# SOLAR RADIATION GLAZING FACTORS FOR ELECTROCHROMIC WINDOWS FOR BUILDING APPLICATIONS

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## ABSTRACT

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.

*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

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 bondings 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. This transmitted UV light affects both materials and living species inside the buildings. Typical examples may be fading, discolouration and degradation of books in book shelves (e.g. in libraries) and other paper materials, wall paintings and exhibits (e.g. in museums), wood materials in walls, floor, ceiling, window frames etc., plastic materials and surface painting in various building structures and equipment and furnitures.

Generally, the most important solar radiation glazing factors are:

1. Ultraviolet Solar Transmittance, $T_{uv}$
2. Visible Solar Transmittance, $T_{vis}$
3. Solar Transmittance, $T_{sol}$
4. Solar Material Protection Factor, SMPF
5. Solar Skin Protection Factor, SSPF
6. External Visible Solar Reflectance, $R_{vis,ext}$
7. Internal Visible Solar Reflectance, $R_{vis,int}$
8. Solar Reflectance, $R_{sol}$
9. Solar Absorbance, $A_{sol}$
10. Emissivity, $\varepsilon$
11. Solar Factor, SF (from $T_{sol}$, $R_{sol}$ and $\varepsilon$)
12. Colour Rendering Factor, CRF

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

Thus, the solar radiation regulation in ECWs enables a dynamic control of the solar radiation glazing factors given above. This work will present and summarize in an abridged way these solar glazing factors together with measurements and calculations carried out on two ECWs.

## 2. SOLAR RADIATION IN WINDOW PANES AND GLASS STRUCTURES

Solar radiation falling onto a material will be transmitted, absorbed and reflected. The amount of sunlight transmitted, absorbed and reflected is dependent upon the wavelength ($\lambda$) of the light, the incident angle and the optical properties of the material. These three processes are characterized by the material's transmittance (T), absorbance (A) and reflectance (R), which denote the fraction of incident light intensity which is transmitted, absorbed or reflected by the material. Conservation of the total energy in the light beam requires that:

$$T(\lambda) + A(\lambda) + R(\lambda) = 1 \quad (100\ \%) \tag{1}$$

For a body in thermodynamically equilibrium with its surroundings the energy absorbed in the material must be equal to the emitted energy (Kirchhoff's law), i.e.

$$E(\lambda) = A(\lambda) \tag{2}$$

where E denotes the emittance.

Whilst the relationship between the spectroscopic quantities is rather straightforward for the single glass pane, the situation is more complex in Fig.1 with multiple transmittance, absorbance and reflectance in a two-layer glass pane.

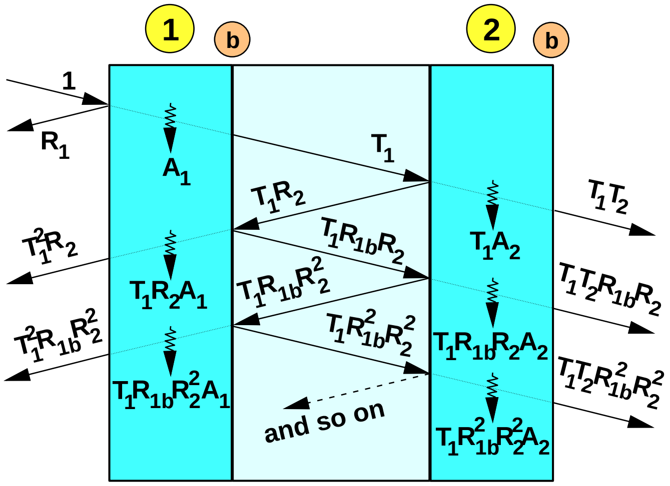

Fig.1. Multiple transmittance (T), absorbance (A) and reflectance (R) in a two-layer glass pane. See e.g. Kimura (1977). Diffuse transmittance, diffuse reflectance and retroreflectance are not depicted, neither reflectance from the interface glass/air(gas) within the glass material.

Figure 1 is simplified with respect to actual refracted light beam paths, e.g. parallel displacement due to different media with unequal refraction indices. In fact, contrary to real situations, this is avoided in the calculations by assuming a light beam with normal incidence. The real transmittance values including the total solar energy transmittance are then somewhat lower. In addition, the reflectance from the interface glass/air(gas) within the glass material is not depicted either. Nevertheless, from Fig.1 analytical expressions for the overall transmittance, absorbance and reflectance may be calculated, where input values for the single glass panes are obtained from UV-VIS-NIR spectrophotometric measurements, i.e. $T_1$, $R_1$, $R_{1b}$, $T_2$, $R_2$, $R_{2b}$, etc. The calculations for a three-layer window pane will naturally be even more complex. In a two-layer window pane which purpose is to act as a blocking screen towards sunlight, a coating is placed on the inside of the outer glass. In a two-layer window pane which purpose is to reduce the heat loss from the inside, a coating is placed on the outside of the inner glass. In both cases, the coating is facing the window pane cavity.

