High-Performance Windows

Dr. Helen Rose Wilson
Interpane Entwicklungs- und Beratungsgesellschaft mbH & Co. KG, Lauenförde
c/o Fraunhofer ISE, Heidenhofstr. 2, 79110 Freiburg, Germany
Email: Helen.Rose.Wilson@ise.fraunhofer.de,
Tel. +49 761 4588-5149, Fax +49 761 4588 -9000

1. Introduction

A "high-performance window" today is one that ensures optimal visual and thermal comfort for the people occupying the corresponding room and simultaneously helps to minimise the amount of non-regenerative energy consumed in the building. With its position in the building envelope, separating the exterior from the interior, it is clear that the window must have properties which are appropriate to the prevailing conditions, both climatic and concerning the building properties and usage. As a result, a considerable range of high-performance windows is already commercially available, and further types are under development. This paper describes such windows and approaches for making an appropriate selection for a specific application. Examples from Interpane's product range are used to illustrate the variety of high-performance glazing types that are commercially available to meet today's wide range of architectural applications.

2. Technical Properties of Windows

2.1 Thermal transmittance - U value

As the temperature range in which people feel comfortable, about 18 to 26 °C, is much smaller than the range of outdoor temperatures, one of the main functions of a window is to reduce the heat flow between indoors and outdoors, i.e. to provide good thermal insulation. The thermal transmittance (or heat transfer coefficient), the so-called U value, quantifies the rate of heat flow through a specimen, in units of heat flow per unit area per degree of temperature difference between indoors and outdoors, and is specified in units of $Wm^{-2}K^{-1}$ (SI) or BTU $h^{-1}ft^{-2}°F^{-1}$ (imperial). The relevant European standards, EN673 and EN674[1], specify a temperature difference of 15 K between the external and internal glazing surface temperatures, whereas North American standards refer to the difference between the external and internal air temperatures.

A single pane of glass, 4 mm thick, has a U_g value of 5.8 $Wm^{-2}K^{-1}$. The U_g value according to EN673 refers to the value at the centre of glazing alone, not to the whole window, which is specified by U_w and includes the effect of the frame and the glazing edge. Increasing the thickness of a single glass pane does not have a significant effect on the U_g value, as a 10 mm pane still has a value of 5.6 $Wm^{-2}K^{-1}$. A more effective reduction is achieved by constructing double glazing, where the insulating effect of a 16 mm air-filled gap approximately halves the U_g value to 2.6 $Wm^{-2}K^{-1}$.

However, air-filled double glazing has been superceded by a new generation of glazing that more than halves the U value again. This truly "high-performance" glazing achieves U values of 1.2 $Wm^{-2}K^{-1}$ and lower by including an almost invisible, thin silver coating on one of the gap-facing glass surfaces to reduce radiative heat losses, and filling the gap with argon to suppress heat transfer by convection and gas conduction.

The U_g value can be further suppressed by measures such as adding further panes and low-emissivity silver coatings and filling the gap with krypton instead of argon. By combining all measures, U_g values down to 0.5 $Wm^{-2}K^{-1}$ can be achieved and are offered in commercially available glazing units. These very low U_g values are particularly interesting where large differences between the outdoor temperature and the desired indoor temperature occur, which can already be the case in Central Europe.

2.2 Total solar energy transmittance - g value

Whereas the U value is an important characteristic of all building envelope components, including opaque ones like walls or roofs, the g value is mainly of interest for transparent components such as glazing. It is defined as the ratio of solar heat gain through a window to the solar radiation striking the outer surface, for a given incidence angle (usually perpendicular to the glazing surface, e.g. as in EN410[2]) and given environmental conditions (indoor and outdoor temperature, wind speed)[3]. The total solar energy transmittance is the sum of two components: the solar radiation which is transmitted by the glazing unit, and that portion of solar energy that is initially absorbed in the glazing and is then transferred as heat to the indoor environment. In addition to the term "total solar energy transmittance", the g value is also known as the solar heat gain coefficient (SHGC) or solar factor.

The ideal g value for a window is one that is high enough to allow solar radiation gains to heat a room effectively in winter, reducing the need for conventional space heating, but low enough to avoid overheating in summer. In general, a higher g value will thus be preferable in cooler climates and for smaller windows, whereas warmer climates and larger windows call for lower g values. Glazing with a g value lower than about 0.5 is often called "solar control" glazing, as it is intended for situations with abundant solar radiation that needs to be controlled to avoid overheating problems. Values down to about 0.2 are generally available on the European market and lower values are obtainable if necessary. By contrast, g values up to 0.64 are offered for high-performance windows intended for use in cold climates.

