Electrochromic Glazing: Avoiding the Blues

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Abstract

The dynamic control of daylight has been called the "Holy Grail" of the fenestration industry. Electrochromic (EC) glass is believed to be the leading contender in the race to manufacture a glazing technology that will achieve the accolade set down by Steve Selkowitz in 1998. With recent investment in the scaling-up of production capacity, EC glass is now set become a mainstream glazing product. As EC glass darkens ('tints') the peak in the spectral transmittance curve shifts to the blue. Whilst control of the luminous and thermal environment is highly desirable, occupants are believed to prefer daylight illumination that is perceived as neutral rather than tinted. Thus the question regarding the neutrality of the illumination spectrum is an important one that needs to be addressed. In this paper the authors show that it is possible to maintain an effectively neutral spectrum of daylight illumination in a space with EC glass in normal operation, provided that a relatively small proportion of the glass is left in the clear state. A theoretical formulation giving the overall spectral transmittance curves for any arbitrary combination of clear and tinted EC glazing in varying proportions is outlined. Applying the theoretical model it should be possible to configure and/or control an actual EC glass installation so that neutral daylight illumination results. The theoretical model is tested using measurements of the daylight spectra in an office space with EC glazing for various combinations of clear and tinted glass.

1. Introduction

The use of daylight in office buildings is generally considered to be a greatly under-exploited resource. In large part this is because of the highly variable nature of daylight illumination. The natural, large variability in daylight means that users will often need to use shades to moderate excessive ingress of daylight. Most shading systems act as a "shutter" that is either open or closed, with users rarely making the effort to optimise the shading for both daylight provision and solar/glare control. And blinds are often left closed long after the external condition has changed. A glazing with a transmissivity that varies continuously between clear and dark extremes could offer a much greater degree of control over the luminous environment.

The principle behind variable transmission glazing (VTG) is straightforward: the transmission properties of the glazing are varied to achieve an 'optimum' luminous and/or thermal environment. The various types of VTG can be grouped into three broad classes: chromogenic coatings, suspended particle device and micro-electromechanical systems. In the chromogenic class there are four distinct types of formulations for coatings that have variable transmission properties. These are: electrochromic, gasochromic, photochromic and thermochromic. The agents causing the change in transmission are: voltage (electrochromic); concentration of pumped gas (gasochromic); localised illumination (photochromic); and, localised temperature (thermochromic). Thermochromic and photochromic are essentially passive devices which respond to changes in the environment, whereas electrochromic and gasochromic are active devices that can be configured to respond to any sensor input, e.g. illumination, temperature, or some combination of the two. Suspended particle device is a film-based technology. The film contains a suspension of rod-like particles in billions of liquid droplets. An applied voltage alters the orientation of the particles and therefore the transmission properties of the film. A VTG based on micro-electromechanical systems (MEMS) has tiny, micron-scale structures that move in response to an applied electrostatic field, thereby altering the transmission properties of the glazing.

The key to performance for a VTG is a high (visible) transmission in the clear state and a sufficiently low (visible) transmission in the darkened (or tinted) state. To be perceived as acceptable to the majority of building occupants, the VTG in the clear state should appear like ordinary (un-tinted) double glazing, and so have a visible transmission of 60% or greater (non-domestic buildings). In the darkened state the transmission should be low enough so that additional shading is required only very rarely, or perhaps not at all. In practice this means a minimum visible transmission of around 2% or less. Additionally, the building occupants should have some degree of control of the glazing, e.g. to manually override an automated control setting. Experience has shown that occupants will often resort to sabotage if an automated building control system fails to do what they wish [1]. So, whilst a 'passive' VTG might seem attractive at first because it allows for autonomous operating behaviour, the corollary of this is a lack of control, e.g. modulation of the glazing transmission by (localised) window temperature will not necessarily offer the luminous environment desired by the occupants.

There are examples of thermochromic glazing on the market, though the narrow visible transmission range (e.g. 13–60% or 6–30%) indicates that additional shading would be needed to control glare. Gasochromic has the potential advantage of rapid switching speeds. A gasochromic system requires that the glazing unit is literally 'plumbed-in' – connected to an electrolyser and pump by piping. The practicalities of a gasochromic installation are such that the technology is still considered the preserve of research. Suspended particle device applications for clear (i.e. view) glass and MEMS window technology are still undergoing development. Thus, of the technologies described above, only electrochromic (EC) glazing appears to have the necessary optical properties (i.e. wide visible transmission range), is relatively straightforward to install, and is already in the marketplace.

