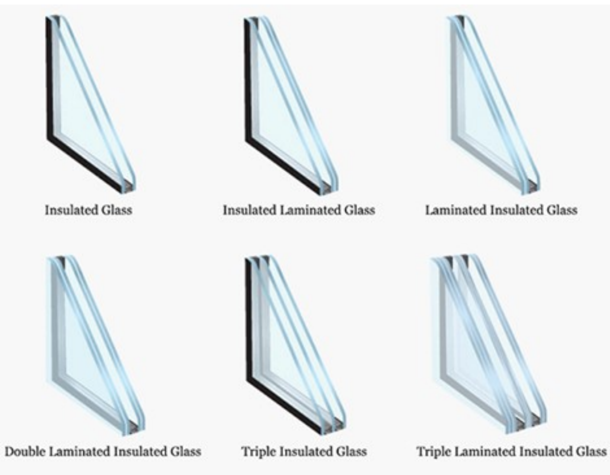

Fig. 2. A few possible combinations of glass lamination [4].

The R-value measures the thermal resistance of the glass combination in m^2K/W. The U-value, in contrast, calculates the heat transfer coefficient in W/m^2K. Along with the thermal conductivity, which measures the rate at which heat moves through a material in W/mK, the thickness of the glass layer is also essential. The R-values of each layer of the glass combination are represented by the letters R1, R2, R3, etc. A denotes the overall area of the glass combination in m^2.

Fundamental properties, including thermal conductivity, R-value, U-value, light transmission, solar heat gain coefficient (SHGC), sound reduction, and structural/mechanical strength, are summarized in Table 3. The performance characteristics of each glass type are listed in a table for easy comparison and evaluation [47].

Thermal performance estimates frequently use an assumed air film coefficient of 0.04 W/m^2K. These factors are necessary for determining the thermal performance of glass combinations and choosing the best setup for a given application. Fig. 3 shows the schematization of a typical Double-Glazed Unit with air/gas that can be for the window or envelope of a building.

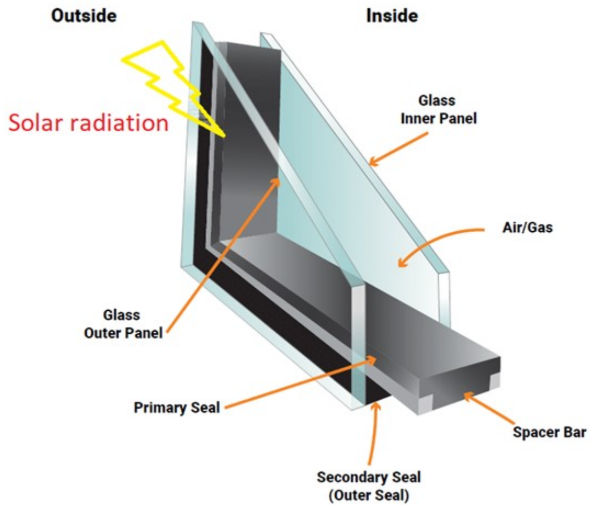

Fig. 3. Schematization of a typical Double-Glazed Unit with air/gas.

In conclusion, this study's approach comprised determining the R-values and U-values of several glass combinations often used in building envelopes. Each layer's thickness and thermal conductivity were used to determine the R-values. On the other hand, the R-values and air film coefficients were used to derive the U-values.

The key characteristics of each glass arrangement in Cases 1 to 9 are shown in Table 4. Light Transmission, Solar Heat Gain Coefficient (SHGC), Thermal conductivity, U-value, R-value, sound reduction, structural strength, and mechanical strength are just a few variables to consider when choosing glass for building applications. Light transmission is the quantity of visible light that may flow through glass. In addition, a lower SHGC denotes a re-

Table 2. Parameters and properties of glass used [45].

Glass Type	Thickness (mm)	U-value (W/m^2 K)	R − value (m^2 K/W)
Single Clear	6	5.80	0.17
Double Clear	6 + 6	2.80	0.36
Double Low-e coated	6 low e + 6 low e	1.89	0.53
Triple Clear	6 + 6 + 6	1.62	0.62
Triple Low-e	6 − 12 (gap)-6-12 (gap)-6	1.4	0.71
Laminated Low e	6 − 12 (gap)-6	1.56	0.64
Insulated Glass Unit with warm Edge Spacers	6 − 12 (gap)-4-12 (gap)-6	1.43	0.70
Insulated Glass Unit with warm Edge Spacers and Argon Fill	6 − 12 (gap)-6-12 (gap)-6	0.79	1.27

duced ability to transmit solar energy. Lower numbers indicate better insulation [48, 49]. The Thermal conductivity and the U-value assess how well any glass can conduct heat. Higher values indicate better insulation. The R-value evaluates the heat resistance of a glass, whereas the glass's capacity to reduce sound transmission is measured by sound reduction. As opposed to this, properties such as structural and mechanical strength evaluate the capacity to withstand external loads, strains, and forces like bending, impact, and thermal stresses. As stated in Table 5, these characteristics should be carefully considered when choosing the best glass structure for a particular application.