2.3 Visible transmittance - τ_v

The third important technical characteristic of glazing is its visible (or light) transmittance τ_v, defined as the ratio of light transmitted by the glazing to light incident on the glazing, for perpendicular incidence if not specified otherwise. "Light" is defined by the photopic sensitivity spectrum of the human eye, $V(\lambda)$, and a standard illuminant such as D_{65}, specified by CIE[4].

Generally a higher value of τ_v is desirable, leading to more daylight indoors and associated psychological benefits, although in specific cases a low value may need to be chosen, e.g. if the contrast becomes too great for work with computer monitors. Values up to 0.81 can be obtained for high-performance glazing.

2.4 Other characteristics

The visible reflectance (outdoors) ρ_v specifies the ratio of incident light that is reflected to the outside by the glazing. In some locations where e.g. reflection of sunlight could present a visual hazard to traffic, an upper limit may be specified.

The general colour rendering index R_a is a quantitative measure for the "trueness" of colours perceived in light that has been transmitted through or reflected by a glazing unit. It is determined by calculating the colour differences for eight standard colour samples when they are illuminated with a standard illuminant such as D_{65} or with the same illuminant filtered through the glass. As a guideline, colour rendering indices > 90 indicate that colours are very well represented and values > 80 are still considered good in lighting technology.

Selectivity, S, is defined as the ratio of visible transmittance to total solar energy transmittance, τ_v:g. This characteristic is of particular interest for solar control glazing in situations where solar gains are to be suppressed but a high lighting level is still desired. If the glazing transmittance spectra are optimised to transmit as much light as possible, but to block solar radiation outside of the visible range, it can attain a maximum value of about 2.

3. Types of High-Performance Glazing

3.1 Thermally insulating or "low-e" glazing

The most widespread type of high-performance thermally insulating glazing, often called "low-e glazing", is illustrated in fig. 1. "Low-e" is an abbreviation for "low emissivity", and refers to the property of the thin silver coating on at least one of the glass surfaces that results in high reflectance of infrared radiation or heat. In insulating glazing units (IGU's), which are designed for cooler climates, this coating is located on the gap-facing surface of the indoor pane, so that the maximum amount of room heat is reflected back into the building. To ensure that as much solar radiation as possible is transmitted through the glazing into the room, the silver film is sandwiched between thin dielectric films that reduce the reflectance of the coated glass in the solar spectral range. Thus, relatively high g and τ_v values of 0.64 and 0.81 are combined with a U_g value of 1.2 $Wm^{-2}K^{-1}$ for the example illustrated, using 4 mm glass and a 16 mm cavity filled with argon.

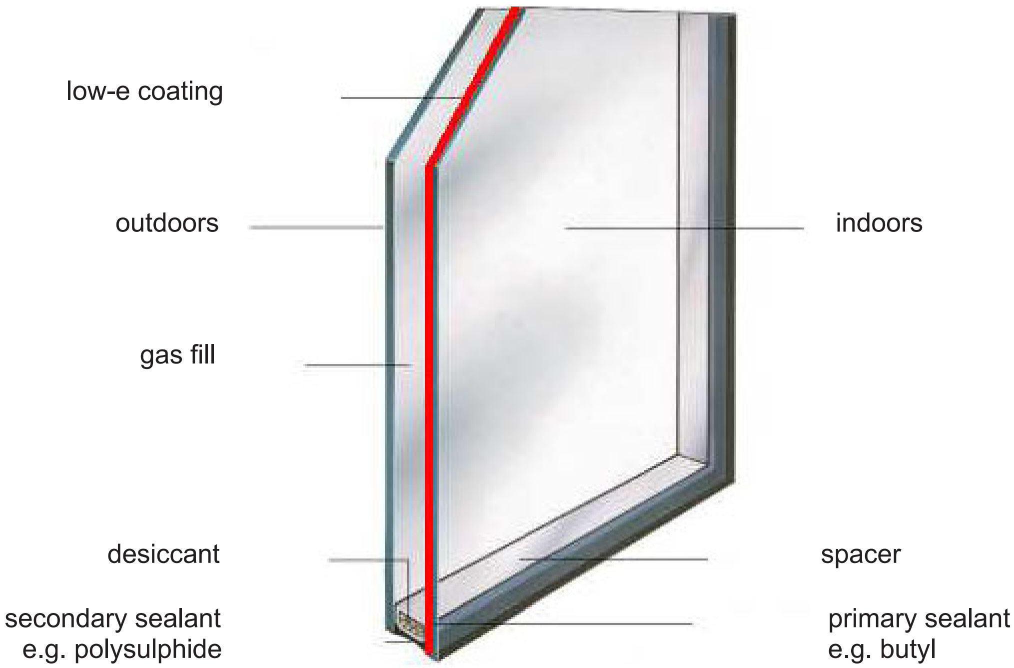


Fig. 1: Construction of a thermally insulating or "low-e" insulating glazing unit (IGU). Source: Interpane, Lauenförde