1.1 Electrochromic glazing

The effectiveness of EC glazing to temper the indoor thermal environment has been demonstrated in a number of theoretical and empirical studies [2], and modelling its performance in a dynamic thermal simulation program is relatively straightforward [3]. It is however the user acceptance of the luminous environment produced by EC glazing that will be the key determinant for the success of this VTG technology [4].

User acceptance for any daylight control technology depends on a number of performance and operational characteristics. For EC glazing these include performance with respect to glazing transmission range (i.e. the values for the maximum and minimum visible transmittances), the switching time between the clear and tinted states and the effectiveness of the automated control to minimise user interventions (e.g. manual overrides). The control of EC glazing can be any combination of manual and automatic, employing whatever sensor inputs are required, e.g. illuminance levels, sun position, internal air temperature, etc. However effective the automatic control for any

Figure 1: Images showing electrochromic glazing in clear and darkened state (photos courtesy SAGE Electrochromics, Inc.)

environmental system (e.g. office lighting), it is generally the case that occupants will always prefer to have a manual override option even if it is rarely used. The same is true for EC glazing. The automatic control can be integrated with building energy management systems (BEMs). An 'out-of-the-box' (i.e. generic) EC control system may work reasonably well. However, fine-tuning and repeat commissioning is likely to improve performance. An optimum, fine-tuned control strategy may depend on several factors: prevailing climate; latitude; site context and obstructions; glazing size, configuration and aspect; internal design, layout and operation. Goals for an optimum control strategy include the simultaneous protection from glare and the provision of sufficient daylight. Optimum control of the EC case-study offices is one of the implementation issues under investigation by the authors (see Section 3).

Another key factor for user acceptance is the *quality* of the luminous environment produced by EC glazing – meaning, the spectral composition of the daylight that is 'filtered' through tinted EC glass. This is because the spectral transmission properties of the EC coating varies as the glass changes state. This can be seen in Figure 1 showing a pair of photographs with EC glass in the clear state (left) and at full-tint (right). As the glass darkens (i.e. 'tints') the longer wavelengths are diminished proportionally to a greater degree than the shorter wavelengths, giving the EC glazing good solar control properties to help prevent overheating. Optically, the consequence of this is to shift the peak in visible transmission to the blue end of the spectrum.

This can be seen in the transmission curves shown in Figure 2. In the clear state the glazing has a visible transmittance of 62% and appears effectively neutral to the eye. There is a slight 'peak' in the curve around 600mn giving a very slight yellow hue, though this is generally not noticeable in normal use. The SageGlass EC glazing installed in the offices has a minimum visible transmission of 2% when fully tinted and can be varied continuously between this and the clear state. However a small number of intermediate states is considered adequate for most practical installations, e.g. 'light-tint' (20%) and 'mid-tint' (6%). The solar heat gain coefficient ranges between 0.47 in the clear state to 0.09 when fully tinted, giving a high degree of solar control to prevent overheating.

2. Theoretical model

The theoretical model is founded on the following principles/hypotheses:

(a) The individual spectral transmittance curves of any arbitrary combination of glazing can be ‘merged’ to give a single spectral transmittance curve which characterises the ensemble.
(b) The spectrum of illumination in a space is the product of the spectral power distribution of the daylight incident on the glazing and the ‘merged’ spectral transmission curve for the glazing ensemble.
(c) For spaces that are not too large and that have ‘typical’ neutral decor, the shape of the (daylight) illumination spectrum will be fairly constant across the space.

The first two of the above are described below. And, together with the third hypothesis, they are tested against measurements taken with a spectrometer in a room with EC glazing (Results section).