Essential metrics for assessing the thermal performance of building materials, including glass, are the R-value and U-value. The resistance of a substance to heat flow is indicated by its R-value. The U-value, in contrast, illustrates how quickly heat moves through a substance. Generally, a higher R-value and a lower U-value indicate superior thermal insulation performance [50–52].

5.1. R-value analysis

The capacity of a material to resist the flow of heat is represented by the R-value, which stands for thermal resistance. The higher the R-value, the material is more effective at insulating against heat flow. Table 6 shows that the R-values rise with the number of glass layers and/or the air gap thickness between the layers. This is because the additional layers and air voids increase the total thermal resistance by adding more obstacles to heat transfer. For instance, when Cases 1 and 2 are compared, the R-value nearly doubles when there are two transparent glass panes instead of just one. The R-value nearly doubles from a double low-e glass pane to a triple clear glass pane in Cases 3 and 4 similarly. It is important to note that laminated glass, the final column in each row, often has greater R-values than the other glass forms. This is because laminated glass has more layers and an interlayer with less heat conductivity than air, increasing thermal resistance.

The kind of glass, the coatings on the glass (such as low-e coatings), and the gas used to fill the space between the glass layers (such as argon) are other variables that can impact the R-values of Glass in addition to the number of glass layers and thickness of air gap.

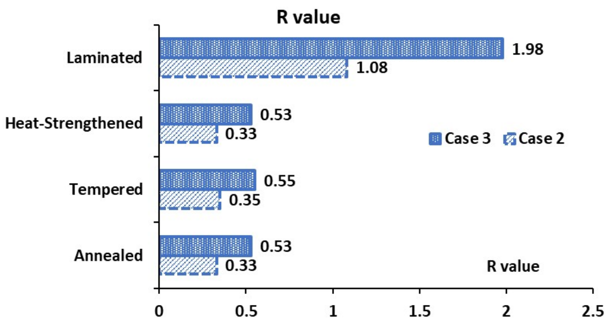

Fig. 4. Comparison of R-value for Case 2 (Double clear) and Case 3 (Double low-e) glass.

For instance, when Case 2 and Case 3 are compared using Fig. 4, the R-values for double clear glass and double low-e glass with a transparent pane are nearly identical. The R-value in Case 3 rises dramatically when the low-e coating is applied to the inner glass pane, proving that low-e coatings may significantly enhance the thermal Performance of the Glass. Comparing Case 5 to the other triple-pane arrangements, the introduction of argon gas in the air gap between the glass layers considerably enhances the thermal Performance of the Glass. In contrast, Case 8 significantly raises the R-value by employing laminated glass rather than clear glass because the interlayer adds additional heat resistance (refer to Fig. 5).

The R-values in the table are based on annealed, tempered, heat-strengthened, and laminated glass. There are many glass varieties with various thermal characteristics. The most common form of glass is annealed, whereas tempered and heat-strengthened glass has been strengthened. A layer of PVB is sandwiched between two panes of glass to create laminated glass. The R-value of a specific setup

Table 3. Parameters and properties of glass used [45].

Glass Configuration	Thermal Conductivity (W/mK)	R-Value (m^2 K/W)	U-Value (W/m^2 K)	Light transmission (%)	SHGC	Sound reduction (dB)	Structural/Mechanical Strength
Clear Glass	1.0	0.95	1.05	90	0.87	30	Moderate
Low-E Glass	0.5	1.90	0.53	80	0.42	35	High
Laminated Glass	0.8	1.20	0.83	70	0.68	40	High
Insulated Glass	0.7	2.50	0.40	65	0.35	40	High
Argon-Filled Glass	0.6	2.10	0.48	75	0.50	35	High

Table 4. Glass combinations from Case 1 to Case 9.

