Dynamic Solar Radiation Control in Buildings by Applying Electrochromic Materials

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ABSTRACT

Smart windows like electrochromic windows (ECWs) are windows which are able to regulate the solar radiation throughput by application of an external voltage. The ECWs may decrease heating, cooling and electricity loads in buildings by admitting the optimum level of solar energy and daylight into the buildings at any given time, e.g. cold winter climate versus warm summer climate demands.

In order to achieve as dynamic and flexible solar radiation control as possible, the ECWs may be characterized by a number of solar radiation glazing factors, i.e. ultraviolet solar transmittance, visible solar transmittance, solar transmittance, solar material protection factor, solar skin protection factor, external visible solar reflectance, internal visible solar reflectance, solar reflectance, solar absorbance, emissivity, solar factor and colour rendering factor. Comparison of these solar quantities for various electrochromic material and window combinations and configurations enables one to select the most appropriate electrochromic materials and ECWs for specific buildings. Measurements and calculations were carried out on two different electrochromic window devices, where one ECW was substantially darker than the other in the coloured state.

Keywords: Solar Radiation, Glazing Factor, Electrochromic Window, Building, Transmittance, Reflectance, Absorbance, Emissivity, Solar Material Protection Factor, Solar Skin Protection Factor, Window Pane, Glass.

1. INTRODUCTION

The electrochromic windows (ECWs) aim at controlling the solar radiation throughput at the earth's surface, which is roughly located between 300 nm and 3000 nm. The ECW solar control is achieved by application of an external voltage. The visible (VIS) light lies between 380 nm and 780 nm. Ultraviolet (UV) and near infrared (NIR) radiation are located below and above the VIS region, respectively. Above 3000 nm, and not part of the direct solar radiation, lies the thermal radiation called infrared (IR) radiation, which all materials radiate above 0 K, peaking around 10 000 nm (10 μm) at room temperature. However, the ECWs are not aimed at controlling the IR radiation. Normally, as low as possible heat loss through windows is desired, i.e. low U-value, which is accomplished by the application of various static low emissivity coatings on the window glass panes. Some commercial ECWs are already on the market (Baetens et al. 2009).

Glass with material additives and different surface coatings may be tailor-made and chosen in order to fulfil the various requirements for the actual building type and function, e.g. office building, hospital, family dwelling etc. The glass and window properties are selected with respect to several, often contradictory, considerations. Generally, a window is supposed to let in as much daylight as possible, give comfortable luminance conditions, give satisfactory view out of (and often into) buildings, transmit a minimum of heat from the interior to the exterior in order to reduce the heating demand, transmit solar radiation from the exterior to the interior in order to reduce the heating demand (i.e. in winter), shut off solar radiation by reflection which otherwise might cause too much heating with subsequent cooling load, not induce air current problems or give a poor thermal comfort and not induce unacceptable interior or exterior water condensation.

In addition to the pure energy and daylighting aspects, it is also important to emphasize the degradation of building materials by solar radiation, especially organic matter where the chemical bonds may be broken up by the more energetic parts of the solar spectrum, i.e. ultraviolet (UV) light. A substantial part of the UV light is blocked by the glass itself, but nevertheless a significant amount of UV light passes through the glass and into the buildings. Generally, the most important solar radiation glazing factors are:

- Ultraviolet Solar Transmittance, T_{uv}
- Visible Solar Transmittance, T_{vis}
- Solar Transmittance, T_{sol}
- Solar Material Protection Factor, SMPF
- Solar Skin Protection Factor, SSPF
- External Visible Solar Reflectance, $R_{vis,ext}$
- Internal Visible Solar Reflectance, $R_{vis,int}$
- Solar Reflectance, R_{sol}
- Solar Absorbance, A_{sol}
- Emissivity, ε
- Solar Factor, SF (from T_{sol}, R_{sol} and ε)
- Colour Rendering Factor, CRF

All these factors will be a number between 0 and 1, where in common usage the factors may often be chosen in percentage, i.e. between 0 and 100 %.

Hence, the solar radiation regulation in ECWs enables a dynamic control of the solar radiation glazing factors given above, where this work presents and summarizes in a very abridged way these solar glazing factors together with measurements and calculations carried out on two ECWs. For calculations with ECWs incorporated in two-layer and three-layer window panes, including spectroscopical measurements on float glass and low emittance glass, it is referred elsewhere (Jelle and Gustavsen 2010).