As already discussed in section 2.1, the U_g value can be further suppressed by measures such as adding further panes and low-emissivity silver coatings and filling the gap with krypton instead of argon. Figure 2 demonstrates the changes in U_g and g values which result from these measures. Replacing argon by krypton allows a lower U_g value to be achieved with a thinner construction, without changing the transmittance values. By contrast, the g value is reduced significantly when a further pane or a low-e coating is added. The most appropriate combination of U_g and g value will depend on climatic conditions and the window-to-wall ratio. With τ_v values exceeding 0.70 even for triple glazing with two low-e coatings, adequate daylighting is easily achieved with this type of window.

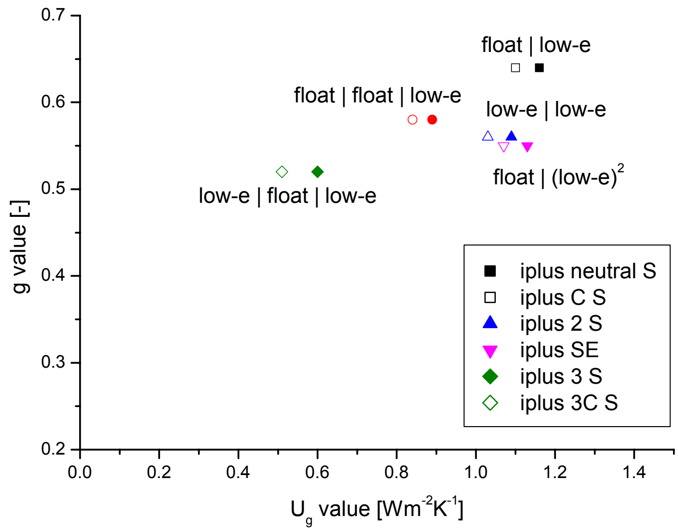


Fig. 2: Total solar energy transmittance (g value) versus thermal transmittance (U_g) for "low-e" glazing. Each pair of points is labelled with the corresponding glazing configuration, with the gas-filled gap represented by the symbol "|". The solid symbols refer to IGU's with 16 mm argon-filled gaps; the hollow symbols refer to IGU's with 12 mm krypton-filled gaps. Values calculated according to EN410 and EN673, using examples from Interpane's iplus® product family[5].

3.2 Solar-control glazing

Effective solar-control glazing is always characterised by U_g values of 1.2 $Wm^{-2}K^{-1}$ or less, as it needs to provide good thermal insulation between a warm outdoor environment and comfortably cooler indoor conditions. The name "solar control", however, refers primarily to the deliberate reduction of solar gains transmitted into the room to 50% or less. It is again best achieved with a coating consisting of thin silver and dielectric films, but in this case, the thicknesses are optimised to obtain the desired combination of g and τ_v values. In accordance with the aim of keeping solar heat out of the building, the coating is typically located on the gap-facing surface of the outdoor pane, as shown in fig. 3, so that incident radiation is effectively reflected and as much of the secondary heat gain as possible is transferred outwards.