Case	Glass Combination	Configuration
1	Single clear	6 mm
2	Double clear	6 mm + 6 mm
3	Double low-e	6 mm low-e +6 mm low-e
4	Triple clear	6 mm + [12 mm] + 6 mm + [12 mm] + 6 mm
5	Triple low-e	6 mm low-e +[10 mm argon-filled cavity] + 6 mm low-e +[10 mm argon-filled cavity] + 6 mm low-e
6	Double low-e with argon fill	6 mm low-e +12 mm argon-filled cavity +6 mm clear
7	Triple low-e with argon fill	6 mm low-e +12 mm argon-filled cavity +6 mm low-e +12 mm argon-filled cavity +6 mm low-e
8	Laminated low-e	6 mm low-e laminated with 1.52 mm PVB interlayer +6 mm clear
9	Insulated glass unit with warm edge spacer	6 mm low-e +16 mm argon-filled cavity +6 mm low-e with warm edge spacer

may vary depending on the type of glass employed [53, 54].

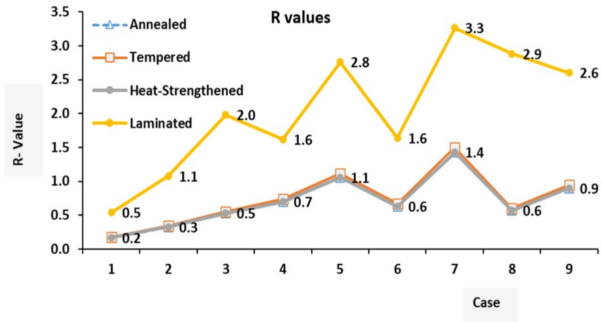

Fig. 5. Comparison of R values for the selected combinations.

5.2. U-value analysis

The U-value indicates the rate of heat transport through a substance. The ability of a material to resist heat transfer increases with decreasing U-value. To put it another way, a lower U-value denotes greater thermal insulation. Table 7 demonstrates that the glass configurations' U-values drop as the number of glass layers and/or the air gap's thickness grows. This is because the extra layers and air voids increase the barriers to heat transmission, lowering the heat transfer rate overall.

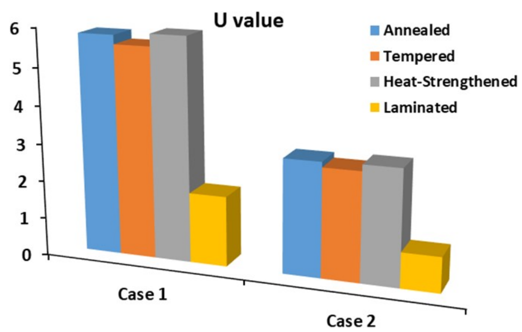

Fig. 6. Comparison of U value for Case 1 (Single clear) and Case 2 (Double clear).

For instance, when upgrading from a single clear glass pane to a double clear glass pane, the U-value drops by approximately half when comparing Cases 1 and 2 (See Fig. 6). From the comparison of Case 3 and Case 4 as shown in Fig. 7, switching from a double low-e glass pane to a triple clear glass pane reduces the U-value by almost half.

The usage of argon gas and low-e coatings both significantly affect the U-values. For instance, when a low-e layer

Table 5. Approximate values of fundamental properties for the considered glass combinations.

Case	Light Transmission	SHGC	Thermal Conductivity (W/m · K)	U-value (W/m^2 K)	R-value (m^2 K/W)	Sound Reduction	Structural Strength (MPa)	Mechanical Strength
1	High	Moderate	1.1	5.8	0.17	Moderate	50	Moderate
2	Moderate	Low	0.9	3.1	0.32	High	50 – 60	High
3	Low	Low	0.8	2.8	0.36	High	50 – 80	High
4	Low	Very low	0.7	1.8	0.56	High	50 – 100	High
5	Very low	Very low	0.6	1.2	0.83	High	50 – 120	High
6	Low	Low	0.8	2.2	0.45	High	50 – 80	High
7	Very low	Very low	0.6	0.9	1.11	High	50 – 120	High
8	Low	Low	0.8	2.5	0.40	High	50 – 80	High
9	Low	Very low	0.6	0.7	1.43	High	50 – 120	High

Table 6. R values for the selected combinations

Case	Annealed	Tempered	Heat-Strengthened	Laminated
1	0.17	0.18	0.17	0.54
2	0.33	0.35	0.33	1.08
3	0.53	0.55	0.53	1.98
4	0.70	0.74	0.70	1.62
5	1.06	1.12	1.06	2.76
6	0.63	0.67	0.63	1.64
7	1.43	1.50	1.43	3.26
8	0.57	0.60	0.57	2.88
9	0.90	0.95	0.90	2.60

Table 7. U values for the selected glass combinations.