2. EXPERIMENTAL

To illustrate various transmittance levels in the solar spectrum, two electrochromic window (ECW) devices, one ECW substantially darker than the other in the coloured state, were selected as examples. Based on the ECW transmittance measurements the solar radiation glazing factors were calculated. The actual fabrication and miscellaneous testing of the ECWs are described elsewhere (Jelle et al. 1998a, 1998b, 1999, 2007).

A Cary 5 UV-VIS-NIR spectrophotometer, with an absolute reflectance accessory (Strong-type, VW principle), was used to measure the transmittance and reflectance of various glass samples in the ultraviolet (UV), visible (VIS) and near infrared (NIR) region, from 290 nm to 3300 nm. However, at the moment of the fabrication and characterizing of the ECW devices, no laboratory resources for determining the absolute reflectance of the ECWs were available. Nevertheless, as the two ECWs consist of solar absorbing electrochromic materials, and not reflecting modulating electrochromics, the measured (low) reflectance values for float glass are applied in the calculation of the various reflectance based solar radiation glazing factors.

The standard ISO/FDIS 9050:2003(E) refers to ISO 10292:1994 E for emissivity determinations, which according to ISO 10292:1994(E) are to be carried out with an infrared spectrometer, measuring the near normal reflectance (≤ 10º) at a temperature of 283 K. More details of the emissivity determinations and measurements are found in EN 12898:2001 E. In order to minimize polarization effects, the angle of incidence with respect to the normal of the sample must be 10º or less (ASTM E 1585-93). For other ambient temperatures than 283 K (≈ 10 ºC), the emissivity is not strongly dependent on the mean temperature (ISO 10292:1994(E)).

The emissivity may also be determined by applying a heat flow meter apparatus according to the standard EN 1946-3:1999 E. For theoretical considerations, referral is made to EN 1946-2:1999 E and EN 1946-3:1999 E.

Furthermore, the emissivity may also be determined by measuring the directional hemispherical reflectance (DHR, direct mode) or the hemispherical directional reflectance (HDR, reciprocal mode). In the DHR method the sample is illuminated from a single direction and all the reflected radiation into the hemisphere surrounding the sample is measured. In the HDR method the sample is uniformly illuminated from all directions by use of a hemisphere and the radiation reflected into a single direction is measured. For both the DHR and HDR methods the single direction may be varied for miscellaneous instruments, i.e. illuminating or detecting at varying angles, respectively.

In this work, a float glass and a low emittance glass were measured by the hemispherical directional reflectance method by applying a SOC-100 HDR Hemispherical Directional Reflectometer from Surface Optics Corporation connected to a Thermo Nicolet 8700 FTIR Spectrometer. The reflected radiation from the sample was detected at the following incident angles: 10, 20, 30, 40, 45, 50, 55, 60, 65, 70, 75 and 80º. 32 scans were performed with 2 repeats at a resolution of 16 cm-1 in the wavelength range 2 – 25 µm. The IR source temperature was 704ºC. The results were ε_{float} = 0.836 and ε_{lowe} = 0.071, for the float and low emittance glass, respectively. The ε_{float} value was applied in the calculation of the solar factor (SF) for both the float glass and the low emittance glass as the ε value in the SF calculations is with respect to the inside facing surface of the innermost glass pane, i.e. normally a float glass. Hence, the ε_{lowe} value is not applied in this context. At the moment of the fabrication and characterizing of the ECW devices, no laboratory resources for determining the emissivity of the ECWs were available, so the nominal value ε_{float} = 0.837 for float glass is applied in the calculation of SF for the ECWs.

