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Multilayer Glazing Technologies: Key Performance Parameters and Future Perspectives

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Abstract

Previous studies show that a large part of the net energy demands of an office building is related to window heat loss and cooling demands induced by solar irradiance. Windows with improved thermal transmittance (U-value) and solar heat gain coefficient (SHGC or g-value) are important for reducing the related energy demands.

There is a scarcity of available scientific work addressing multilayer window technologies. Hence, in this study, simulations with the aim of identifying the parameters that play a key role in improving thermal performance of multilayer glazing units have been carried out. A state-of-the-art review is presented, alongside an overview of promising new products and future perspectives and improvement possibilities for multilayer glazing technologies.

It has been found that increasing the number of glass panes in the insulating glazing units (IGU) yields U-value reductions that decrease for each added glass pane. Cavity thicknesses between 8 and 16 mm were found to be optimal for IGUs with four or more panes. Reducing cavity gas thermal conductivity was found to impact IGU U-value. Improving low-emissivity surface coatings beyond the best-available technology has minor effect on U-value reductions.

In addition to the thermal performance of the glazing units, optical properties, aesthetics, ageing properties and robustness should be further studied before the use of such multilayer IGUs may be recommended. Preliminary numerical simulations have demonstrated that thermal stresses to the glazing units due to high cavity temperatures can pose a problem for the robustness and lifetime of such units.

1. Introduction

Buildings account for a significant part of the total manmade greenhouse gas emissions and energy use. Optimizing the building envelope and its components is one of the key factors for reducing the energy demand of buildings.

Windows are key elements in buildings that have an explicit goal of reducing energy demands both in operation and material use. Previous studies show that a large part of the net energy demands of an office building is related to window heat loss and cooling demands induced by solar irradiance [1, 2]. The balance between visual and energy aspects must also be addressed, as pointed out by Hee et al. [3] and it is crucial that the combined effects of solar heat gains and thermal losses must be investigated [4]. Large window areas are beneficial in terms of increasing daylight availability, whereas smaller window areas are desirable in terms of heat loss reductions [5-7].

In a study investigating façade design principles in nearly zero-energy buildings, Thalfeldt et al. [8] found that for an office building situated in the Danish climate with conventional windows (e.g. with 2- and 3-pane glazing units), heating demands dominated the energy balance of the building. However, when improving the thermal properties of the window and reducing U-values to 0.2–0.3 W/m^2K (e.g. windows with five- or four-pane glazing units), heat losses became negligible as the thermal insulation level was similar to that of the opaque parts of the envelope. These results indicate that the primary design optimization of the transparent façades in cold climates should be to improve the window thermal performance.

Increasing the number of glazing layers in insulating glazing units is an efficient way of reducing thermal transmittance values of the IGUs [2, 9]. However, one disadvantage of IGUs with several glazing layers is the increased weight of the IGU. In order to maintain the favorable thermal and optical properties while keeping the weight of the IGUs at an acceptable low level a solution would be to use non-structural intermediate layers in the IGU. The outer panes can be kept as thick as needed for maintaining the function of structural integrity, safety, soundproofing, etc. while the thickness of the intermediate layers can be reduced.

Using suspended foil is a promising window technology that is starting to permeate the market. Here, intermittent glazing layers in an IGU are replaced with thin, polymer films as discussed by Arasteh et al. [10]. This gives a substantial weight reduction of the glazing units compared to their all-glazed counterparts.

In two recent review articles of fenestration products, Jelle et al. [11] and Cuce and Riffat [12] present, among other topics, current and future glazing technologies. Multilayer glazing units using conventional float glass, suspended film technologies and ultra-thin glass technologies for future applications in glazing units are also discussed [11]. Miscellaneous energy aspects of windows and window frames in [2, 13, 14], and a state-of-the-art review and future perspectives on window spacers and edge seals in IGUs can be found in [15].

The total performance of a window is made up of three main components: the glazing unit, the frame and the spacer. With respect to frame and spacer technologies, suggested reading can be found in various studies in the literature [14-16].

However, there is a scarcity of published scientific work related to the topic of multilayer window technologies. Thus, in this study, an overview of promising new products, applications and future perspectives and improvement possibilities for multilayer glazing technologies are presented. The focus of the optimization study carried out in this work is the improvement of the thermal properties of the windows.

2. Glazing units – thermal properties

The following discussion is related to the centre-of-glazing thermal performance of an IGU. Edge-of-glass losses due to the spacers and window frame effects are not included in this work. The reader may find more information in the work carried out by Gustavsen et al. [14, 16].

