Theoretical background of ideal glazing based on adaptive thermal-optical parameters

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Abstract

The theoretical overview serves as a basis for the design of a separate adaptive glass system. An overview of current directions is processed, which reflects the actual user requirements in relation to the thermal comfort. The concept is based on knowledge and practical experience in the field of progressive glass systems today. It uses formulated shortcomings as a tool for their elimination in the further development of the future concept. It is based on the customization of the glass system as a means of achieving the optimal temperature state of the indoor environment in order to eliminate the additional need for cooling and heat for heating buildings.

Key words: U-factor, visible transmittance, total solar energy transmittance

1 Introduction

As a result of increasing demands on the heat-insulating ability of window structures, emphasis has been placed in the first place on the reduction of the U-factor, which is one of the main evaluation parameters of the window structure. One of the tools to achieve a reduction in the heat transfer coefficient has been and is to increase the heat-insulating ability of the sash, but this only affects the area by which it contributes to the overall window area. At the same time, glass systems were improved from single to double, and later triple with the use of low-emissivity layers. Further development of glass improvement is main aspect in different directions. One of them is to increase the number of glasses with the intention of increasing the total thickness of the insulating gas in the glass system in the form of four to six glasses [1, 2, 3, 4], which can achieve U_g up to $0.26 \text{ W}/(\text{m}^2\cdot\text{K})$ in the center of the glass system without the use of low-emissivity layers [4]. However, this solution has not proved to be successful as the gas leakage due to sealant stress is too high [4] and the standard permits an annual gas leakage of 1% [5] and such glass systems are therefore not produced in series.

In general, sunlight falling on any structure is released, absorbed and reflected to some extent. This ratio is determined by the optical parameters of the structure. A sun radiation consists of a visible and invisible component of different wavelengths. By design, these components penetrate differently into interiors. In the case of a glass system, the quantity of the permeated component is defined by its thermal-optical parameters, which are the result of taking into account all layers of the glass system (declared by the manufacturer), but consisting of partial permeability of the individual layers (glass, low-E layer, gas gap). The invisible component represents approximately 50% of total solar energy [6]. By targeted selection of the composition of the glass system in the range of kinds of panes and low-emissivity layers, it is possible to regulate the heat gains in the desired manner.

In addition to the U-value (heat transfer coefficient), the thermal-optical properties of the glass system also contribute to g-value (total solar energy transmittance), τ_v (visible transmittance) and emissivity. g-value is calculated as the direct solar energy transmittance (T_{sol}) times the inward heat transfer coefficient of the glazing, which later results in heat transfer by convection and long-wave IR radiation of this energy from the incident solar radiation absorbed by the glazing [7,8].

2 Glazing species with constant thermal-optical properties

2.1 Single, double (multiple) glazing

The thermal-optical properties of insulating double and multiple insulating glass unit without the use of low-emissivity layers depend on the glass and insulating gas used as well as on the window angle closest to the horizontal. In all cases, we consider a 90° angle for the relevance of the information. Common 4 mm float glass has approximate parameters: $U = 5.880$ W/(m².K), $\tau_{vis} = 0.988$ (-), $g = 0.868$ (-) (see Table 1), which may vary depending on the product. The results were obtained using Window 7.4.14 software from Lawrence Berkley University [9].

Table 1: Thermal–optical properties of multiple glass units

Glass unit	Specification	Gas filling	U_g [W/(m ² .K)]	τ_{vis} [-]	g [-]
Single	4mm Float glass	-	5.880	0.988	0.868
Double	2x4mm Float	Air/Ar	2.591	0.813	0.774
Double	2x4mm Float	Air/Kr	2.554	0.813	0.774
Triple	3x4mm Float	Air/Ar	1.617	0.739	0.698
Triple	3x4mm Float	Air/Kr	1.590	0.739	0.698
Quadruple	4x4mm Float	Air/Ar	1.171	0.675	0.634
Quadruple	4x4mm Float	Air/Kr	1.114	0.675	0.635
Quintuple	5x4mm Float	Air/Ar	0.918	0.618	0.580
Quintuple	5x4mm Float	Air/Kr	0.890	0.618	0.581
Sixfold	6x4mm Float	Air/Ar	0.757	0.567	0.534
Sixfold	6x4mm Float	Air/Kr	0.726	0.567	0.535

Figure 1: The effect of radiative heat transfer on the overall heat transfer coefficient ($T_0 = -25^\circ\text{C}$) [10].