3. SOLAR RADIATION GLAZING FACTOR DEFINITIONS

The ***Ultraviolet Solar Transmittance*** (T_{uv}) is given by the following expression:

$$T_{uv} = \frac{\sum_{\lambda=300nm}^{380nm} T(\lambda) S_\lambda \Delta\lambda}{\sum_{\lambda=300nm}^{380nm} S_\lambda \Delta\lambda} \tag{1}$$

The ***Visible Solar Transmittance*** (T_{vis}), often denoted Light Transmittance, is given by:

$$T_{vis} = \frac{\sum_{\lambda=380nm}^{780nm} T(\lambda) D_\lambda V(\lambda) \Delta\lambda}{\sum_{\lambda=380nm}^{780nm} D_\lambda V(\lambda) \Delta\lambda} \tag{2}$$

The ***Solar Transmittance*** (T_{sol}) is given by:

$$T_{sol} = \frac{\sum_{\lambda=300nm}^{2500nm} T(\lambda) S_\lambda \Delta\lambda}{\sum_{\lambda=300nm}^{2500nm} S_\lambda \Delta\lambda} \tag{3}$$

The ***Solar Material Protection Factor*** (SMPF) is given by:

$$SMPF = 1 - \tau_{df} = 1 - \frac{\sum_{\lambda=300nm}^{600nm} T(\lambda) C_\lambda S_\lambda \Delta\lambda}{\sum_{\lambda=300nm}^{600nm} C_\lambda S_\lambda \Delta\lambda} \tag{4}$$

The ***Solar Skin Protection Factor*** (SSPF) is given by:

$$SSPF = 1 - F_{sd} = 1 - \frac{\sum_{\lambda=300nm}^{400nm} T(\lambda) E_\lambda S_\lambda \Delta\lambda}{\sum_{\lambda=300nm}^{400nm} E_\lambda S_\lambda \Delta\lambda} \tag{5}$$

The ***External Visible Solar Reflectance*** ($R_{vis,ext}$), often denoted External Light Reflectance, is given by:

$$R_{vis,ext} = \frac{\sum_{\lambda=380nm}^{780nm} R_{ext}(\lambda) D_\lambda V(\lambda) \Delta\lambda}{\sum_{\lambda=380nm}^{780nm} D_\lambda V(\lambda) \Delta\lambda} \tag{6}$$

The ***Internal Visible Solar Reflectance*** ($R_{vis,int}$), often denoted Internal Light Reflectance, is given by:

$$R_{vis,int} = \frac{\sum_{\lambda=380nm}^{780nm} R_{int}(\lambda) D_\lambda V(\lambda) \Delta\lambda}{\sum_{\lambda=380nm}^{780nm} D_\lambda V(\lambda) \Delta\lambda} \tag{7}$$

The ***Solar Reflectance*** (R_{sol}), implicitly external solar reflectance, is given by:

$$R_{sol} = \frac{\sum_{\lambda=300nm}^{2500nm} R_{ext}(\lambda) S_\lambda \Delta\lambda}{\sum_{\lambda=300nm}^{2500nm} S_\lambda \Delta\lambda} \tag{8}$$

The ***Solar Absorbance*** (A_{sol}) is calculated from T_{sol} and R_{sol} in Eq.3 and Eq.8 using the fact that T + A + R = 1, giving the following expression:

$$A_{sol} = 1 - T_{sol} - R_{sol} = 1 - \frac{\sum_{\lambda=300nm}^{2500nm} T(\lambda) S_\lambda \Delta\lambda}{\sum_{\lambda=300nm}^{2500nm} S_\lambda \Delta\lambda} - \frac{\sum_{\lambda=300nm}^{2500nm} R_{ext}(\lambda) S_\lambda \Delta\lambda}{\sum_{\lambda=300nm}^{2500nm} S_\lambda \Delta\lambda} \tag{9}$$

The ***Emissivity*** (ε), implicitly corrected emissivity, may be determined from specular IR reflectance measurements by:

$$\varepsilon = c_{corr}\varepsilon_n = \frac{\varepsilon}{\varepsilon_n}\varepsilon_n = c_{corr}(1 - R_n) = c_{corr}\left[1 - \frac{1}{30}\sum_{i=1}^{30} R_n(\lambda_i)\right] \tag{10}$$

or by heat flow meter measurements by:

$$\varepsilon = \frac{2(q_{tot} - \frac{\kappa}{d}\Delta T)}{4\sigma T_m^3 \Delta T + q_{tot} - \frac{\kappa}{d}\Delta T} \tag{11}$$

or as the total hemispherical emissivity by applying a hemispherical reflectometer and integrating over the hemisphere by

$$\varepsilon = 2\int_0^{\pi/2} \varepsilon_t(\theta) \sin\theta \cos\theta d\theta \tag{12}$$