Case	Annealed	Tempered	Heat-Strengthened	Laminated
1	5.8	5.56	5.88	1.85
2	3.0	2.86	3.03	0.93
3	1.9	1.82	1.89	0.51
4	2.4	2.06	2.44	0.62
5	1.0	0.89	1.02	0.36
6	1.6	1.49	1.59	0.61
7	0.7	0.67	0.70	0.31
8	2.8	2.65	2.81	0.35
9	1.1	1.05	1.12	0.38

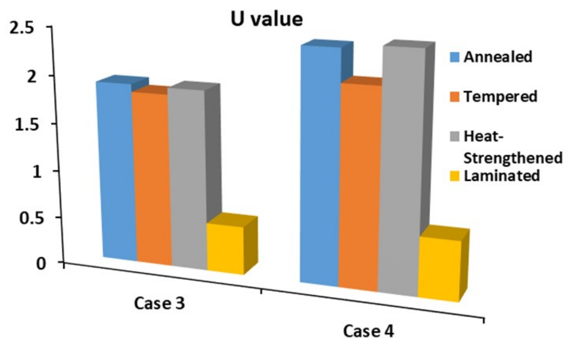

Fig. 7. Comparison of U value for Case 3 (Double low-e) and Case 4 (Triple clear).

is put to the inner glass pane, the U-value dramatically drops compared to Cases 2 and 3. Comparing Case 5 to the other triple-pane arrangements, the U-value is significantly lower due to the use of argon gas in the air gap between the glass layers. However, laminated glass reduces U-value since the interlayer adds heat insulation.

The U-values in Table 7 are based on annealed, tempered, heat-strengthened, and laminated glass; these are also shown in Figure 8 for brevity. As previously discussed, these glass materials have various thermal characteristics that might influence the U-value. Additionally, elements, including the size and orientation of the glass, the kind of frame being used to support the glass, and the regional environment, might impact the U-value of a particular glass arrangement. The size and orientation of the glass, the kind of frame used to support the glass, and the environment in the area can all impact the U-value of a given glass arrangement.

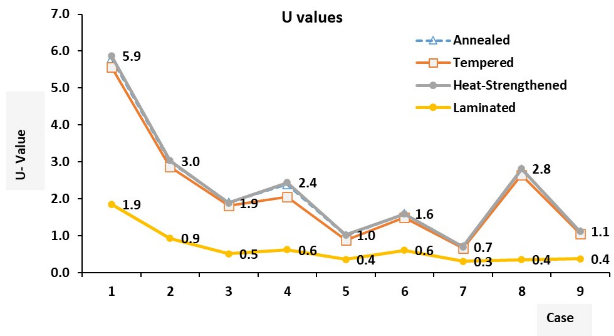

Fig. 8. Comparison of U values for the selected combinations.

For instance, larger windows often have higher U-values than smaller ones due to their larger surface areas for heat transfer. As a result of receiving more direct sunshine and heat, windows facing south or west often have greater U-values than those facing north or east. Additionally, because certain materials are better than others at insulating against heat transfer, the type of frame used to support the glass might impact the U-value. Remember that the U-value is one factor to consider when evaluating a glass construction's thermal performance. The solar heat gain coefficient (SHGC) also measures the amount of solar radiation that enters the building via the glass. Visual transmittance (VT) measures the visible light that passes through the glass. There are several factors to consider while deciding on the optimal glass layout, including the preferences of the building's owner or occupants. A laminated glass of the same thickness has smaller U values, so it is usually advisable.

According to the findings, single transparent glass has an R-value of 0.17 m^2K/W, whereas triple low-e glass with argon fill has an R-value of 3.26 m^2K/W. The U-values for single transparent glass vary from 5.8 W/m^2K to 0.31 W/m^2K for triple low-e glass with argon fill. The findings also demonstrate that insulated and low-e glass units often offer more thermal insulation than transparent glass. In contrast, double clear glass, which has an R-value of 0.33 m^2K/W, and double low-e glass has an R-value of 0.53 m^2K/W. Transparent triple glass has an R-value of 0.70 m^2K/W and insulated glass units with edge spacers have an R-value of 0.90 m^2K/W. Argon-filled glass combinations offer superior thermal insulation to those without. For instance, a triple low-e glass with argon fill has an R-value of 1.43 m^2K/W as opposed to 1.06 m^2K/W for a glass without argon fill.