Transmittance T and reflectance R as functions of wavelength λ for a ***single glass pane*** given by

$$T(\lambda) = T_1 \tag{3}$$

$$R(\lambda) = R_1 \tag{4}$$

may be calculated for a ***two-layer window pane*** by applying Fig.1 and infinite series expansion to give the following expressions (Kimura 1977, Rubin et al. 1998):

$$T(\lambda) = \frac{T_1 T_2}{1 - R_{1b} R_2} \tag{5}$$

$$R_{ext}(\lambda) = R_1 + \frac{T_1^2 R_2}{1 - R_{1b} R_2} \tag{6}$$

$$R_{int}(\lambda) = R_{2b} + \frac{T_2^2 R_{1b}}{1 - R_{1b} R_2} \tag{7}$$

and for a ***three-layer window pane*** the following formulas (Kimura 1977, Rubin et al. 1998):

$$T(\lambda) = \frac{T_1 T_2 T_3}{[1 - R_{1b} R_2][1 - R_{2b} R_3] - T_2^2 R_{1b} R_3} \tag{8}$$

$$R_{ext}(\lambda) = R_1 + \frac{T_1^2 R_2 [1 - R_{2b} R_3] + T_1^2 T_2^2 R_3}{[1 - R_{1b} R_2][1 - R_{2b} R_3] - T_2^2 R_{1b} R_3} \tag{9}$$

$$R_{int}(\lambda) = R_{3b} + \frac{T_3^2 R_{2b} [1 - R_{1b} R_2] + T_2^2 T_3^2 R_{1b}}{[1 - R_{1b} R_2][1 - R_{2b} R_3] - T_2^2 R_{1b} R_3} \tag{10}$$

where

> $T_1$, $T_2$, $T_3$, $R_1$, $R_2$ and $R_3$ denote the transmittance and reflectance for glass number 1, 2 and 3, respectively, i.e. exterior (outer) glass towards incident light beam, middle glass and interior (inner) glass, respectively.

The index ”b” for $R_{1b}$ and $R_{2b}$ designates that the reflectance measurement is performed on the back (reverse) side of the glass as compared to the normal incident light beam direction, e.g. $R_{1b}$ versus $R_1$. For simplicity reasons, the wavelength ($\lambda$) dependence of $T_1$, $T_2$, $T_3$, $R_1$, $R_2$ and $R_3$ is omitted in Eqs.3-10 above. $R_{ext}(\lambda)$ and $R_{int}(\lambda)$ denote the external and internal light reflectance, i.e. outdoor light reflected back to the outside and indoor light reflected back to the inside, respectively. All the calculated factors for multi-layer window panes are based on transmittance and reflectance measurements carried out on single glass panes, with subsequent calculations applying Eqs.3-10 above. The absorbance is then calculated by applying the expression in Eq.1.

## 3. EXPERIMENTAL

### 3.1. Glass Samples and Window Pane Combinations

To illustrate various transmittance, absorbance and reflectance levels in the solar spectrum, one float glass, one glass with low emittance coating and two electrochromic window (ECW) devices, were selected as examples. Based on these measurements the solar radiation glazing factors were calculated, including selected two-layer and three-layer window pane combinations with ECWs. The actual fabrication and miscellaneous testing of the ECWs are described elsewhere (Jelle et al. 1998a, 1998b, 1999, 2007).

### 3.2. UV-VIS-NIR Spectrophotometry

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 these glass samples in the ultraviolet (UV), visible (VIS) and near infrared (NIR) region, from 290 nm to 3300 nm. The absorbance was calculated from the expression given in Eq.1. 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.

### 3.3. Emissivity Determination by Specular IR Reflectance

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 ($\leq 10^\circ$) 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 $10^\circ$ or less (ASTM E 1585-93). For other ambient temperatures than 283 K ($\approx$ 10 ºC), the emissivity is not strongly dependent on the mean temperature (ISO 10292:1994(E)).

### 3.4. Emissivity Determination by Heat Flow Meter

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.

### 3.5. Emissivity Determination by Hemispherical Reflectance

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.

### 3.6. Actual Emissivity Determinations within 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 $\text{cm}^{-1}$ in the wavelength range 2 – 25 μm. The IR source temperature was 704ºC. The results were $\varepsilon_{\text{float}} = 0.836$ and $\varepsilon_{\text{lowe}} = 0.071$, for the float and low emittance glass, respectively. The $\varepsilon_{\text{float}}$ 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 $\varepsilon_{\text{lowe}}$ 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 $\varepsilon_{\text{float}} = 0.837$ for float glass is applied in the calculation of SF for the ECWs.