Figure 1 presents the dependency between the thickness of the gas layer and the U-factor, with and without radiation considered. The graph shows that the greatest influence on U-factor is first of all the number of glass panes; the second most important is the emissivity of the surface and third is the thickness of the gas gap. Significant improvement of the U-factor can be achieved by forming a high-reflection layer on the glass surface. At a gas layer thickness of 9 mm, it is thus possible to achieve a U-factor change from 5.66 to 2.63 W/(m².K). The thickness of the gas layer in terms of its impact on U-factor is only significant up to a thickness of 15 mm, for larger thicknesses the difference is negligible. Transmittance and reflectance of clear glass is demonstrated in Figure 2.

Figure 2: a) Sunlight transmitted and reflected by 6.35mm clear glass as a function of the incident angle, b) Solar energy transmission through the glass after standard ASHRAE conditions [11].

2.2 Low emissivity coated (double) glass unit

Metal layer between dielectric layers together forming transparent heat reflective coating is nowadays known as Low-E coating. Silver as an element which infrared reflectivity is high and absorption in visible part of spectra is low were chosen as a part of most metal compounds of low-emissivity coatings. However, since silver compounds have a moisture resistance problem resulting in, for example, white dots, aluminum is added to the compound to reduce such internal stresses [12]. Spectral properties of glazing of various low-E compounds are shown in Figures 3, 4. Film thickness were determined to obtain a peak transmittance of about 46% in the visible range, Figure 3.

Figure 3: a) Transmittance b) Reflectance and c) Absorbance of Ag (40 nm), TiN (20 nm), Au (20 nm), Cu (18 nm) and Al (6 nm) for the UV-IR wavelength range [13].

A low-emissivity coating known as hard multilayer metal coatings can be applied to the exterior of the glass surface, but the soft coatings are positioned at position 2 from the exterior, i.e. on the exterior glass pane, on the surface in contact with the insulating gas due to atmospheric reactions. Abundiz-Cisneros [13] and his team are working on replacing silver in the compound with other elements to eliminate the problems associated with silver.

Figure 4: Spectral transmittance curves for glazing with three different types of low-emittance coatings. Image Credit: Lawrence Berkeley National Laboratory [14].

2.3 Water flow glazing

In case of water-filled prismatic louvre which is designed to absorb solar infrared and ultraviolet radiation for harvesting energy, visible light pass for daylighting. The absorption spectrum of pure water shows that water has a low absorption coefficient at shorter wavelengths that increases over the visible light spectrum until the near infrared region and slightly depends on the thickness L , see Figure 5, [15]. Transmittance of water at room temperature is shown in Figure 6.

Figure 5: Transmissivity and absorption coefficient of pure water at various wavelengths [15]

Figure 6: Measured transmittance spectra of water at room temperature [16].

2.4 Aerogel glazing

Due to the small size of material pores, the aerogels have a thermal conductivity in the range of 0.01 - 0.02 W/m.K, as a result of a well balanced relationship between low solid conductivity, low gaseous conductivity and low radiation infrared transmission. This balanced relationship between the different heat transfer modes is difficult to achieve because each heat transfer mode is firmly linked to the other [17]. Various glass systems based on the aerogel

layer were measured and evaluated [18]. Comparison of transmission coefficient of aerogel pane is shown in Figures 7, 8.

Figure 7: Comparison of solar spectral transmission of aerogel and float glass pane [19].

Figure 8: Transmission coefficient vs. wavelength of pane aerogel measured without the integrating sphere (standard method) and with the integrating sphere compared to a 6 mm float glass [18].