The ***Solar Factor*** (SF) is the Total Solar Energy Transmittance and is given by:

$$SF = T_{sol} + q_i \tag{13}$$

The ***Colour Rendering Factor*** (CRF) is given by:

$$\mathrm{CRF} = \frac{R_a}{100} = \frac{1}{800}\sum_{i=1}^{8} R_i \tag{14}$$

where

λ = wavelength (nm)

$\Delta\lambda$ = wavelength interval (nm)

$T(\lambda)$ = spectral transmittance of the glass

$R_{ext}(\lambda)$ = external spectral reflectance of the glass

$R_{int}(\lambda)$ = internal spectral reflectance of the glass

R_n = average spectral reflectance calculated by summation of spectral reflectance values at 30 distinct wavelengths and divided by 30 as shown in Eq.10 above

λ_i = wavelength and λ_i values for the 30 wavelengths are given in ISO 10292:1994(E) and EN 12898:2001 E

S_λ = relative spectral distribution of ultraviolet solar radiation or solar radiation (ISO/FDIS 9050:2003(E), ISO 9845-1:1992(E))

D_λ = relative spectral distribution of illuminant D65 (ISO/FDIS 9050:2003(E), ISO 10526:1999(E))

$V(\lambda)$ = spectral luminous efficiency for photopic vision defining the standard observer for photometry (ISO/FDIS 9050:2003(E), ISO/CIE 10527:1991(E))

$S_\lambda\Delta\lambda$ values at different wavelengths for ultraviolet solar radiation or solar radiation are given in ISO/FDIS 9050:2003(E)

$D_\lambda V(\lambda)\Delta\lambda$ values at different wavelengths are given in ISO/FDIS 9050:2003(E)

τ_{df} = CIE damage factor (ISO/FDIS 9050:2003(E), CIE No 89/3:1990)

$C_\lambda = e^{-0.012\lambda}$ (λ given in nm)

$C_\lambda S_\lambda\Delta\lambda$ values at different wavelengths are given in ISO/FDIS 9050:2003(E)

F_{sd} = skin damage factor (ISO/FDIS 9050:2003(E), McKinlay and Diffey 1987)

E_λ = CIE erythemal effectiveness spectrum

$E_\lambda S_\lambda\Delta\lambda$ values at different wavelengths are given in ISO/FDIS 9050:2003(E)

q_{tot} = total heat flow density between two parallel, flat infinite isothermal surfaces (W/m^2) (EN 1946-2:1999 E, EN 1946-3:1999 E)

κ = thermal conductivity of the medium separating the two surfaces (W/(mK))

$\kappa = \kappa_{air} = 0.0242396(1 + 0.0030520\theta - 1.282 \cdot 10^{-6}\theta^2)$ (W/(mK))

(values accurate to 0.6 % between θ = 10ºC and θ = 70ºC)

(θ given in ºC) (EN 1946-2:1999 E, EN 1946-3:1999 E)

$\theta = (T_m - 273.15\ \mathrm{K})$ºC/K (ºC)

T_m = mean temperature of the two surfaces (K)

ΔT = temperature difference between the two surfaces (K)

d = distance between the two surfaces (m)

$\sigma = \pi^2 k^4/(60\hbar^3 c^2)$ = Stefan-Boltzmann's constant $\approx 5.67\cdot 10^{-8}$ W/(m^{2}K^4)

$$\varepsilon_t(\theta,\phi,\lambda) = 1 - \frac{\int_0^\infty R(\lambda)P(\lambda,T)d\lambda}{\int_0^\infty P(\lambda,T)d\lambda}$$ (Surface Optics Corporation 2009)

$$P(\lambda,T) = \frac{8\pi hc}{\lambda^5 (e^{hc/(\lambda kT)} - 1)}$$ = Planck's function (Surface Optics Corporation 2009)

R = hemispherical reflectance

T = temperature (K)

θ and ϕ are integrating angles over the hemisphere

h = Planck's constant ≈ $6.63 \cdot 10^{-34}$ Js

k = Boltzmann's constant ≈ $1.38 \cdot 10^{-23}$ J/K

c = velocity of light ≈ $3.00 \cdot 10^8$ m/s

T_{sol} = solar transmittance (Eq.3)