In general, it is suggested to utilize glass with low solar heat gain coefficients and low U-values in hot areas with high solar radiation. A low SHGC number means that less solar radiation can penetrate the glass, which lowers the amount of heat entering the occupancy's interior. The quantity of heat that is carried through the glass is reduced when the U-value of the Glass is low, indicating that it has high insulation characteristics.

The local environment can considerably impact the U-value of glass considerations. For instance, it is recommended to utilize glass configurations with an SHGC of 0.25 or less and a U-value of 1.1 W/m^2K or less in hot and dry regions, such as those prevalent in the Middle East. It is advised to employ glass with an SHGC of 0.4 or less and a U-value of 1.6 W/m^2K or less in hot, humid regions like Southeast Asia. In colder climates, having a low U-value glass arrangement is also important to prevent heat loss. However, in hotter climates, it is essential to consider a configuration that reduces the heat that enters a building through its fenestrations.

The research shows that insulated glass units with warm edge spacers, laminated glass, and low-e glass provide better thermal insulation than transparent glass. Furthermore, argon-filled glass combinations offer better thermal insulation than non-argon-filled glass combinations. Architects and facade engineers may use these results to choose the optimal glass types and thicknesses for building envelopes in hot locations.

6. Results and discussions

The results show that low U-values and high R-values are characteristic of the best glass pairings for hot climates. The use of triple low-e Glass with argon fill, double low-e glass with argon fill, or an insulated glass unit with a warm edge spacer are all specifically recommended. The thermal insulation properties of laminated glass, low-e glass, and insulated glass units with warm edge spacers have been superior to those of transparent glass. Furthermore, argon-filled glass combinations provide better thermal insulation than non-argon-filled glass combinations. Consistent with previous research, this study confirms what others have found. The study's findings significantly impact architects and facade engineers in choosing the best glass kinds and thicknesses for building envelopes in hot climes. Architects and facade engineers may minimize cooling loads and increase energy efficiency by selecting glass combinations with greater R-values and lower U-values. It is important to remember that the calculations employed in this study are based on simplified assumptions and do not take edge effects, air penetration, and the solar heat gain coefficient into account. As a result, the actual thermal performance of an envelope for a structure may not match the projections made in this study.

Glass combinations with higher R-values and lower U-values, such as Cases 5, 7, and 9, are advised for applications with high thermal needs. This would apply to circumstances where it is essential to maintain a cozy interior temperature while using the least amount of energy possible for heating or cooling. For instance, a triple low-e glass with argon fill would be ideal for exterior windows in a cold region since it offers high thermal insulation and sun control to reduce heat absorption and loss through the glass. This glass in Case 7, is ideally suited for exterior windows. On the other hand, indoor applications with low to moderate thermal needs, including internal walls or ornamental glazing, are advised to use glass configurations with lower R-values and higher U-values, such as Cases 1 and 2. Some glass shapes could not offer sufficient insulation for outside windows in regions with severe temperatures.

Nevertheless, they may still separate interior rooms and let light in. For various applications, such as reducing noise transmission in a noisy location or supplying additional safety and security in a hurricane-prone area, other factors besides thermal performance, such as light transmission, solar heat gain coefficient (SHGC), sound reduction, and structural and mechanical strength, are crucial. The study's findings indicate that the thermal performance of building envelopes in hot areas depends on the choice of glass combinations.

Based on each glass configuration's essential characteristics, such as light transmission, solar heat gain coefficient (SHGC), thermal conductivity, U-value, R-value, sound reduction, structural strength, and mechanical strength, applications are suggested for each kind of Glass in Table 7. These generic recommendations might change based on building requirements and regional climate conditions.

It is significant to highlight that the calculations utilized in this study are based on simplified hypotheses and do not consider crucial elements such as the solar heat gain coefficient, air penetration, and edge effects. These elements should be considered during the design phase since they substantially influence the thermal performance of the building envelope. The figures employed in this study are also based on air film coefficients and industry-standard thermal conductivity values, which could not precisely reflect the thermal performance of particular glass products. Therefore, the actual thermal performance of a building envelope may not match the projections made in this study. In addition, this study only examined the thermal performance of typical glass arrangements utilized in building envelopes. Other elements, including shading devices, reflective coatings, and building orientation, were not considered. This study's findings may not necessarily apply to other regions because they are peculiar to hot climates. Finally, the accuracy of the study's findings may be constrained by the absence of experimental evidence to support them [28].