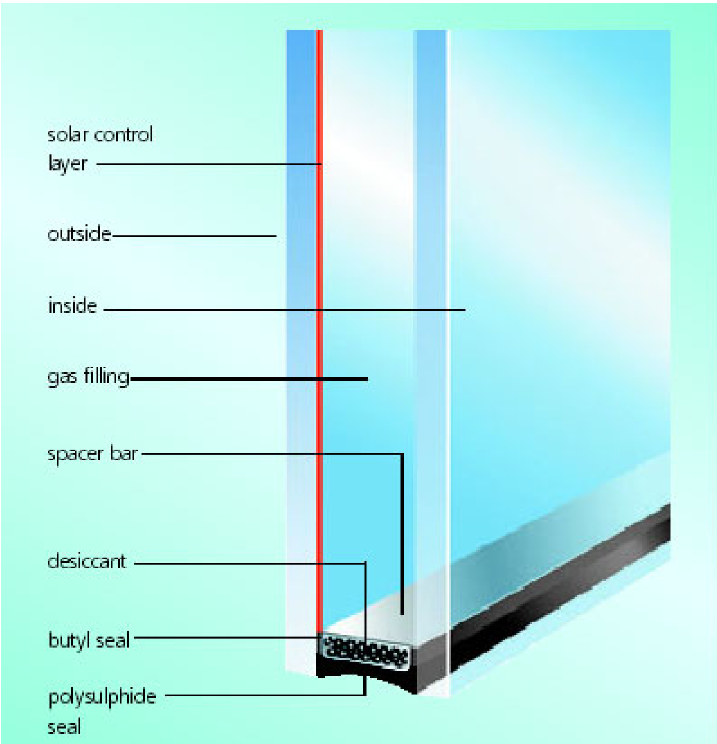


Fig. 3: Construction of a solar-control glazing unit (IGU). Source: Interpane, Lauenförde

Some coatings are optimised to be highly selective, transmitting as much light as possible while reducing the total solar energy transmittance significantly. Others are intended to provide both reduced g and τ_v values. Figure 4 illustrates some of the possible combinations. Although some solar-control glazing units are neutrally coloured, other products are designed to be coloured or metallic in their outward appearance, to provide different architectural options. Nevertheless, they are usually also designed such that the transmitted light retains good colour neutrality, with R_a values in transmission exceeding 90.

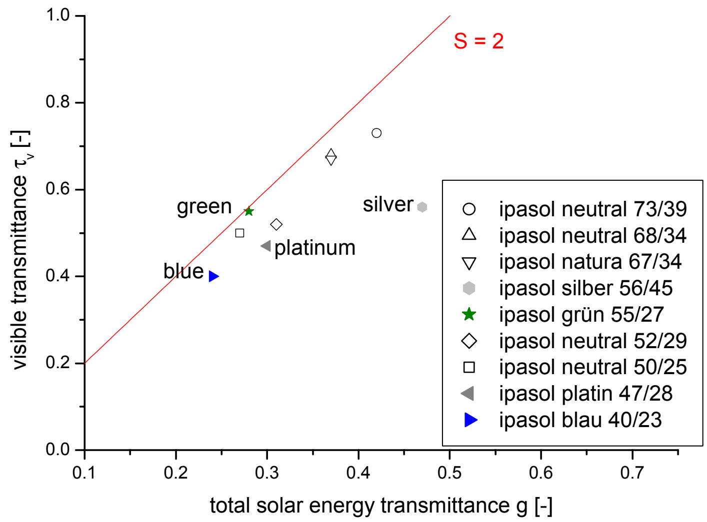


Fig. 4: Visible transmittance versus total solar energy transmittance for some solar-control IGU's. The hollow symbols indicate IGU's, which give neutral colour rendering in transmission and reflection. The colour labels refer primarily to the outward reflected appearance. The red line corresponds to a selectivity value of 2, indicating the maximum ratio of visible transmittance to total solar energy transmittance. Values calculated according to EN410, using examples from Interpane's ipasol® product family[6].

In order to minimise thermal stress on the glass, it is preferable to reduce the transmittance by a combination of reflection and absorption, as occurs with coated glass, rather than by absorption alone, as is the case for body-tinted glass. Another approach to increase the reflectance is to add a light-scattering ceramic coating to the gap-facing surface of the outdoor pane. Depending on its thickness, a white ceramic coating can decrease the transmittance and increase the outward reflectance by factors of about two to four. It should be noted that in this case, it is not possible to see through the glazing. Instead, it appears translucent or opaque. Accordingly, the significant transmittance and reflectance values should be specified as normal-hemispherical quantities (rather than normal-normal, as for non-scattering glazing), so that all of the energy entering the building is taken into account.

3.3 Chromogenic glazing

Chromogenic glazing, characterised by the property of variable transmittance, is able to respond appropriately to varying external environments, so that its potential for improving the visual and energy-saving conditions in buildings is still greater than glazing with unchanging technical characteristics. Different physical mechanisms are exploited to achieve switching in the selection presented here, which corresponds to products that are either on the market or close to market introduction. A further criterion is that there be significant switching of the g value, ruling out the switchable glazing based on polymer-dispersed liquid crystals that protects privacy by switching between an opaque and a transparent state, but does not significantly change the g value[7].