## 4. SOLAR RADIATION GLAZING FACTOR DEFINITIONS

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

$$T_{uv} = \frac{\sum_{\lambda=300\,\text{nm}}^{380\,\text{nm}} T(\lambda) S_\lambda \Delta\lambda}{\sum_{\lambda=300\,\text{nm}}^{380\,\text{nm}} S_\lambda \Delta\lambda} \tag{11}$$

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

$$T_{vis} = \frac{\sum_{\lambda=380\,nm}^{780\,nm} T(\lambda) D_{\lambda} V(\lambda) \Delta\lambda}{\sum_{\lambda=380\,nm}^{780\,nm} D_{\lambda} V(\lambda) \Delta\lambda} \tag{12}$$

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

$$T_{sol} = \frac{\sum_{\lambda=300\,nm}^{2500\,nm} T(\lambda) S_{\lambda} \Delta\lambda}{\sum_{\lambda=300\,nm}^{2500\,nm} S_{\lambda} \Delta\lambda} \tag{13}$$

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

$$SMPF = 1 - \tau_{df} = 1 - \frac{\sum_{\lambda=300\,nm}^{600\,nm} T(\lambda) C_{\lambda} S_{\lambda} \Delta\lambda}{\sum_{\lambda=300\,nm}^{600\,nm} C_{\lambda} S_{\lambda} \Delta\lambda} \tag{14}$$

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

$$SSPF = 1 - F_{sd} = 1 - \frac{\sum_{\lambda=300\,nm}^{400\,nm} T(\lambda) E_{\lambda} S_{\lambda} \Delta\lambda}{\sum_{\lambda=300\,nm}^{400\,nm} E_{\lambda} S_{\lambda} \Delta\lambda} \tag{15}$$

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

$$R_{vis,ext} = \frac{\sum_{\lambda=380\,nm}^{780\,nm} R_{ext}(\lambda) D_{\lambda} V(\lambda) \Delta\lambda}{\sum_{\lambda=380\,nm}^{780\,nm} D_{\lambda} V(\lambda) \Delta\lambda} \tag{16}$$

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

$$R_{vis,int} = \frac{\sum_{\lambda=380\,nm}^{780\,nm} R_{int}(\lambda) D_{\lambda} V(\lambda) \Delta\lambda}{\sum_{\lambda=380\,nm}^{780\,nm} D_{\lambda} V(\lambda) \Delta\lambda} \tag{17}$$

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

$$R_{sol} = \frac{\sum_{\lambda=300\,nm}^{2500\,nm} R_{ext}(\lambda) S_\lambda \Delta\lambda}{\sum_{\lambda=300\,nm}^{2500\,nm} S_\lambda \Delta\lambda} \tag{18}$$

The ***Solar Absorbance*** **($A_{sol}$)** is calculated from the expression in Eq.1 with insertion of $T_{sol}$ and $R_{sol}$ from Eq.13 and Eq.18, giving the following expression:

$$A_{sol} = 1 - T_{sol} - R_{sol} = 1 - \frac{\sum_{\lambda=300\,nm}^{2500\,nm} T(\lambda) S_\lambda \Delta\lambda}{\sum_{\lambda=300\,nm}^{2500\,nm} S_\lambda \Delta\lambda} - \frac{\sum_{\lambda=300\,nm}^{2500\,nm} R_{ext}(\lambda) S_\lambda \Delta\lambda}{\sum_{\lambda=300\,nm}^{2500\,nm} S_\lambda \Delta\lambda} \tag{19}$$

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

$$\varepsilon = c_{corr}\varepsilon_n = \frac{\varepsilon}{\varepsilon_n}\varepsilon_n = c_{corr}(1 - R_n) = c_{corr}\left[1 - \frac{1}{30}\sum_{i=1}^{30} R_n(\lambda_i)\right] \tag{20}$$

or by heat flow meter measurements by:

$$\varepsilon = \frac{2(q_{tot} - \frac{\kappa}{d}\Delta T)}{4\sigma T_m^3 \Delta T + q_{tot} - \frac{\kappa}{d}\Delta T} \tag{21}$$

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

$$\varepsilon = 2\int_0^{\pi/2} \varepsilon_t(\theta) \sin\theta \cos\theta d\theta \tag{22}$$

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

$$SF = T_{sol} + q_i \tag{23}$$

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

$$CRF = \frac{R_a}{100} = \frac{1}{800}\sum_{i=1}^{8} R_i \tag{24}$$

where

$\lambda$ = 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.20 above

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

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

$D_\lambda$ = 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)

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

$C_\lambda = e^{-0.012\lambda}$ ($\lambda$ 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)

$E_\lambda$ = 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)

$\kappa$ = thermal conductivity of the medium separating the two surfaces (W/(mK))

$\kappa = \kappa_{air} = 0.0242396(1 + 0.0030052\theta - 1.282 \cdot 10^{-6}\theta^2)$ (W/(mK))

(values accurate to 0.6 % between $\theta = 10$ºC and $\theta = 70$ºC)
($\theta$ given in ºC) (EN 1946-2:1999 E, EN 1946-3:1999 E)

$\theta = (T_m - 273.15\ K)$ºC/K (ºC)

$T_m$ = mean temperature of the two surfaces (K)

$\Delta T$ = 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 $\approx 5.67\cdot10^{-8}\ W/(m^2K^4)$

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

$\theta$ and $\phi$ are integrating angles over the hemisphere

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

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

c = velocity of light $\approx 3.00 \cdot 10^{8}$ m/s

$T_{sol}$ = solar transmittance (Eq.13)

$A_{sol} = q_i + q_e$ ($A_{sol}$ from Eq.19)