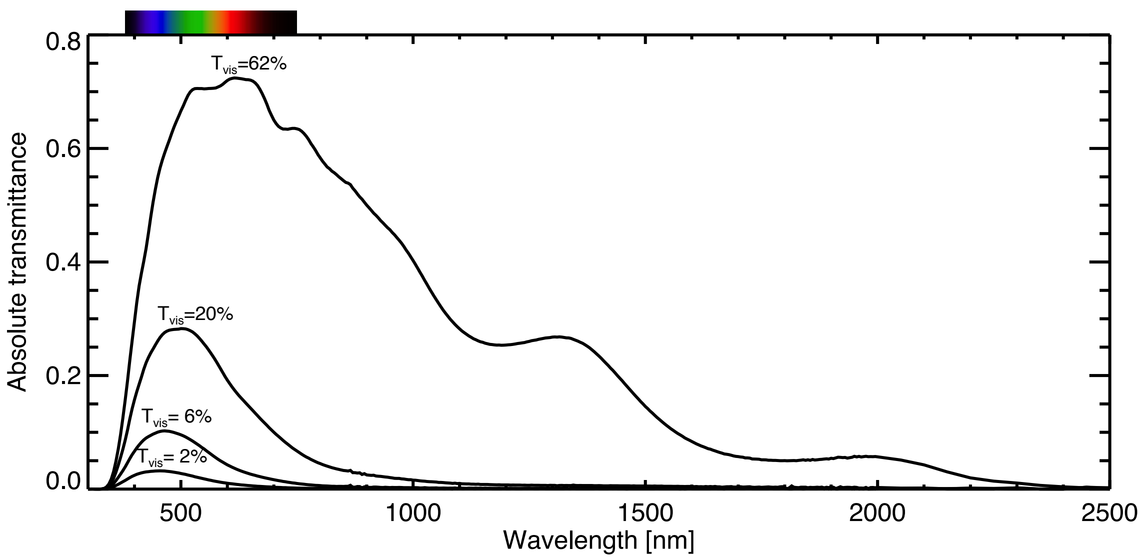

Figure 2: Absolute spectral transmission curves for SageGlass electrochromic glazing in clear (62%), fully tinted (2%) and two intermediate states. Data from the IGDB files supplied by SAGE Electrochromics, Inc.

2.1 Glazing transmission model

A general matrix formulation to determine the overall spectral transmittance curve for any arbitrary combination of EC glass with known transmission spectra is described in full in a paper in preparation [5].

With even a small number of independently controlled EC panels there are many unique combinations of tint state possible. Initial tests showed that to achieve high levels of overall daylight control, whilst maintaing at the same time the potential for neutral daylight illumination, a combination of clear and fully tinted panels is particularly effective. For example, a two panel combination with one set to fully clear (62%) and one to full-tint (2%) has an equivalent visible transmittance of 32%, i.e. (62+2)/2. However, approximately 97% of that equivalent visible transmittance is due to the panel in the clear state, because of course the clear state panel has 31 $\times$ the visible transmittance of the glass at full-tint. Below we compare the overall spectra for one clear panel with up to eight panels at full-tint (with none set to either of the intermediate states):

$$\mathbf{R} = \begin{bmatrix} 1 & 0 & 0 & N_d \end{bmatrix} \text{ where } N_d = 1, 2, 3, 4, 5, 6, 7 \text{ or } 8 \tag{1}$$

For each of the eight values of N_d in $\mathbf{R}$, the transmission model described in the full paper [5] was used to determine the spectral transmittance curve $\mathbf{T_R}$ of the combination.

Any comparison of spectral transmittance curves will depend to a degree on how the data are normalised. The combination spectral curves (Figure 3) are shown in two ways: (i) each normalised to peak value equals 1; and, (ii) relative to the transmittance curve for EC glass in the clear state (i.e. peak value for clear equals 1). Additionally, the plot shows the transmittance curves for EC glass in the clear state (dashed line) and at full-tint (dotted line), Figure 3. For reference, the plot also includes the visual sensitivity curve $V(\lambda)$ (also normalised to peak equals 1).