2.5 Thermochromic glazing

Thermochromic glass simply uses the heat of direct sunlight to color the windows as needed. The more direct and intense the sunlight, the darker it will be on the glass. This allows windows to significantly reduce the thermal load coming into the building, and because the glass permeability constantly adjusts over the temperature range, a natural balance and maximum use of daylight is achieved.

Thermochromic windows consist of a common safety interlayer which is produced by extruding special thermochromic materials into polyvinylbutyral (PVB), laminated between two pieces of heat-strengthened or tempered glass and placed in an insulated glass unit (IGU) with a low emissivity coating.

Figure 9 presents the normal-hemispherical transmittance measurements of a thermochromic complex based on a lactone dye. A significant decrease in transmittance can be observed with increasing temperature. The decrease in transmittance is due to a significant increase in absorption and is effective in the visible range of solar radiation. This is not associated with increased reflection of incident solar radiation. The effect of molecular switching between different structures cannot contribute to the reflection control. The reduction of the transmittance in the visible wavelength range of 27% is only accompanied by a 6% reduction in solar transmittance [20].

Figure 9: Normal-hemispherical transmittance of a thermochromic film with a green dye at different temperatures [21].

2.6 Electrochromic glazing

The unit consists of ceramic metal oxide coatings with three electrochromic layers sandwiched between two transparent electrical conductors. When a voltage is applied between the transparent electrical conductors, a distributed electrical field is set up. This field moves various coloration ions (most commonly lithium or hydrogen) reversibly between the ion storage film through the ion conductor (electrolyte) and into the electrochromic film.

Figure 10: Change of the transmittance of an electrochromic glass with ion conducting PVB interlayer between 380 and 780 nm during bleaching [22].

Typical electrochromic windows have an upper visible transmittance range of 0.50–0.70 and a lower range of 0.02–0.25 (see Fig. 10). The g-factor (total solar energy transmittance) ranges

from 0.10-0.50. A low transmission is desirable for privacy during the day and for control of direct sun and glare, potentially eliminating the need for interior shading. A high transmission is desirable for admitting daylight during the time of the day that the sun is not shining directly into the space, during overcast periods and for passive solar heating in winter.

2.7 Suspended particle device

This electrically controlled film utilizes a thin, liquid-like layer in which numerous microscopic particles are suspended. In its unpowered state the particles are randomly oriented and partially block sunlight transmission and view. Transparent electrical conductors allow an electric field to be applied to the dispersed particle film, aligning the particles and raising the transmittance. Typical visible transmittance and total solar energy transmittance ranges for the film alone are $\tau_v = 0.22 - 0.005$ or $0.57 - 0.12$ and $g = 0.56 - 0.41$ or $0.70 - 0.50$, respectively, with near instant switching times (less than one second), see Figure 11. The SHGC switching range is more limited than electrochromic windows.

Figure 11: Solar transmittance for SPD glazing after exposure at variable voltage [23].

2.8 Liquid crystal

A very thin layer of liquid crystal is sandwiched between two transparent electrical conductors on thin plastic films, and the entire emulsion or PDLC or polymer dispersed liquid crystal device, is laminated between two layers of glass. When the power is turned off, the liquid crystals are in a random and unaligned state. They scatter light and glass appears as a translucent layer that obscures direct view and provides privacy. The material transmits most of the incident solar radiation in the diffuse mode so that its heat gain coefficient of solar energy remains high. When energy is applied, the electrical field in the device aligns the liquid crystals and the glazing becomes transparent in a fraction of a second, allowing viewing in both directions. Most such devices have only two states, clear and diffuse, and the

power (about 0.5 W, operation between 24 and 100V AC) must be continuously applied to keep the glazing clear. The visible transmittance range is typically 50-80% and the total solar energy transmittance (g-factor) is 0.55-0.69 [24], see Figure 12.