3.3.1. Gasochromic glazing system

The optically active component of a gasochromic IGU is a film of WO_3, less than 1 µm thick, which is coated with a thin film of a catalyst[8]. It is located on the inner surface of the outer pane of a triple IGU (Fig. 5). When the gasochromic film is exposed to a low concentration of hydrogen (well below the combustion limit of 3 %) in a carrier gas of argon or nitrogen, it colours blue. This reduces the visible and total solar energy transmittance values of a triple glazing unit from 0.63 and 0.49 to 0.20 and 0.17 respectively, when the indoor pane is coated with a standard low-e coating. If a solar-control coating is used in this position, lower g values can be obtained. On exposure to a low concentration of oxygen, the WO_3 film bleaches to the original transparent state. The gas mixture is introduced into the cavity between the outer and middle panes of a triple IGU. The second gas-filled cavity and third pane with its low-emissivity coating ensure that the IGU has a low U_g value of 0.9 $Wm^{-2}K^{-1}$.

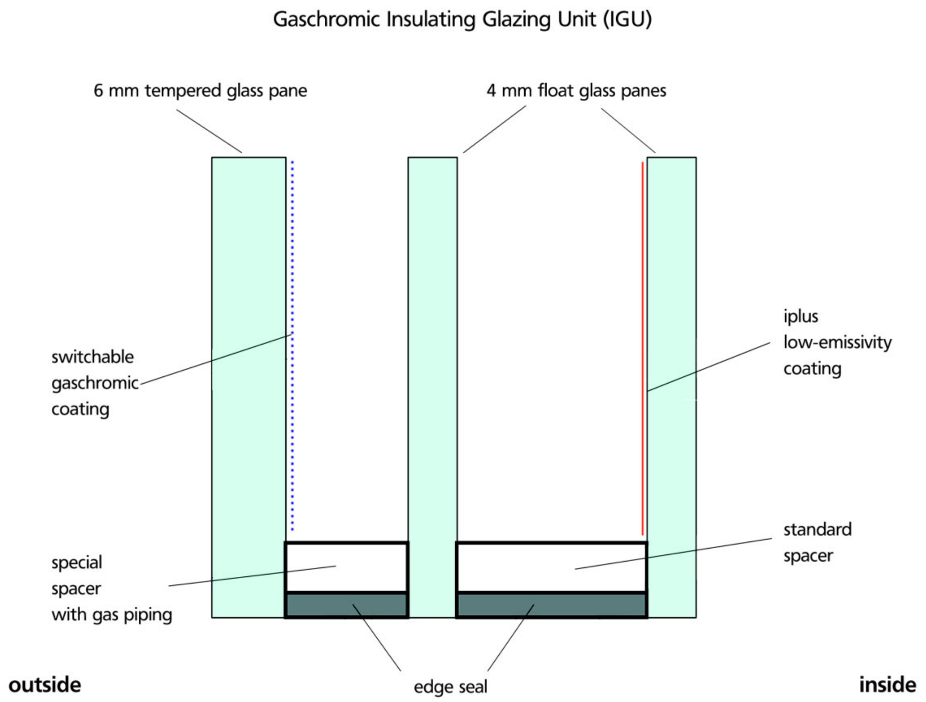


Fig. 5: Cross-section through a gasochromic IGU[9]

Clear visibility from inside to outside is retained in all switching states. In contrast to conventional, external shading systems, gasochromic glazing can also be used in the upper storeys of high-rise buildings.

In addition to the gasochromic insulating glazing unit, a gasochromic fenestration system has two further main components, a gas supply unit and a control unit.

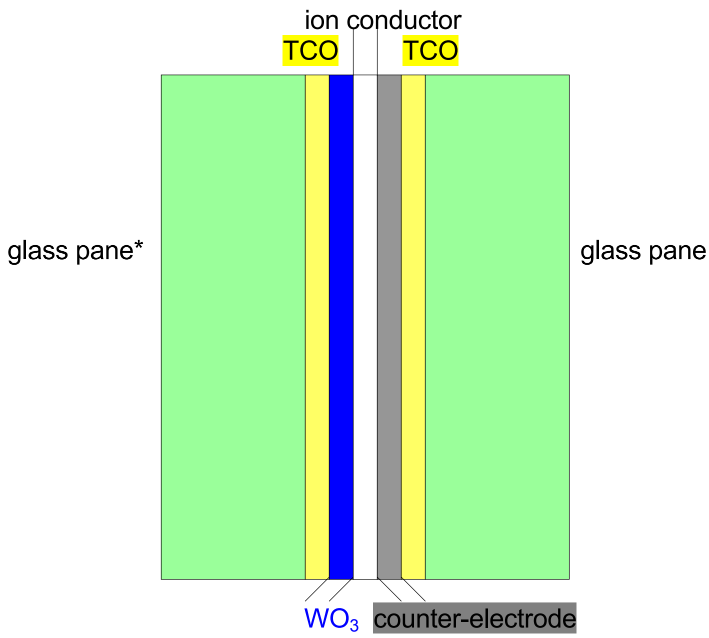
The gas supply unit consists of an electrolyser and a pump, which is connected by pipes to the window in a closed-loop configuration. Ideally, the gas supply unit is integrated into the external building facade. One gas supply unit is able to provide sufficient gas to switch 10 m^2 of gasochromic glazing.