The curve for $\mathbf{R} = \begin{bmatrix} 1 & 0 & 0 & 1 \end{bmatrix}$ (i.e. 1 clear panel and 1 at full-tint) is shown in olive. With gradually increasing values for N_d, the colour used for the curve transitions from olive through red to blue, i.e. for $\mathbf{R} = \begin{bmatrix} 1 & 0 & 0 & 8 \end{bmatrix}$. Although containing many curves, the plot is quite easy to interpret when viewed in colour since the progression with increasing number of full-tint panels is quite pronounced and 'orderly'. Firstly, for the case with 1 clear and 1 full-tint panel, the combined spectral transmittance curve (olive) is almost identical to that for the glass in the clear sate (dashed line). Relative to the clear state, there is a very slight suppression of wavelengths longer than 500 nm (i.e. the 'red' end of the visible spectrum), and a slight enhancement of wavelengths shorter than 500 nm (i.e. the 'blue' end). With each additional full-tint panel this trend persists, with the crossover point around 500 nm seeming to act as a 'pivot'.

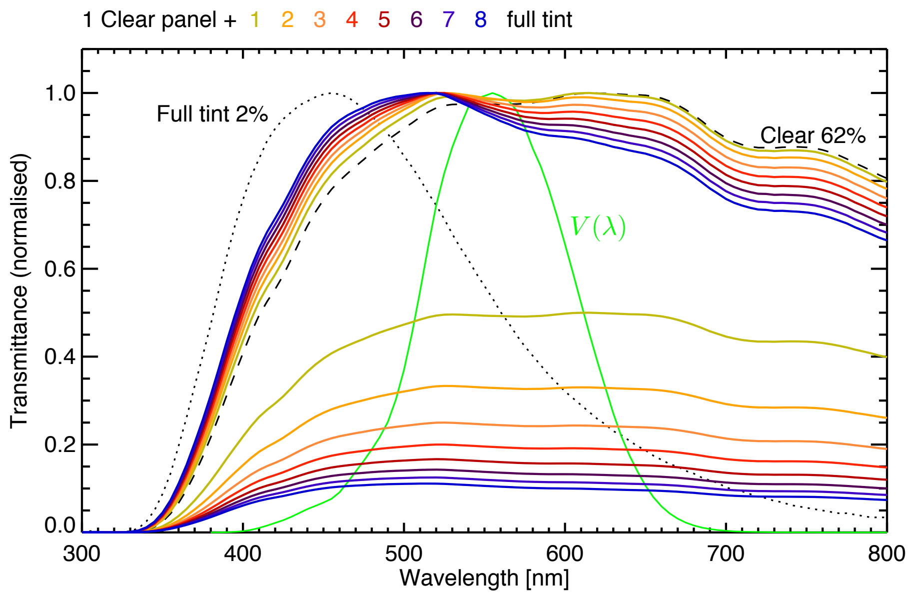

Figure 3: Eight spectral transmittance curves for SageGlass EC glazing in the combinations given in Equation (1).

2.2 The illumination spectrum

In addition to the transmittance spectrum of the glazing, the illumination spectrum – that is, the daylight that passes through the glazing to illuminate the space – will depend also on the spectrum of light that is incident on the glass. The illumination spectrum is given by the vector $\mathbf{I_{T_R,D_K}}$ where $\mathbf{T_R}$ refers to transmittance spectrum produced by EC combination $\mathbf{R}$, and $\mathbf{D_K}$ is the vector containing the spectral power distribution for one of the standard daylight illuminants, e.g. D_{55}, D_{65}, etc. The illumination spectrum is given by:

$$\mathbf{I_{T_R,D_K}} = \mathbf{T_R} \circ \mathbf{D_K} \tag{2}$$

Where $\circ$ is the symbol for the element-by-element or Hadamard product.

3. Validation

The theoretical schema outlined above was tested in an office space containing eight panels of SageGlass electrochromic glazing which have the spectral characteristics shown in Figure 2. The validation scenario is described in the following section.

3.1 The electrochromic glazing installation

Although EC glass has been available for a number of years and evaluated under various experimental conditions (e.g. test cells), the first commercial installation in the UK happened only in late 2012. Two offices at De Montfort University (Leicester, UK) were fitted with EC glazing produced by SAGE Electrochromics. The user acceptance of the installation is being evaluated as part of a long-term case study [6].