Figure 12: Transmission spectrum. a) The IR reflector on varying the applied voltage from 0 V/μm to 8.6 V/μm b) Transmission spectrum of cholesteric gel in reflective and transmissive states at 0 V/μm and 8.6 V/μm [25]

3 Idea base of ideal glazing

The idea of an ideal glass system arises from the current state of the issue of fenestration and the development of various directions as well as in construction or material range. A structurally oriented direction is an increase in the number of glasses in the glass system, which, even for float glass, represents a significant improvement in the thermal properties of the glass system. The disadvantage of this idea is the high weight increase of the structure, which is associated with additional transport and assembly problems as well as the need for more robust and stronger fittings. The high weight of the system thus implies a certain dimensional limitation in the case of opening structures. In the case of fully glazed facades this problem disappears and ventilation is solved by smaller window segments, or natural ventilation is fully replaced by controlled ventilation. An improvement in the heat transfer coefficient is thus possible to approximately 0.7 W/(m².K), and if low-emissivity coatings were used, this improvement would be even more noticeable. The g-value of multi-insulating glass systems is in the range of 0.87 - 0.54 and the visible transmittance in the range of 0.99 - 0.57. These thermal and optical properties are mainly due to the number of glasses in the glass system, the gas filling used has almost no effect on it. In the case of glass systems using low-emissivity coatings or separate films, these values are significantly lower due to the emissivity of the film used. There are several types of films on the market that can be applied to the glass system according to its future location (cardinal orientation). The films are customized for specific orientation according to the climate and desired heat gains or unwanted heat losses respectively. In addition to low-emissivity coatings and films, other materials and technologies are used to improve thermal insulation properties. Water is a suitable absorbent of near infrared and ultraviolet radiation while maintaining excellent transmission of the visible part of spectrum. Aerogel is a progressive to a certain thickness transparent thermal insulator based on nanoparticles of various sizes. Thermochromic and electrochromic glazing

based on materials changing the structure of their structure when a certain temperature is reached or a voltage is applied into the glass system. On the principle of the voltage application functioning liquid crystals and SPD systems, together with the electro and thermochromic ones, the idea of an autonomous adaptive glass system, which regulates heat losses and gains according to current needs (see Fig. 13), has been approached so far.

Figure 13: Comparison of annual energy use for a normal double glazed window, static IR reflector and the switchable (responsive) infrared reflector for three different climates [25].

Figure 14: Model of operation of the ideal glass system. a) Summer situation. b) Winter situation [26].

An ideal fully autonomous glass system should reflect the climate conditions in which it is installed, including customization within the cardinal points. In a hot climate, a glass system that reflects all infrared radiation (from the sun and surrounding surfaces) as well as all UV radiation is suitable. At the same time, it is able to transmit all infrared radiation from the interior to the exterior and at the same time maintain the transparency and allow the visible component of light to penetrate. In cold climates, it would be able to transmit radiation of all wavelengths except UV into the interior while reflecting all infrared radiation is backed to the interior [26], see Figure 14. So far, the glass system has to reach minimum parameters depending on the climate, see Table 2.

Table 2: Required parameters of the glass system for a specific climate [27]

Climate	τ_v	SHGC (g)	U (W/(m².K))
Cool climate (prevailing heating loads)	> 0.70	> 0.60	< 2
Temperate climate (prevailing heating loads)	> 0.70	> 0.50	< 2.5
Hot climate (prevailing cooling loads)	> 0.60	< 0.40	< 4

4 Conclusion

Increasing the thermal insulation properties of glass systems was one of the first tools to achieve the goal of eliminating the window structure as a thermal bridge in the building envelope. Gradually, however, more emphasis has also been placed on the other thermal-optical parameters of the glass system, which have become a tool to reduce the need for heating and cooling energy due to heat losses in winter and gains in summer. The next step is to create the concept of an adaptive glass system whose properties will vary depending on the immediate environmental conditions in relation to indoor thermal comfort. Its concept is customized for a specific climate and orientation towards cardinal points. An adaptable glass system capable of operation should be able to regulate its properties while maintaining a high level of transparency, which is currently a major disadvantage of other adaptive glass systems on the principle of power supply or reaching a temperature limit.

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