$q_i$ = secondary heat transfer factor towards the inside

$q_e$ = secondary heat transfer factor towards the outside

(complete details for calculation of SF given in ISO/FDIS 9050:2003(E), with additions in ISO 10292:1994(E) and EN-ISO 6946:1996, note that $\varepsilon$ and $R_{sol}$ enter into $q_i$ in Eq.22, $R_{sol}$ 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)

## 5. MISCELLANEOUS SOLAR RADIATION GLAZING FACTOR DETAILS

### 5.1. Solar Radiation Glazing Factors in General

All the solar radiation glazing factors will be a number between 0 and 1. In common usage the factors may often be chosen in percentage, i.e. between 0 and 100 %. It should be noted that the whole solar spectrum is not covered in the calculations of various glazing factors, and in future versions of ISO/FDIS 9050:2003(E) the wavelength range may favourably be extended to cover an even larger part of the solar radiation, e.g. including the lower limit down to 290 nm and the upper limit up to 3000 nm. Also note that $A_{sol}$ is a calculated value from measured $T(\lambda)$ and $R(\lambda)$ spectra, i.e. no direct measurements of absorbance $A(\lambda)$ spectra are performed.

## 5.2. SMPF and SSPF

A low SMPF value indicates a low material protection, whereas a high number represents a high degree of material protection. It should be noted that the wavelength region for the calculation of SMPF has been extended from the earlier 500 nm upper limit till today's value of 600 nm (ISO/FDIS 9050:2003(E)), demonstrating an increased awareness that a much larger part of the visible solar spectrum also contributes to the degradation of materials. Earlier a Krochmann damage factor for materials was calculated, with integration between 300 nm and 500 nm (ISO/DIS 9050:2001). A low SSPF value indicates a low skin protection, whereas a high number represents a high degree of skin protection. The calculation of the SSPF extends over the ultraviolet spectrum (at earth's surface) and the low wavelength part of the visible spectrum, which may contribute to the solar radiation damage of the human skin. It may be noted that earlier there existed another definition of a skin protection factor, denoted SPF (ISO/DIS 9050:2001), with the following correlation between the different terms: SSPF = 1 - (1/SPF) = 1 - $F_{sd}$ = (SPF - 1)/SPF.

## 5.3. Emissivity

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). Confer Eq.1 and Eq.2 with zero transmittance and the emittance equal to the absorbance. Determination of the emissivity is required in order to further determine the solar factor (SF) and the thermal transmittance (U-value).

## 5.4. Solar Factor (SF)

The Solar Factor (SF) for *single glazing* is given by:

$$SF = T_{sol} + q_i = T_{sol} + A_{sol}\frac{h_i}{h_e + h_i} \qquad (25)$$

The Solar Factor (SF) for *double glazing* is given by:

$$SF = T_{sol} + q_i = T_{sol} + \frac{\dfrac{A_{sol,1} + A_{sol,2}}{h_e} + \dfrac{A_{sol,2}}{\Lambda}}{\dfrac{1}{h_i} + \dfrac{1}{h_e} + \dfrac{1}{\Lambda}} \qquad (26)$$

The Solar Factor (SF) for *triple glazing* is given by:

$$SF = T_{sol} + q_i = T_{sol} + \frac{\dfrac{A_{sol,1} + A_{sol,2} + A_{sol,3}}{h_e} + \dfrac{A_{sol,2} + A_{sol,3}}{\Lambda_{12}} + \dfrac{A_{sol,3}}{\Lambda_{23}}}{\dfrac{1}{h_i} + \dfrac{1}{h_e} + \dfrac{1}{\Lambda_{12}} + \dfrac{1}{\Lambda_{23}}} \qquad (27)$$

where

$A_{sol}$ = 1 - $T_{sol}$ - $R_{sol}$ = solar absorbance given by Eq.19

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

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

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

Λ = thermal conductance between the outer surface of the outer (first) pane and the innermost surface of the inner (second) pane (double glazing)

$\Lambda_{12}$ = thermal conductance between the outer surface of the outer (first) pane and the centre of the middle (second) pane (triple glazing)

$\Lambda_{23}$ = thermal conductance between the centre of the middle (second) pane and the centre of the inner (third) pane (triple glazing)

$$\frac{1}{U} = \frac{1}{h_e} + \frac{1}{\Lambda} + \frac{1}{h_i}$$

$$\Lambda = \left(\sum^{N} \frac{1}{h_s} + \sum^{M} d_m r_m\right)^{-1}$$

and e.g.

$$A_{sol,1} = \frac{\displaystyle\sum_{\lambda = 300\text{ nm}}^{2500\text{ nm}} \left\{A_1 + \frac{A_{1b} T_1 R_2}{1 - R_{1b} R_2}\right\} S_\lambda \Delta\lambda}{\displaystyle\sum_{\lambda = 300\text{ nm}}^{2500\text{ nm}} S_\lambda \Delta\lambda} \qquad (28)$$

$$A_{sol,1} = \frac{\displaystyle\sum_{\lambda = 300\text{ nm}}^{2500\text{ nm}} \left\{A_1 + \frac{T_1 A_{1b} R_2 (1 - R_{2b} R_3) + T_1 T_2^2 A_{1b} R_3}{(1 - R_{1b} R_2)(1 - R_{2b} R_3) - T_2^2 R_{1b} R_3}\right\} S_\lambda \Delta\lambda}{\displaystyle\sum_{\lambda = 300\text{ nm}}^{2500\text{ nm}} S_\lambda \Delta\lambda} \qquad (29)$$

where the two different expressions for $A_{sol,1}$ above denote the solar absorbance of the outer (first) pane within a double and a triple glazing, respectively. For further details, complete nomenclature, specific values and a full set of equations it is referred to ISO/FDIS 9050:2003(E).