$A_{sol} = q_i + q_e$ (A_{sol} from Eq.9)

q_i = secondary heat transfer factor towards the inside

q_e = secondary heat transfer factor towards the outside

$q_i = A_{sol} \frac{h_i}{h_e + h_i}$ for a single pane window

$h_e = 23$ W/(m^{2}K)

$$h_i = \left(3.6 + \frac{4.4\varepsilon}{0.837}\right) \mathrm{W/(m^2K)}$$

ε = emissivity of the innermost glass inside surface (ε of other surfaces is taken care of by the reflectance values)

(complete details for calculation of SF, also including two-layer and three-layer window panes, are given in ISO/FDIS 9050:2003(E), with additions in ISO 10292:1994(E) and EN-ISO 6946:1996, note that ε and R_{sol} enter into q_i in Eq.13, R_{sol} from A_{sol})

$R_a = \frac{1}{8}\sum_{i=1}^{8} R_i$ = general colour rendering index (EN 410:1998 E)

$R_i = 100 - 4.6\Delta E_i$ = specific colour rendering index

$$\Delta E_i = \sqrt{(U^*_{t,i} - U^*_{r,i})^2 + (V^*_{t,i} - V^*_{r,i})^2 + (W^*_{t,i} - W^*_{r,i})^2}$$ = total distortion of colour i

(complete details for calculation of CRF given in EN 410:1998 E)

For further and complete calculation details, it is referred to the literature in the reference list.

The emissivity (ε) is a measure of a material's radiative properties, i.e. the emission of infrared radiation. The higher emissivity, the higher emission. Highly reflective materials of infrared radiation have low emissivity values, e.g. polished surfaces of gold, silver or copper. The ε value will be a number between 0 and 1. Oxidation of metallic surfaces will increase the emissivity substantially, e.g. polished aluminium with $\varepsilon = 0.05$ (reflectance 0.95) and oxidized aluminium with $\varepsilon = 0.30$ (reflectance 0.70). Determination of the emissivity is required in order to further determine the solar factor (SF) and the thermal transmittance (U-value).

The Colour Rendering Factor (CRF) expresses synthetically a quantitative evaluation of the colour differences between eight test colours lighted directly by the reference illuminant D65 and by the same illuminant transmitted through the glazing. The CRF value will thus be a number between 0 and 1, calculated in the visible part of the solar spectrum, i.e. 380-780 nm. A high number indicates a good colour rendering. Ideally, the maximum value of 1 will be obtained by glazing whose spectral transmittance is completely constant in the whole visible spectral range, i.e. no variation of transmittance with wavelength. A CRF value > 0.9 characterizes a very good colour rendering and CRF > 0.8 represents a good colour rendering (ISO/FDIS 9050:2003(E), EN 410:1998 E).

4. ELECTROCHROMIC WINDOW MEASUREMENTS

Electrochromic windows (ECWs) are able to control the colour of the window, thereby also the solar radiation throughput, by varying the applied electrical potential. Schematic drawings of two ECWs are shown in Fig.1, constructed in a sandwich form from the electrochromic materials polyaniline (PANI), prussian blue (PB) and tungsten oxide (WO_3), transparent conducting glass plates with an indium-tin oxide coating (indium oxide doped with tin, $In_2O_3(Sn)$, ITO, typical surface resistivity of 90 $\Omega/\square$) and the solid state polymer electrolyte poly(2-acrylamido-2-methyl-propane-sulphonic acid) (PAMPS) as an ionic conductor. Both the PANI, PB and WO_3 coating thicknesses have been less than 1 μm, while the PAMPS layer thickness has been about 0.1 mm. Applying a positive potential to the PANI/PB electrode, both PANI, PB and WO_3 turn to a blue colour, while the window is bleached (made almost transparent) by reversing the polarity of the electrodes. Only a small charge density of about 3 mC/cm^2, corresponding to a low energy consumption of about 5 mWh/m^2, is required for either the colouring or the bleaching process (Jelle et al. 1998a).