3.2 Glazing states tested

The zoning arrangement used to control the glazing in room 0.30 is shown in Figure 4 (zones 1–4 were assigned to the the four zones in Room 0.29). In the full-height six pane window, each row-pair of panels constitutes a zone – thus there are five zones in total. The ‘housekeeping’ label used to describe a particular state for the EC glass in Room 0.30 is a series of five numbers between 1 and 4, e.g. 41-441, where 1 is for fully clear, 4 full-tint, with 2 and 3 for the light- and mid-tint states respectively. The ordering follows the numbering of the zones. Thus, for the label 41-441, zones 5, 7 and 8 are set to full-tint (i.e. five panels altogether), and zones 6 and 9 are set to full clear (i.e. three panels altogether). The ratio vector $\mathbf{R}$ for this combination is therefore $\begin{bmatrix} 3 & 0 & 0 & 5 \end{bmatrix}$. For this combination of clear and tinted EC glass, the overall visual transmittance of was predicted to be 0.25 (or 25%), of which 94% was due to the glass in the clear state.

Alongside the zoning graphic is a sketch showing the approximate positions of the four occupants and their typical view directions (A–D) whilst working. View E is a general view from the back of the room looking towards the glazing, and F is the view from the window wall towards the back of the room. Illumination spectra were measured at each of these six view points/directions for every combination of glazing state described below. To avoid contamination of the spectra, all electric lighting and computer monitors were switched off.

3.3 Measurement and normalisation of the spectra

Spectra were measured using an MK350 handheld spectrometer produced by UP-Rtek. The spectra cover the range 360 to 760 nm and are output as normalised curves (peak equals 1). The sensor has an approximate cosine response, and so the spectra recorded are equivalent to spectral irradiance by a device that measures absolute units. The measured spectra are therefore also similar to what would be received by the eye when located at the various measurement positions and view directions indicated in

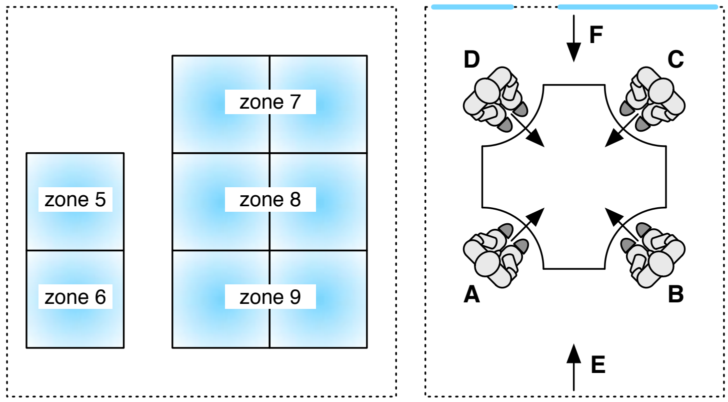

Figure 4: Zoning of the EC glass in Office 0.30 and a schematic (not to scale) of the office layout showing the occupant workstation positions and the six view directions (A–F) at which spectra were measured.

Figure 4. The MK350 also records illuminance and various derived quantities including correlated colour temperature (CCT) and colour rendering index (CRI). Tests showed that repeatability was very good and there was no practical advantage in taking multiple spectra at individual measurement points – an important consideration since we did not want the sun position to change significantly during each set of measurements.

The measurements were taken under sunny, clear sky conditions on a weekend day in order to not disrupt the normal occupants. The conditions were very stable with an almost total absence of clouds. The measurements were taken between ∼11am to ∼1pm on the 6th July 2013. Tests showed that repeatability was very good and there was no practical advantage in taking multiple spectra at individual measurement points – an important consideration since the sun position should not change significantly during each set of measurements. The sun azimuth was almost normal to the facade during the measurement period, and the sun was overwhelmingly the dominant source of illumination in the office space under those conditions. Thus, standard illuminant D_{55} was chosen as the source used to predict the illumination spectrum for the office space.

Predicted and measured spectra were normalised to $V(\lambda)$ such that the area under the normalised curve was the same for each, i.e. each of the spectra would produce the same illuminance. Thus any variation in the absolute levels of illumination (e.g. due to changing sun position) was not a factor in this evaluation, provided of course that the illumination spectrum remained constant during each set of measurements, which we believed was the case.