### 5.5. Colour Rendering Factor

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).

## 6. SPECTROSCOPICAL GLASS MEASUREMENTS

In the following, spectrophotometric measurements are depicted for one float glass, one glass with a low emittance coating and two electrochromic window (ECW) devices at various colouration levels. CRF values have not been calculated yet. The absorbance spectra depicted in the following sections below comply with the absorbance definition in Eq.1, a number between 0 and 1, i.e. the absorbance is not written on the often used/measured logarithmic scale called optical density.

### 6.1. Float Glass and Low Emittance Glass Spectroscopical Data

The transmittance, absorbance and reflectance in the whole solar spectrum were measured for one float glass and one glass with low emittance coating, depicted in Fig.2. The measured wavelength range is from 290 nm to 3300 nm. The upper border of 3300 nm represents the spectrophotometer’s long wave limit, while below 290 nm the absorption in glass becomes very large. The most noticeable difference is the large reflectance values, and thereby small transmittance values, in the near infrared region for the glass with the low emittance coating. By taking a closer look at the ultraviolet and visible region it is observed that the low emittance glass is absorbing more light at these lower wavelengths than the float glass, i.e. the transmittance is lower for the low emittance glass than the float glass in the UV-VIS region.

The drop in transmittance at around 1000 nm, with a corresponding absorbance peak, as seen for the float glass in Fig.2, is due to a certain impurity amount of ferric oxide ($Fe_2O_3$) in the glass. The sharp transmittance cutoffs located around 400 nm and 2700 nm are due to the large absorption in glass into the ultraviolet and infrared region, respectively. The sharp transmittance cutoff, with corresponding absorbance increase, at around 2700 nm, is also observed for the low emittance glass, but much smaller in value since the largest part of the incoming light in this wavelength region is reflected from the low emittance coating (the coating surface is facing the incident light beam in the spectrophotometer).

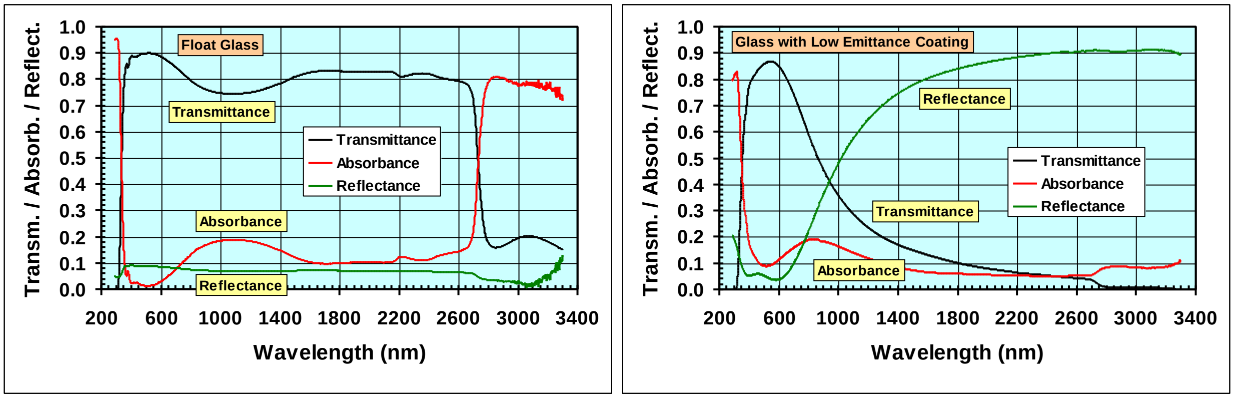

Fig.2. Transmittance, absorbance and reflectance versus wavelength in the whole solar spectrum measured for a float glass (left) and for a glass with low emittance coating (right). Incident light beam towards surface coating during reflectance measurements. Redrawn from Jelle et al. (2007).

## 6.2. Electrochromic Window Spectroscopical Data

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.3, 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 Ω/□) 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.3), which is depicted in Fig.4 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.3) of the same construction, though with PANI-PB multilayers and a very dark colour in the coloured state, are shown in Fig.4 (solar regulation 49 %) (Jelle et al. 1998b). 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.