The control unit allows both manual and automatic control. Integration into a bus system allows the glazing to be switched to optimise lighting conditions, thermal comfort and/or building energy consumption.

Gasochromic glazing is currently commercially available from Interpane for field-testing in buildings.

3.3.2 Electrochromic glazing

The same active component, a thin film of WO_3, is also employed in electrochromic glazing, but here it is sandwiched between other films that act as transparent conductors, ion conductor and counter-electrode, as illustrated in fig. 6.



** A second glass pane is needed if a polymer ion conductor is used, but is not required with a ceramic ion conductor.*

Fig. 6: Cross-section through an electrochromic glazing element.

Two different concepts are currently being pursued. One uses a polymer ion conductor as the laminating material between two glass panes, the other is an all-solid-state system that can be deposited as a series of coatings on a single glass pane. When a voltage is applied between the two transparent conducting oxides, lithium or hydrogen ions are intercalated into the tungsten oxide layer for the darkening process, and are extracted to cause bleaching. As an example, an electrochromic laminate combined with a low-e coated pane switches the g value from 0.36 to 0.12 and τ_v from 0.50 to 0.15, for a U_g value of 1.2 $Wm^{-2}K^{-1}$.[10] Absorption in the transparent conducting oxide layers reduces the maximum possible transmittance compared to that of the gasochromic configuration, which means that solar gains through the bleached window are not as effective in reducing the conventional heating load. Although electrochromic glazing made a brief appearance on the market several years ago, to the author's knowledge there are no electrochromic products for architectural glazing currently available.

3.3.3 Suspended particle devices

An applied voltage is also the driving force for suspended particle devices (SPD), but in this case the voltage is applied constantly to maintain the clear state by aligning the particles. When no voltage is applied, the particles in a thin film orientate randomly, reducing the transmittance by absorption, as illustrated in fig. 7. The specifications for an SPD laminate with untinted glass, combined with a low-e coated pane are: g value switching from 0.48 to 0.30 and τ_v from 0.45 to 0.09, for a U_g value of 1.7 $Wm^{-2}K^{-1}$.[11]

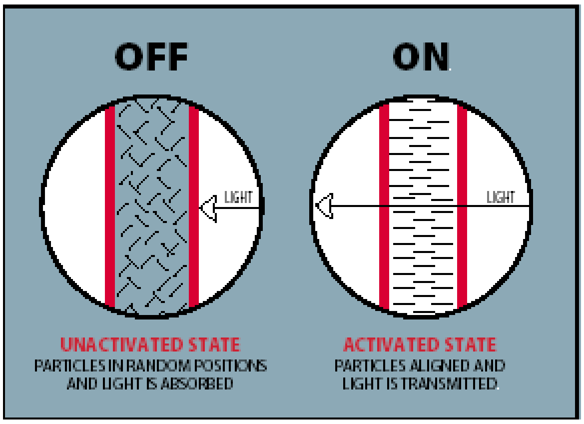


Fig. 7: Switching principle for a thin film containing suspended particles[12].

3.3.4 Thermotropic glazing

Thermotropic glazing differs from the other types of chromogenic glazing presented above in two major aspects: It switches between a transparent and an opaque state, meaning that visibility is not retained in the "solar control" mode, and it reacts automatically to changes in the glazing temperature, rather than being activated by an external switch. The two states are illustrated in Fig. 8.