The total heat transfer in a glazing unit is the sum of gas convection, conduction and radiation as well as the solid-state conduction in the glass panes. One or more of these heat transfer mechanisms can be reduced in order to improve the thermal performance of the IGU.

The bulk of the heat resistance in an IGU is made up of the surface heat transfer coefficients and the thermal resistance of the cavities in the IGU. It is primarily the heat resistance of the cavities that can be increased in order to lower the thermal transmittance (U_{cog}-value) of the IGU. The U-value is the inverse value of the total heat resistance of the centre-of-glazing. The thermal resistance of a single cavity, R_{cavity}, is affected by the sum of the three heat transfer mechanisms: gas conduction, convection and radiation.

3. Methodology

The performance of glazing units is complex to assess. Thermal performance are possibly the most important parameter alongside optical performance, but factors like aesthetics, durability, robustness and environmental impact are all crucial aspects that need to be addressed in order to make a well-functioning glazing unit and ultimately a window. The weight of the glazing units should also be included as both mounting and operating the windows become cumbersome when the weight increases. For refurbishment, this is important, especially when mounting glazing units in old frames.

To limit the scope of this study, mainly the thermal performance improvement possibilities related to the thermal transmittance value (U-value) have been assessed. Further research regarding optical and other aspects should also be evaluated based on the results found in this study, as the U-value is a key performance parameter, especially in cold climates.

A parametric study of centre-of-glazing U-values of IGUs with three to ten panes have been carried out, where the effects of varying the cavity thickness, emissivity of glass panes and cavity gas thermal conductivity have been assessed using the WINDOW software [17] . All values have been calculated according to ISO 15099 [18] using standardized boundary conditions as given in ISO 10077-1 [19].

In addition to assessing the thermal performance, thermal stresses to the IGU caused by high temperatures in central cavities of the IGU are discussed.

4. Future improvement possibilities – Key elements

4.1 Cavity thickness

Figure 1 show U_{cog}-values for different cavity thicknesses as a function of the number of panes in the IGU. The U_{cog}-values are calculated under the assumption that gas thermal conductivity and surface emissivity are kept constant at 0.00516 W/(mK) (xenon at standard temperature and pressure conditions (STP) of T = 0 °C and p = 101 kPa) and 0.01, respectively. Changing the thickness of the cavities in the IGUs was found to have a substantial effect for all samples regardless of the number of panes in the glazing unit. One can observe that increasing the cavity thickness from 4 to 8 mm yielded U-value reductions of approximately U = 0.1 to 0.2 W/(m²K). A further increase of cavity thickness had a minor effect on the calculated U-values as shown in Figure 1 and Table 1. Furthermore it is clear that every additional pane added to the glazing unit has a diminishing effect in decreasing the U_{cog}-value.

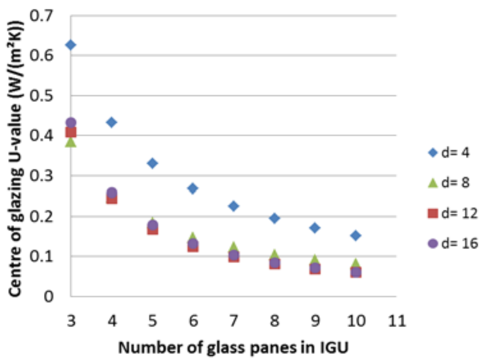

Figure 1. U-value for centre-of-glass as a function of the number of glass panes for different cavity thicknesses (d = 4, 8, 12 and 16 mm).

4.2 Improved glazing surface emissivity

Figure 2 (left) show calculated U_{cog}-values for different qualities of the low-e coating of the glass panes as a function of the number of glass panes in the IGU. The U_{cog}-values are calculated under the assumption that gas thermal conductivity and cavity thicknesses are kept constant at 0.00516 W/(mK) (xenon at STP) and 12 mm, respectively. It can be seen that reducing the emissivity of the glass panes gives a theoretical reduction potential that is small compared to that of adding additional glass panes. Reducing the emissivity further than what is available on the market today (emissivity lower than 0.013) gives a resulting U_{cog}-value reduction potential of 6 to 10 % depending on the number of panes, as shown in Figure 2 and Table 2. The reduction potential is low regardless of the number of glass panes in the IGU.