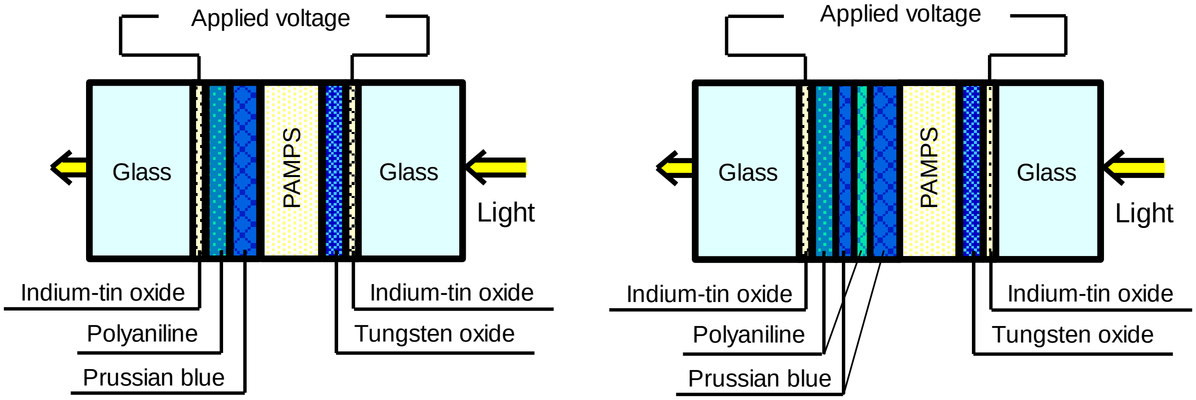

Fig.3. Schematic drawing of the two electrochromic window configurations ECW1 (left) and ECW2 (right, PANI-PB multilayer) based on the electrochromic materials polyaniline (PANI), prussian blue (PB) and tungsten oxide ($WO_3$). From Jelle and Hagen (1999).

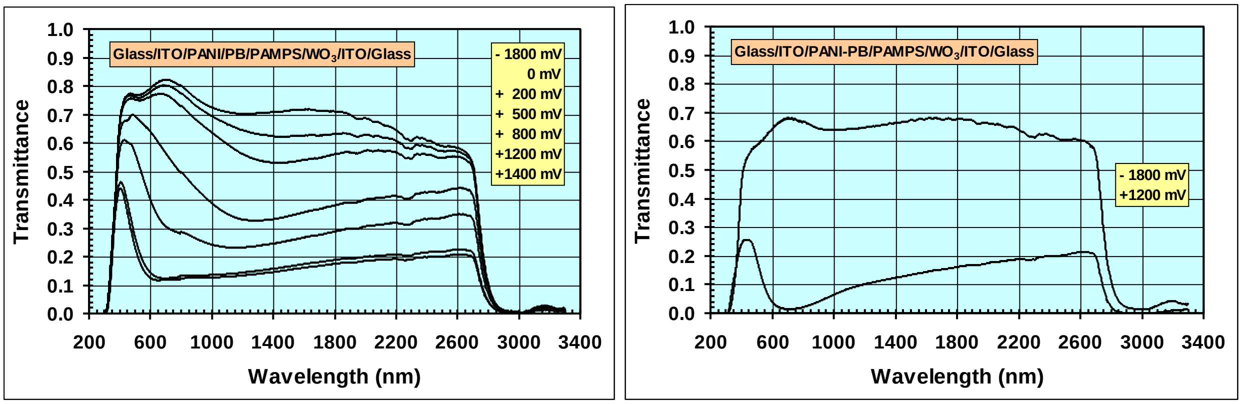

Fig.4. Transmittance vs. wavelength in the whole solar spectrum measured for two different ECWs at various applied potentials. The total solar energy regulation is 53 % (left, ECW1) and 49 % (right, ECW2, PANI-PB multilayer). Highest colouration level is at +1400 mV (left) and +1200 mV (right). Redrawn from Jelle et al. (2007).

## 7. SOLAR RADIATION GLAZING FACTOR CALCULATIONS

In the following, solar radiation glazing factors are calculated based on spectrophotometric measurements given in Fig.2 and Fig.4 for one float glass, one glass with a low emittance coating and two electrochromic window (ECW) devices at various colouration levels, including selected two-layer and three-layer window pane combinations with ECWs. CRF values have not been calculated yet.

## 7.1. Solar Radiation Glazing Factors for Float Glass and Low Emittance Glass

In Table 1 there is given calculated solar radiation glazing factors for a float glass and a low emittance glass. From Table 1 it is seen that the float glass and the low emittance glass have quite large and similar $T_{vis}$ values, i.e. 0.89 and 0.86, respectively. However, the $T_{sol}$ value for float glass is substantially higher than the $T_{sol}$ value for the low emittance glass, i.e. 0.83 vs. 0.56. This is readily observed from the transmittance spectra in Fig.2. Furthermore, it is also observed that the float glass has substantially lower $R_{sol}$ value than the low emittance glass, i.e. 0.08 vs. 0.27, which is also confirmed by inspecting the reflectance spectra in Fig.2. Thereby, the float glass have a larger SF value than the low emittance glass, i.e. 0.85 vs. 0.62.