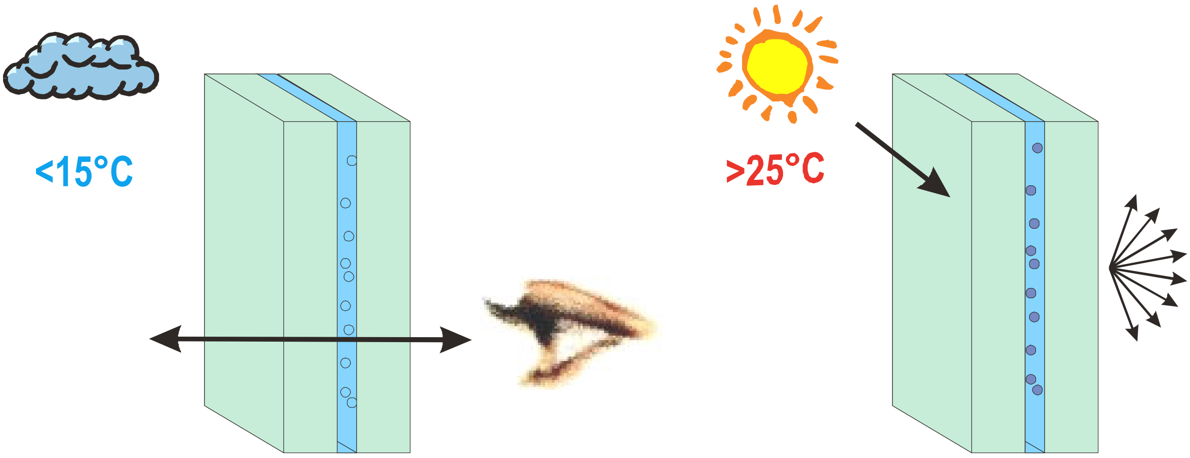


Fig. 8: Transparent and opaque states of a thermotropic laminate[13].

These two properties mean that this type of glazing is better suited for clerestory windows or skylights, where a direct view is not significant, and is more appropriately combined with glazing units that already include translucent insulation materials such as capillary panels. For such a combination, a U_g value of 0.8 $Wm^{-2}K^{-1}$ is achieved, and the visible and total solar energy transmittance respectively vary between 0.64 and 0.52 at lower temperatures and 0.37 and 0.34 at higher temperatures[13].

4. Examples of Performance Evaluation

As already stated, the "best" window for a specific application will depend on a number of parameters, particularly the meteorological conditions at the site, the window orientation and the window-to-wall ratio. One practicable approach toward making a selection is to use a building energy simulation program designed to implement energy-saving regulations such as the German "Energie-Einsparverordnung EnEV" (energy-saving regulation), in which relevant aspects of a building construction and its technical services are taken into account[14]. Using calculations of building heat losses and gains according to EN 832[15], which are based on monthly averages of regional meteorological data, results are obtained which should usually give a reliable ranking order of different glazing types, even if absolute values are clearly also influenced by further aspects such as details of the other building components and user behaviour. Where very large areas of glazing are involved, or where complex interactions occur, e.g. with lighting systems for chromogenic glazing in commercial buildings, use of more sophisticated programs with dynamic calculations hour by hour for the whole year may well be indicated, but they will not be considered here.

The calculation result specified by EN 832 relates only to the heating energy demand of a residential building, but information concerning the need for cooling energy can also be extracted from the calculations. When the heat gains exceed the heat losses in a given month for a specified indoor temperature of e.g. 26°C, the difference can be treated as the cooling energy needed to prevent overheating, or alternatively, as a measure of the resulting discomfort. This approach has been taken in the results presented here, as consideration of the heating energy demand alone gives an incomplete representation of the energy-relevant window performance.

For the following calculations, the EnEV procedure was applied using monthly meteorological data for Freiburg, Germany and a commercially available program[16]. An indoor temperature of 19°C was taken for calculating the heating energy demand, and a setpoint of 26°C for the cooling energy demand. The two-storey house studied has a floor area of 84.6 m^2, a net heated floor area as defined by EnEV of 130.8 m^2, and an external building envelope area (roof and walls) of 251 m^2. It is insulated according to the specifications listed for type EFH_I (construction date between 1995 and 2001) in the German building typology[17], with the exception of the windows. These were varied according to the specifications listed in Table 1, whereby "high Tv" and "low Ug" are examples of "low-e" glazing from fig. 2, and "low g value" is an example of solar-control glazing from fig. 4. Two different total window areas were investigated, 40.5 m^2, including a skylight area of 8 m^2, and 52.5 m^2, including a skylight area of 20 m^2. Frames occupied 21 % of the window area, and the reduction in solar gains due to shading in the building neighbourhood was set to 10 %.

glazing type	τ_v [-]	g value [-]	U_g value [$Wm^{-2}K^{-1}$]
high Tv	0.81	0.64	1.2
low Ug	0.72	0.52	0.5
low g value	0.50	0.27	1.1
gasochromic	0.63 - 0.20	0.49 - 0.17	0.9

Table 1: Specifications of glazing for energy performance comparison.