A high transmission regulation and solar modulation (solar regulation 53 %, calculated based on the solar spectral irradiance given in CRC Handbook of Chemistry and Physics 1989-1990) (Jelle et al. 1998a) have been achieved with this type of ECW (ECW1, left Fig.1), which is depicted in Fig.2 covering the whole solar spectrum. The inclusion of PB in PANI enhances the colouration (wavelength dependent absorption), while the adhesion of PB is improved by PANI, i.e. in this respect there exists a symbiotic relationship between PANI and PB (Jelle et al. 1998a). Transmittance curves for a second ECW (ECW2, right Fig.1) of the same construction, though with PANI-PB multilayers and a very dark colour in the coloured state, are shown in Fig.2 (solar regulation 49 %) (Jelle et al. 1998b). These solar regulations might be compared to the ΔT_{sol} values of 0.57 and 0.51 for ECW1 and ECW2, respectively, thus obtaining somewhat larger values when using the same calculation method but with a bit different solar reference spectrum.

In addition to their evident potential benefits and savings in solar energy control, the ECWs may also be employed in order to achieve the desired protection of materials and human skin inside buildings during direct sunlight. That is, the dynamic characteristics of ECWs may allow diffuse daylight through the window panes in the required amount in order to obtain a satisfactory room illumination, whereas at direct sunlight exposure, the SMPF and SSPF values for the window panes may be increased to a sufficient high protection level.

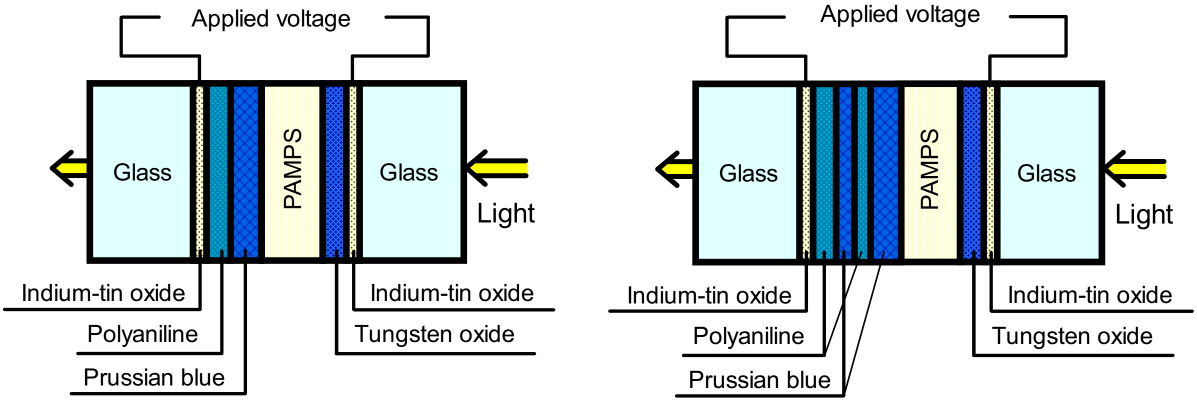

Fig.1. Schematic drawing of the two electrochromic window configurations ECW1 (left) and ECW2 (right, PANI-PB multilayer) based on the electrochromic materials polyaniline (PANI), prussian blue (PB) and tungsten oxide (WO_3). From Jelle and Hagen (1999).