In conclusion, although the study offers insightful knowledge about the thermal performance of various glass combinations, several limitations must be considered when extrapolating the findings to design projects.

Future research on the thermal efficiency of glass combinations in building envelopes has several potential directions. First, future research might examine how various glass combinations and shading devices affect the thermal performance of building envelopes and how they interact with reflective coatings and shade devices. Second, edge effects might be researched to determine how they affect building envelopes' thermal performance and how they change with various glass combinations and frame systems. Thirdly, climate-specific research considering regional weather patterns and construction standards might consider the best glass combinations for various climates and places. Fourthly, by experimenting with various glass combinations in building envelopes, experimental valida-

Table 8. Recommended applications and corresponding glass thickness range

Case	Applications	Thermal and Solar Control Requirements	Recommended in	Glass Thickness Range (mm)
1	Indoor	Low	Interior partitions or decorative glazing	3-6
2	Indoor	Moderate thermal	Exterior windows in mild climates	4 – 10
3	Indoor or utdoor	High	Exterior windows in cold climates	6 – 12
4	Indoor or utdoor	High	Exterior windows in very cold climates	8 – 16
5	Indoor or utdoor	High	Exterior windows in extremely cold climates	10 – 20
6	Indoor or utdoor	High thermal and moderate solar control	Exterior windows in moderate to hot climates	6 – 12
7	Indoor or utdoor	High thermal and very high solar control	Exterior windows in extremely hot climates	8 – 16
8	Indoor or utdoor	High thermal requirements, moderate solar control	Exterior windows in hurricane-prone regions	8-16 or higher
9	Indoor or tdoor	High thermal and solar control	Exterior windows in hot and sunny climates	6 – 12

tion might be done to support the findings of earlier investigations. Finally, to forecast the thermal performance of building envelopes more precisely with various glass combinations, future research may apply sophisticated modelling approaches like computational fluid dynamics and dynamic thermal simulation.

Future studies might further our knowledge of building envelope thermal performance by addressing these study areas and assisting architects. Facade engineers make more educated choices about glass combinations in building design.

7. Conclusions

Architects and facade engineers should choose the best glass kinds and thicknesses when designing building envelopes in hot regions by considering the thermal performance of various glass combinations. Suitable glass configurations for a particular application should be carefully selected to achieve a comfortable and energy-efficient indoor environment while maintaining safety and security. This must be based on various factors, including thermal performance, light transmission, SHGC, sound reduction, and structural and mechanical strength. The discussion's main findings are summed up in the following, which also offer suggestions for feasible glass combinations in hot regions like Saudi Arabia and the Middle East.

For applications with exceptionally high thermal requirements, such as external windows in severely cold or hot regions, glass combinations with higher R-values and lower U-values provide greater thermal insulation performance. For indoor applications with low to moderate thermal needs, including internal walls or ornamental glazing, glass combinations with lower R-values and higher U-values are appropriate. Better thermal insulation is offered by low-e, laminated, and insulated glass units with warm edge spacers than by clear glass and by combining argon-filled glass with other types of glass. However, a building envelope's actual thermal performance might not match the estimations made in this study because of things like the solar heat gain coefficient, air infiltration, and edge effects. When choosing the best glass for a particular application, it is essential to consider the qualities of the glass configurations for light transmission and solar heat gain coefficient (SHGC). For colder areas, glass setups with higher SHGC values are appropriate.

In contrast, those with lower SHGC scores are ideal for warmer regions. When choosing glass for specific purposes, such as in noisy areas or hurricane-prone regions, structural/mechanical strength attributes should also be considered. Ultimately, expert advice is necessary to choose the optimal glass configuration for a specific application based on unique needs and regional climate conditions.

To further enhance building envelope thermal efficiency, the design process should consider using shading devices, reflective coatings, and building orientation. Although the findings of this research can be used as a starting point for choosing glass combinations. In addition, thorough simulations and professional advice are usually required to identify the best glass combinations for projects. To effectively forecast the thermal performance of building envelopes with various glass combinations in hot climates, it is advised to seek professional advice and use cutting-edge modelling approaches, such as computational fluid dynamics and dynamic thermal simulation.

Conflict of interest

The author declares that there is no conflict of interest in the publication of this article and that no known competing financial interests or personal relationships could have appeared to influence the work reported in this paper.

Funding

There is no funding sponsor for this work.

Data availability

The data used to support the findings of this study are included in the article.

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