Table 1. Calculated solar radiation glazing factors for float glass and glass with low emittance coating. Corresponding transmittance spectra are given in Fig.2. The emissivity of the float glass was determined to $\varepsilon_{float} = 0.836$ by hemispherical directional reflectance measurements and was applied in the calculation of the solar factor (SF) for both the float glass and the low emittance glass as the emissivity 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 $\varepsilon_{lowe} = 0.071$ value was not applied in this context.

| Glass Type | $T_{uv}$ | $T_{vis}$ | $T_{sol}$ | SMPF | SSPF | $R_{vis,ext}$ | $R_{vis,int}$ | $R_{sol}$ | $A_{sol}$ | $\varepsilon$ | SF |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Float Glass<br>G | 0.65 | 0.89 | 0.83 | 0.20 | 0.81 | 0.09 | 0.09 | 0.08 | 0.09 | 0.836 | 0.85 |
| Low Emittance Glass<br>LE/G | 0.41 | 0.86 | 0.59 | 0.32 | 0.89 | 0.04 | 0.04 | 0.27 | 0.14 | 0.836 | 0.62 |

The glass with the low emittance coating has SMPF and SSPF values of 0.32 and 0.89, respectively, which gives better material and skin protection than the float glass with SMPF and SSPF values of 0.20 and 0.81, respectively.

## 7.2. Solar Radiation Glazing Factors for Electrochromic Windows

Table 2 gives the solar radiation glazing factors for different colouration levels, i.e. at different applied potentials, in an electrochromic window (ECW), in addition to selected two-layer and three-layer window pane configurations with incorporated electrochromic materials.

From Table 2 it is observed that various solar radiation glazing factors may obtain both high and low values depending upon the applied electrical potential, 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.

Table 2. Calculated solar radiation glazing factors for two different electrochromic windows (ECWs) at different colouration levels, i.e. at different applied potentials, and selected two-layer and three-layer window pane configurations with ECWs. Highest colouration level is at +1400 mV (ECW1) and +1200 mV (ECW 2, PANI-PB multilayer). Corresponding transmittance spectra are given in Fig.4. 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. The following configuration denotations are employed: G = Glass, LE = Low emittance coating, A = Air cavity, EC1 = ECW device between two glass plates, EC2 = ECW2 device between two glass plates (PANI-PB multilayer), T or C behind EC1 and EC2 denote transparent or coloured state, respectively.

| Glass Configuration | $T_{uv}$ | $T_{vis}$ | $T_{sol}$ | SMPF | SSPF | $R_{vis,ext}$ | $R_{vis,int}$ | $R_{sol}$ | $A_{sol}$ | ε | SF |
|---|---|---|---|---|---|---|---|---|---|---|---|
| ECW1 (-1800 mV) | 0.23 | 0.78 | 0.74 | 0.43 | 0.93 | 0.09 | 0.09 | 0.08 | 0.18 | 0.837 | 0.79 |
| ECW1 (0 mV) | 0.23 | 0.77 | 0.72 | 0.43 | 0.93 | 0.09 | 0.09 | 0.08 | 0.21 | 0.837 | 0.77 |
| ECW1 (+200 mV) | 0.24 | 0.75 | 0.68 | 0.44 | 0.93 | 0.09 | 0.09 | 0.08 | 0.24 | 0.837 | 0.74 |
| ECW1 (+500 mV) | 0.25 | 0.66 | 0.52 | 0.48 | 0.93 | 0.09 | 0.09 | 0.08 | 0.40 | 0.837 | 0.62 |
| ECW1 (+800 mV) | 0.26 | 0.47 | 0.36 | 0.54 | 0.92 | 0.09 | 0.09 | 0.08 | 0.56 | 0.837 | 0.51 |
| ECW1 (+1200 mV) | 0.24 | 0.19 | 0.19 | 0.68 | 0.93 | 0.09 | 0.09 | 0.08 | 0.73 | 0.837 | 0.38 |
| ECW1 (+1400 mV) | 0.23 | 0.17 | 0.17 | 0.71 | 0.93 | 0.09 | 0.09 | 0.08 | 0.75 | 0.837 | 0.37 |
| ECW2 (-1800 mV) | 0.10 | 0.62 | 0.61 | 0.61 | 0.97 | 0.09 | 0.09 | 0.08 | 0.31 | 0.837 | 0.69 |
| ECW2 (+1200 mV) | 0.12 | 0.10 | 0.10 | 0.82 | 0.97 | 0.09 | 0.09 | 0.08 | 0.82 | 0.837 | 0.31 |
| EC1/Float (-)<br>EC1T/A/G | 0.18 | 0.70 | 0.62 | 0.50 | 0.95 | 0.14 | 0.04 | 0.12 | 0.26 | 0.837 | 0.65 |
| EC1/Float (+)<br>EC1C/A/G | 0.18 | 0.15 | 0.15 | 0.75 | 0.95 | 0.09 | 0.04 | 0.08 | 0.77 | 0.837 | 0.25 |
| EC1/LowE (-)<br>EC1T/A/LE/G | 0.12 | 0.67 | 0.45 | 0.55 | 0.97 | 0.11 | 0.03 | 0.23 | 0.32 | 0.837 | 0.54 |
| EC1/LowE (+)<br>EC1C/A/LE/G | 0.12 | 0.14 | 0.11 | 0.78 | 0.97 | 0.09 | 0.03 | 0.09 | 0.80 | 0.837 | 0.22 |
| EC1/Float/Float (-)<br>EC1T/A/G/A/G | 0.15 | 0.63 | 0.53 | 0.55 | 0.96 | 0.18 | 0.17 | 0.15 | 0.32 | 0.837 | 0.60 |
| EC1/Float/Float (+)<br>EC1C/A/G/A/G | 0.14 | 0.14 | 0.13 | 0.78 | 0.96 | 0.09 | 0.17 | 0.08 | 0.79 | 0.837 | 0.20 |
| EC1/LowE/LowE (-)<br>EC1T/A/LE/G/A/LE/G | 0.07 | 0.58 | 0.33 | 0.64 | 0.98 | 0.13 | 0.09 | 0.25 | 0.41 | 0.837 | 0.45 |
| EC1/LowE/LowE (+)<br>EC1C/A/LE/G/A/LE/G | 0.07 | 0.12 | 0.08 | 0.83 | 0.98 | 0.09 | 0.09 | 0.09 | 0.83 | 0.837 | 0.17 |
| EC2/LowE/LowE (-)<br>EC2T/A/LE/G/A/LE/G | 0.03 | 0.46 | 0.26 | 0.74 | 0.99 | 0.11 | 0.09 | 0.22 | 0.52 | 0.837 | 0.38 |
| EC2/LowE/LowE (+)<br>EC2C/A/LE/G/A/LE/G | 0.03 | 0.07 | 0.04 | 0.89 | 0.99 | 0.09 | 0.09 | 0.08 | 0.87 | 0.837 | 0.13 |