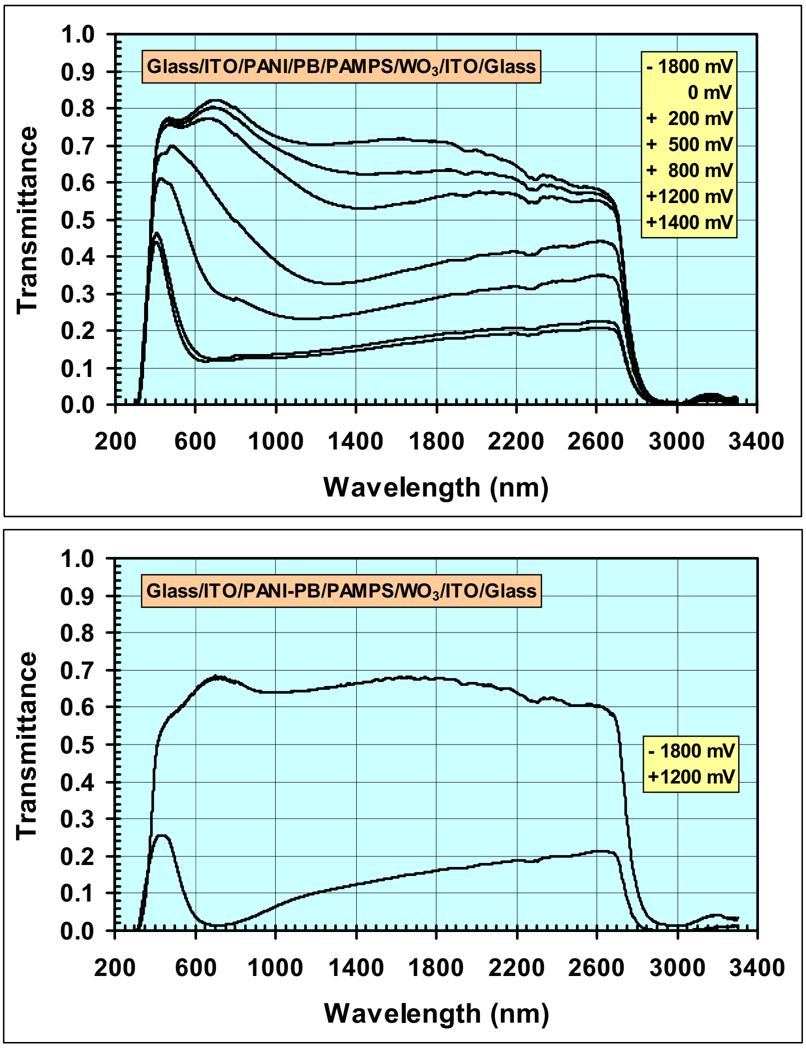

Fig.2. Transmittance vs. wavelength in the whole solar spectrum measured for two different ECWs at various applied potentials. Highest colouration level is at +1400 mV (ECW1, top) and +1200 mV (ECW2, bottom). Redrawn from Jelle et al. (2007).

5. SOLAR RADIATION GLAZING FACTOR CALCULATIONS

Solar radiation glazing factors for different colouration levels, i.e. at different applied potentials, in two electrochromic windows (ECW) are given in Table 1. From Table 1 it is observed that various solar radiation glazing factors may obtain both high and low values depending upon the applied electrical potential (intermediate values not shown here), e.g. changing the T_{vis} value from 0.78 to 0.17 for the ECW1 device and from 0.62 to 0.10 for the darker ECW2 device. It is also noted that these ECWs contain solar radiation absorbing electrochromic materials, i.e. not reflecting materials, as the changes with applied potential occur in the transmittance (e.g. T_{sol}) and absorbance (e.g. A_{sol}) values, and not in the reflectance (e.g. R_{sol}) values. As expected, the highest colouration level gives the largest SMPF values, i.e. the best protection of materials is achieved with the darkest ECW, e.g. compare a SMPF value of 0.71 for ECW1 and 0.82 for ECW2 in the coloured state.

Incorporating the ECWs into two-layer and three-layer window pane configurations reduces the total solar energy throughput in the windows, e.g. as seen in the T_{sol} and SF values, as several layers of glass and coatings will increase the total reflectance and absorbance. Note that some of the reflectance values $R_{vis,ext}$, $R_{vis,int}$ and R_{sol} may have errors due to parallel displacement of solar radiation through glass causing parts of the radiation to not enter the spectrophotometer detector during the measurements. For daylight and solar energy control the T_{vis}, T_{sol} and SF values are among the most crucial factors to be determined for ECWs working in the absorption mode.

Furthermore, solar radiation glazing factor modulations are calculated for the two different electrochromic windows ECW1 and ECW2 and given in Table 1. The modulation level is calculated by subtracting the solar radiation glazing factors for the same ECW at the high and low potentials given in Table 1, e.g. $\Delta T_{sol} = 0.74 - 0.17 = 0.57$ for ECW1.