4. Results

Spectra measured at the six view points/directions shown in Figure 4 were compared to the theoretical illumination spectrum for six combinations of EC glazing in various states. The results for one of those are shown in Figure 5. The predicted illumination spectrum in shown in red and the six measured spectra in blue. Additionally, the visual sensitivity curve $V(\lambda)$ is shown in green (normalised to peak equals 1). Inset photographs show two views of the space at the time of measurement. The complete set of results will be presented in a later paper [5].

Qualitatively, the agreement between theory and measurement seems remarkably good. Quantitative comparison was made by determining the Pearson correlation coefficient (r) between the theoretical illumination spectrum and each of the six measured spectra. Since the individual measured spectra were very similar, the mean for the six values (r_{mean}) is used to summarise the correspondence between theory and measurement. In this case it was 0.980, confirming the good fit evident from the plots.

Subjectively, at the time of measurement the illumination in the space appeared effectively neutral for this case (Figure 5). The correlated colour temperature (CCT) and colour rendering index (CRI) were also measured by the spectrometer. These further support the qualitative appearance of neutrality. For this combination of clear and tinted glazing the mean CCT was 4970 K and the mean CRI was 93.

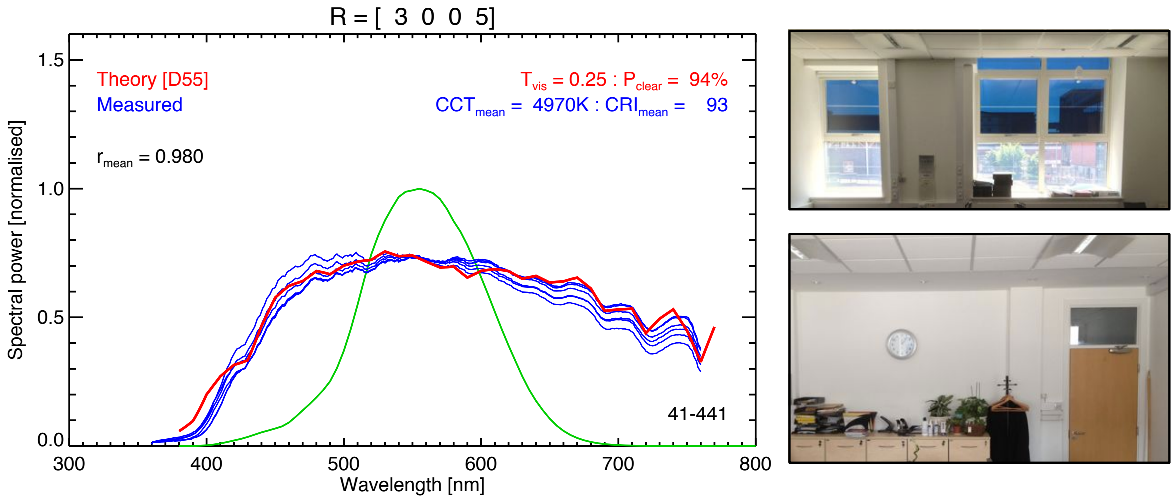

Figure 5: Predicted illumination spectrum and measured spectra for combination 41-441, i.e. five fully tinted and three fully clear panels.

5. Discussion

A theoretical model giving the spatially homogeneous spectral transmission curve for a combination of clear and tinted glass in arbitrary proportions has been outlined. When combined with an applied daylight illuminant, the model gives the predicted (spatially homogeneous) illumination spectrum for any particular combination of glazing. The model was tested against measurements of daylight spectra in an office with electrochromic glazing. Agreement between theory and measurement was good, perhaps remarkably so, and the authors consider the model to be fit for practical application in real world settings. Applying the model it should be possible to design EC zoning strategies and control algorithms to ensure an effectively neutral daylight illumination spectrum whilst maintaing high levels of daylight control.

Funding

The EC glazing in the two offices was installed by SAGE Electrochromics, Inc., and Ms. Kelly is supported by a De Montfort University PhD Studentship. However, no other grant or commercial funding was received for the work reported in this article.

Acknowledgements

Prof. Mardaljevic acknowledges the support of Loughborough University and Dr. Painter the support of De Montfort University. Dr. Ivan Korolija (De Montfort University) assisted with the measurement of the spectra in the EC office.

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