4.3 Improved gas thermal conductivity

Figure 2 (right) show calculated U_{cog}-values for different gas conductivities as a function of the number of glazing layers in the IGU. The effective thermal conductivity of a gas filling varies, depending on several factors like cavity thickness, temperature gradients, etc. Thus, the gas thermal conductivities given in Figure 6 and Table 3 are for still gas at STP of T = 0 °C and p = 101 kPa. A conductivity of 0.005 corresponds to the thermal conductivity value of xenon at STP (λ = 0.00516 W/(mK)). In the simulations, however, convection effects are accounted for, thus reducing the effective conductivity used in the calculations. The lower thermal conductivity values could be considered as xenon at lower pressures than 101 kPa.

The calculations show that a reduction of gas thermal conductivity of the gas fillings can give a substantial reduction in the U_{cog}-values. Halving the thermal conductivity will reduce the U_{cog}-value by approximately 25 % for the three- and four-pane IGUs. For a four-pane IGU, the U_{cog}-value reduction caused by halving the gas filling improves the U_{cog}-value similar to that of adding an additional pane to the IGU.

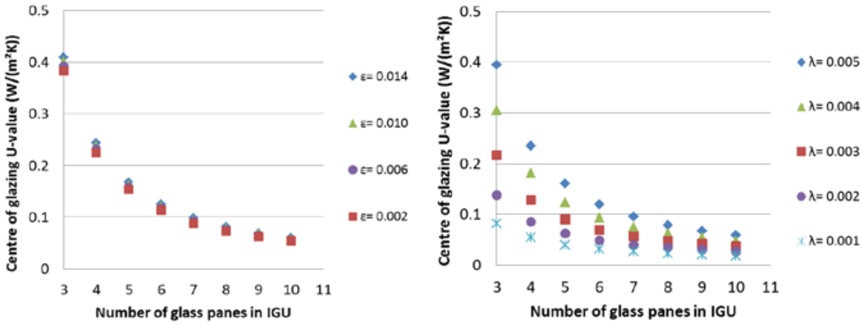

Figure 3. U-value for centre-of-glass as a function of the number of glass panes for different emissivity of the reverse side (i.e. the surface facing the interior) of each glazing layer (left). U-value for centre-of-glass as a function of the number of glass panes with different gas thermal conductivities. Surface emissivity and cavity thicknesses are kept constant at 0.014 and 12 mm, respectively. (right)

4.4 Temperature peaks in centre-layers

Simulations carried out using the WINDOW software [17] for a worst-case scenario for a ten-pane glazing unit with xenon gas fillings, low-e coatings with emissivity 0.013 and 12 mm cavity thicknesses using CEN summer conditions, $T_{interior}$ = 25 °C, $T_{exterior}$ = 35 °C and an incident solar flux of 500 W/m² [18] gave a maximum surface temperature of 130 °C on the interior side of glazing number 4 (counted from the outside).

Hence, internal temperatures in multilayer structures might be a limiting factor in terms of durability, in particular for thin polymer-based intermediate layers, and should be further studied.

5. Systems – Multilayer IGUs

There are several producers of multilayer glazing units using different technologies. Multilayer windows as discussed here can be divided into the following three main categories: 1) Multilayer all-glass products, 2) Outer glass layers with suspended polymer foils and 3) All-polymer-based products.

The following section is an overview of some producers of systems and components for multilayer glazing units fitting into the three categories mentioned above.

5.1 Traditional insulated glazing units

By far the most common construction for a modern IGU uses glazing layers approximately 4 mm or thicker. Cavities are gas-filled and a selection of the glass panes is coated with low-e films. These films are typically placed on glazing surface number 3 (counting from the outside) in a two-pane window. Glazing surface numbers 2 and 5 are typical placements for low-e coatings in three-pane IGUs. The low-e coatings are vital in reducing U-values of an IGU, even if the low-e coatings will, in general, result in a reduction of the visible solar transmittance of the IGU. The best-performing commercially available low-e coating has an emissivity of 0.013 [20].

5.2 Multilayer all-glass products

Multilayer all-glass products are products where the entire unit (i.e. the transparent parts) is made of glass. The traditional IGUs belong to this category. New products using thin glass layers with thicknesses as small as 0.1 mm are available on the market. Figure 4, shows two system which both have a total thickness of 160 mm and uses ten intermediate layers placed parallel (left) and in curves (right) to the inner and outer panes The benefit of using thin intermediate glass layers is primarily that of weight reduction of the IGU. A thinner glass pane will also absorb less solar energy, thus maintaining higher solar gains and visible solar transmittance values than a thicker glass pane.

Figure 4. Cross-section of the Superwindow 160 STACK (left) and the 160 TWEED (right) [21, 22].