Table 1. Calculated solar radiation glazing factors, and modulations, for two different electrochromic windows ECW1 (left) and ECW2 (right) at different colouration levels, i.e. at different applied potentials. Highest colouration level is at +1400 mV (ECW1) and +1200 mV (ECW 2, PANI-PB multilayer). Corresponding transmittance spectra are given in Fig.2. Reflectance values of the ECWs have not been measured, but as the (absorbing) electrochromic coatings are located between two glass plates, the (low) reflectance values will be close to the values for float glass, and these are hence employed in the current calculations. As there at the time of ECW fabrication were no resources for emissivity determinations, the nominal value of 0.837 for float glass was assumed (ε). The calculation of the SF is performed with respect to ε of the inside facing surface of the innermost glass pane, i.e. normally a float glass.

Solar Radiation Glazing Factor	ECW at -1800 mV	ECW at +1400 mV	Change in Solar Radiation Glazing Factor	ECW from -1800 mV to +1400 mV
T_{uv}	0.23	0.23	ΔT_{uv}	0.00
T_{vis}	0.78	0.17	ΔT_{vis}	0.61
T_{sol}	0.74	0.17	ΔT_{sol}	0.57
SMPF	0.43	0.71	ΔSMPF	-0.28
SSPF	0.93	0.93	ΔSSPF	0.00
$R_{vis,ext}$	0.09	0.09	$\Delta R_{vis,ext}$	0.00
$R_{vis,int}$	0.09	0.09	$\Delta R_{vis,int}$	0.00
R_{sol}	0.08	0.08	ΔR_{sol}	0.00
A_{sol}	0.18	0.75	ΔA_{sol}	-0.57
ε	0.837	0.837	Δε	-
SF	0.79	0.37	ΔSF	0.42

Solar Radiation Glazing Factor	ECW at -1800 mV	ECW at +1200 mV	Change in Solar Radiation Glazing Factor	ECW from -1800 mV to +1200 mV
T_{uv}	0.10	0.12	ΔT_{uv}	-0.02
T_{vis}	0.62	0.10	ΔT_{vis}	0.52
T_{sol}	0.61	0.10	ΔT_{sol}	0.51
SMPF	0.61	0.82	ΔSMPF	-0.21
SSPF	0.97	0.97	ΔSSPF	0.00
$R_{vis,ext}$	0.09	0.09	$\Delta R_{vis,ext}$	0.00
$R_{vis,int}$	0.09	0.09	$\Delta R_{vis,int}$	0.00
R_{sol}	0.08	0.08	ΔR_{sol}	0.00
A_{sol}	0.31	0.82	ΔA_{sol}	-0.51
ε	0.837	0.837	Δε	-
SF	0.69	0.31	ΔSF	0.38

Note that incorporating the ECWs into two-layer and three-layer window pane configurations (not depicted here) reduces the total solar energy throughput modulation in the windows, as several layers of glass and coatings will increase the total reflectance and absorbance, i.e. less solar radiation left for the ECWs to modulate (regulate). That is, the solar radiation regulation by an ECW will decrease with the number of glass panes and low emittance coatings added to the total window configuration. It is observed that the ΔSSPF modulation is more or less insignificant for the ECW glass configurations given in Table 1, as the change in ECW colouration state at low wavelengths is almost negligible due to the highly increasing absorption in the glass system from 400 nm and below (see Fig.2).

Thus, the ECWs may contribute to elegant, flexible glazing systems with dynamical control of the solar radiation, both with regard to daylight, energy aspects and protection of materials inside buildings. The ECWs may readily be characterized by spectroscopic measurements and subsequent calculations of the solar radiation glazing factors.

6. CONCLUSIONS

Solar radiation glazing factors, i.e. ultraviolet solar transmittance, visible solar transmittance, solar transmittance, solar material protection factor, solar skin protection factor, external visible solar reflectance, internal visible solar reflectance, solar reflectance, solar absorbance, emissivity, solar factor and colour rendering factor, characterize window panes and other glass structures in buildings. These factors for different glass fabrications may readily be compared in order to choose the most appropriate glass material for the building in question. Spectroscopical measurements and corresponding calculations of the solar radiation glazing factors were performed on two electrochromic window devices, and selected two-layer and three-layer window pane combinations incorporating electrochromic materials. It is concluded that the solar radiation glazing factors offer a suitable and powerful characterizing tool for comparing electrochromic windows at their various colouration states.

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