Furthermore, based on values in Table 2, solar radiation glazing factor modulations are calculated for the two different electrochromic windows (ECWs) and selected two-layer and three-layer window pane configurations with ECWs and given in Table 3. 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 2.

Incorporating the ECWs into two-layer and three-layer window pane configurations reduces the total solar energy throughput modulation in the windows, e.g. as seen in the $\Delta T_{sol}$ and $\Delta$SF values, 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 $\Delta$SSPF modulation is more or less insignificant for the ECW glass configurations given in Table 3, 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.4).

Table 3. Calculated solar radiation glazing factor modulations for two different electrochromic windows (ECWs) and selected two-layer and three-layer window pane configurations with ECWs. 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 2.

| Glass Configuration | $\Delta T_{uv}$ | $\Delta T_{vis}$ | $\Delta T_{sol}$ | $\Delta$SMPF | $\Delta$SSPF | $\Delta R_{vis,ext}$ | $\Delta R_{vis,int}$ | $\Delta R_{sol}$ | $\Delta A_{sol}$ | $\varepsilon$ | $\Delta$SF |
|---|---|---|---|---|---|---|---|---|---|---|---|
| ECW1 (-1800 mV) | 0.00 | 0.61 | 0.57 | -0.28 | 0.00 | 0.00 | 0.00 | 0.00 | -0.57 | - | 0.42 |
| ECW1 (+1400 mV) | | | | | | | | | | | |
| ECW2 (-1800 mV) | -0.02 | 0.52 | 0.51 | -0.21 | 0.00 | 0.00 | 0.00 | 0.00 | -0.51 | - | 0.38 |
| ECW2 (+1200 mV) | | | | | | | | | | | |
| EC1/Float (-)<br>EC1T/A/G | 0.00 | 0.55 | 0.47 | -0.25 | 0.00 | 0.05 | 0.00 | 0.04 | -0.51 | - | 0.40 |
| EC1/Float (+)<br>EC1C/A/G | | | | | | | | | | | |
| EC1/LowE (-)<br>EC1T/A/LE/G | 0.00 | 0.53 | 0.34 | -0.23 | 0.00 | 0.02 | 0.00 | 0.14 | -0.48 | - | 0.32 |
| EC1/LowE (+)<br>EC1C/A/LE/G | | | | | | | | | | | |
| EC1/Float/Float (-)<br>EC1T/A/G/A/G | 0.01 | 0.49 | 0.40 | -0.23 | 0.00 | 0.09 | 0.00 | 0.07 | -0.47 | - | 0.40 |
| EC1/Float/Float (+)<br>EC1C/A/G/A/G | | | | | | | | | | | |
| EC1/LowE/LowE (-)<br>EC1T/A/LE/G/A/LE/G | 0.00 | 0.46 | 0.25 | -0.19 | 0.00 | 0.04 | 0.00 | 0.16 | -0.42 | - | 0.28 |
| EC1/LowE/LowE (+)<br>EC1C/A/LE/G/A/LE/G | | | | | | | | | | | |
| EC2/LowE/LowE (-)<br>EC2T/A/LE/G/A/LE/G | 0.00 | 0.39 | 0.22 | -0.15 | 0.00 | 0.02 | 0.00 | 0.14 | -0.35 | - | 0.25 |
| EC2/LowE/LowE (+)<br>EC2C/A/LE/G/A/LE/G | | | | | | | | | | | |

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.

## 8. CONCLUSIONS

Several 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 various glass materials, including 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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