5.3 Multilayer glass/polymer combination products

Multilayer glass/polymer combination products are glazing units similar to the all-glass units where the exterior structural (i.e. load-bearing) layers are made of traditional glass. However, instead of intermediate glass layers, polymers (or similar materials) are used to create the multi-cavity glazing unit.

The structural stability of a multilayer glass/polymer combination system like this is dependent on several factors. Existing products using polymer-based intermediate layers have been prone to shrinking and/or swelling of the polymer. This phenomenon affects the visible qualities of the window as it creates wavelike patterns in the foils. Proper installation of the foils is vital in order to provide durable windows. No literature describing ageing and robustness have been found for the Visionwall products.

5.4 Multilayer all-polymer products

The third category of multilayer IGUs is entirely made of polymers (plastic). The entire system is made of plastic/polymer and it is primarily designed for refurbishments of existing windows.

5.5 Product summary

Key parameters of the various window systems are given in Table 4. Key properties for different film technologies are given in Table 5. The 3-, 4-, and 10-pane traditional units have been calculated with xenon gas fillings and low-e coatings (e = 0.013) on one of the glass panes facing each cavity.

Table 4. Key parameters for the glazing systems. IGU weight is given for weight of glass/foils only. Weight of spacers is not included.

Window type / manufacturer	U_{cog}-value (W/(m²K))	SHGC (-)	T_{vis} (-)	Weight of IGU (kg/m²)	Thickness of IGU (mm)	Ref.
3-pane traditional	0.43	0.35	0.58	26	36	[20]
4-pane traditional	0.24	0.29	0.48	35	52	[20]
10-pane traditional	0.07	0.13	0.19	88	148	[20]
All-glass: Superwindow STACK	0.30			20	160	[22]
All-glass: Superwindow TWEED	0.72			20	160	[21]
All-glass: Qbiss Air	0.2-0.5	0.09-0.34	0.1-0.56	55-125	117-149	[23]
Glass/polymer: Southwall SGQ TC88	0.46	0.39	0.5	18		[24, 25]
Glass/polymer: Visionwall 4-Element	0.82 (whole window)	0.26	0.46	18		[26]

Table 5. Product summary of the thin glass and polymer non-structural centre-glazing layers.

Film type / Brand name	Glass	Polymer	Low-e coating?	Thickness (μm)	Reference
AGC-glass (Asahi Glass)	X		No	100	[27]
Schott	X		No	25–100	[28, 29]
Corning	X		No	100	[30, 31]
DuPont		X	Yes (0.66)	51	[32, 33]
Heat Mirror		X	Yes (0.02)	76	[34-36]

6. Conclusions

There is a lack of available scientific studies regarding multilayer glazing technologies, i.e. insulating glazing units (IGU) utilizing several layers of thin glass and/or polymer-based non-structural intermediate layers. Selections of products using only glass, glass in combination with polymer-based intermediate layers and all-polymer-based units on the market have been identified and discussed.

Simulations with the aim of identifying the parameters that play the key role in improving thermal performance have been carried out. Increasing the number of glass panes in the IGU yields U-value reductions that decrease for each added glass pane. Further research should be coupled with life cycle assessments in order to investigate if there is an optimal number of panes when embodied energy is also accounted for. Further improving the low-e surface coatings of panes in an IGU yields little improvement possibilities compared with today’s state-of-the-art technologies. Cavity thicknesses between 8 and 16 mm were found to be optimal for IGUs with four or more panes. Only small variations within the 8 to 16 mm range were found. Hence, cavities can be kept at 8 mm in multilayer IGUs in order to keep the total thickness of the IGU as thin as possible. Reducing the gas thermal conductivity was found to have the largest impact on the U-value. The effect gets less pronounced with an increased number of panes in the IGUs.

In addition to the thermal performance of the glazing units, optical properties, aesthetics, ageing properties and robustness should be further studied before the use of such multilayer IGUs may be recommended. Preliminary numerical simulations have demonstrated that thermal stresses to the glazing units due to high cavity temperatures can pose a problem for the robustness and lifetime of such units. However, the reliability of these results should be treated with caution and further studies and validation experiments of the algorithm used in the software should be carried out.

Further studies should be carried out keeping the following factors in mind: improved solid materials (i.e. lowered thermal conductivity and/or weight of glass or polymer layers), geometry of intermittent layers, reduce weight without comprising the performance, prevent/slow the ageing processes and reduce/prevent temperature peaks in central layers.

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