Evaluation of chromogenic windows is not explicitly foreseen in EN 832, but a useful approach is to carry out the calculations twice, for the bleached and darkened window states separately. The resulting energy totals for heating and cooling can then be compared month by month, and the minimum total taken for each month. For the gasochromic glazing included in figures 9(a) and 9(b), values for the bleached state were taken from October to April, and for the darkened state from May to September. The results for this "seasonal switching" can be expected to present an upper limit for the energy demand if the windows were switched more frequently according to the prevailing conditions.

The results for the different types of glazing are shown in Fig. 9(a) for the smaller and 9(b) for the larger glazing area. If only the heating energy demand were considered, as foreseen in the EnEV, the "high Tv", "low Ug" and gasochromic glazing would appear to be almost equivalent. However, if the total energy consumption is taken into account, it becomes clear that the gasochromic option is the best for both total window areas, as it greatly reduces the cooling load. It is also significant to note that for this switchable glazing, the total energy demand for the larger glazing area is lower than for the smaller glazing area, opening up new design options for energy-saving building.

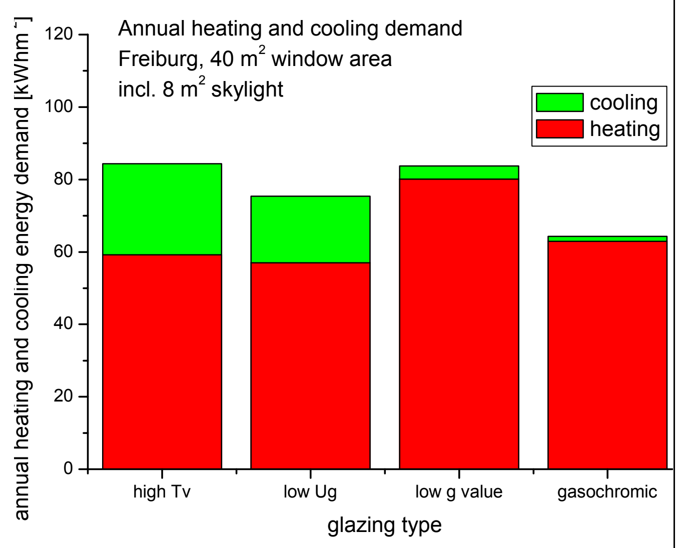


Fig. 9(a): Variation of building energy demand with glazing type, for a two-storey house in Freiburg with 40.5 m^2 window area, including 8 m^2 skylight.

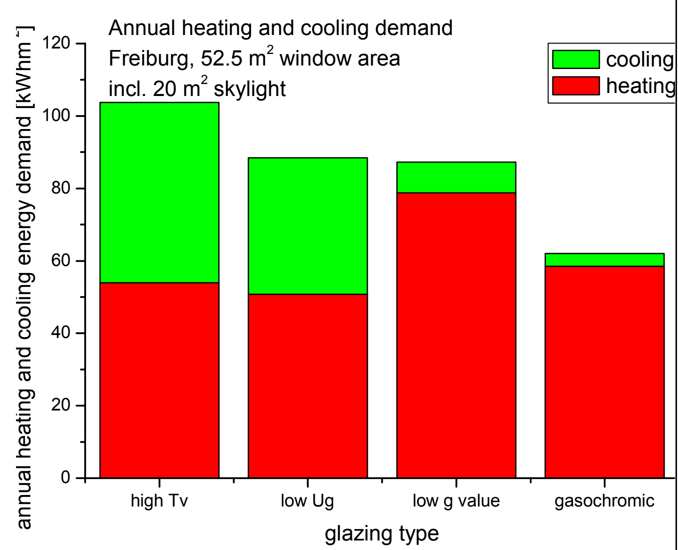


Fig. 9(b): Variation of building energy demand with glazing type, for a two-storey house in Freiburg with 52.5 m^2 window area, including 20 m^2 skylight.

5. Conclusions

High-performance glazing is available today with a wide range of technical specifications. With the help of building energy simulation, the most appropriate type for each specific application can be identified, so that the overall aim of energy-saving buildings can be achieved.

6. Literature

(Where full bibliographic details have not been given, the information can be obtained via the Internet home pages of the specified sources.)

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Further sources of information:

www.interpane.net
www.efficientwindows.org
www.caddet-ee.org
windows.lbl.gov
www.nfrc.org
www.windat.org