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Heat Transport and Thermal Expansion of Electrochromic Glazing Systems Due to Solar Irradiation[1]

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For many technical and architectural applications of electrochromic glazings a thorough understanding of the heat transport and the optical and thermal radiative properties of the system is essential. Furthermore, the thermal expansion and eventually the induced stresses within the laminated system are of interest. To meet these demands the solar absorptance of the electrochromic glazings at different tinted states were measured using an UV–VIS-NIR spectrometer. The thermal expansion coefficients of the glass materials were determined by a push-rod dilatometer. Then the instationary coupled conductive and radiative heat transfer due to solar irradiation were calculated for various pane configurations by finite element analysis. Starting from the resulting instationary temperature fields, the stress and strain states within the laminated glazing system were calculated.

KEY WORDS: electrochromic glazing; heat transport; solar reflectance; solar transmittance; spectroscopy; temperature stress.

1. INTRODUCTION

In recent years research in the field of electrochromic films led to the development of a new type of a glazing system with voltage controlled transmittance [1]. The system consists of two glass panes coated firstly

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with an electroconductive layer and secondly with an electrochromic film. The glass panes are laminated together with an ion conducting polymer foil. It is possible to reversibly switch the visible light transmittance from 0.08 with the glaze in the colored state to 0.75 in the bleached state with very low electric energies. A multitude of different colors such as blue, green, red, brown, violet, and grey can be provided depending on the composition of the electrochromic film. The switching time between the fully colored and bleached states is in the range of 30 s to 10 min.

There is tremendous potential for such electrochromic glazings. For example, switchable filters for light and heat within optical instruments, rapid responding sunglasses, and large area information displays are feasible. In the car industry the adoption of electrochromic systems in sunroofs with overheating protection and for windshields and rear view mirrors with glare protection is advantageous. Electrochromic glazing can be used in smart windows without any mechanical sun protection systems which can change gradually the transmittance in response to the intensity of the solar radiation according to Fig. 1. Such windows prevent overheating of rooms during intense sunshine and therefore minimize energy for climatization. Protection against glare and electromagnetic radiation are additional advantages.

Transmittance and absorptance data are needed for the calculation of the instationary temperature fields within the electrochromic glazings during solar irradiation. High temperatures within the glass material are expected especially in the colored state of the electrochromic glazing. To ensure a damage-free function of the glazings, maximal temperature-stresses due to solar irradiation in some critical cases have to be calculated.

2. ELECTROCHROMIC GLAZING SYSTEM: DESIGN AND FUNCTION

A schematic of the electrochromic glazing system is shown in Fig. 2. Two glass panes with a transparent electroconductive film (e.g., fluorine-doped tin oxide) were secondly coated with complementary electrochromic layers using an electrochemical deposition technology. These layers consist of $\mathrm{Fe^{III}Fe^{II}(CN)_6}$ (Prussian Blue) and $\mathrm{WO_3}$ (tungsten oxide), respectively. Both films can be switched between a blue colored and an uncolored state. Finally, the glass panes were laminated together with an ion conductive polymer foil. If a dc voltage in the range of 1.2 to 2.4 V is applied, oxidation and reduction reactions in the electrochromic layers are induced that are accompanied by insertion or extraction of ions. Due to this process these layers change their transmittance—especially for radiation within the

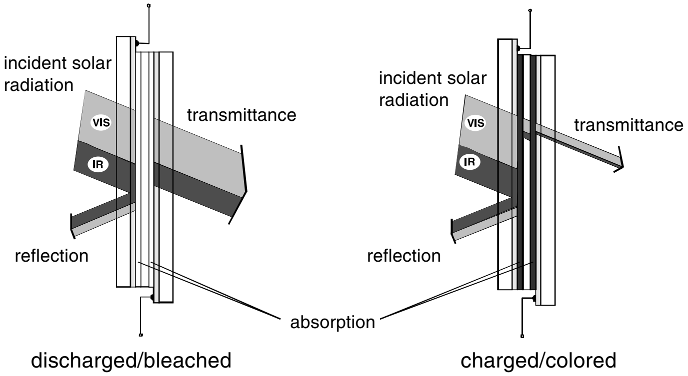

Fig. 1. Schematic of the controlled transmittance of solar radiation by means of the electrochromic glazing.

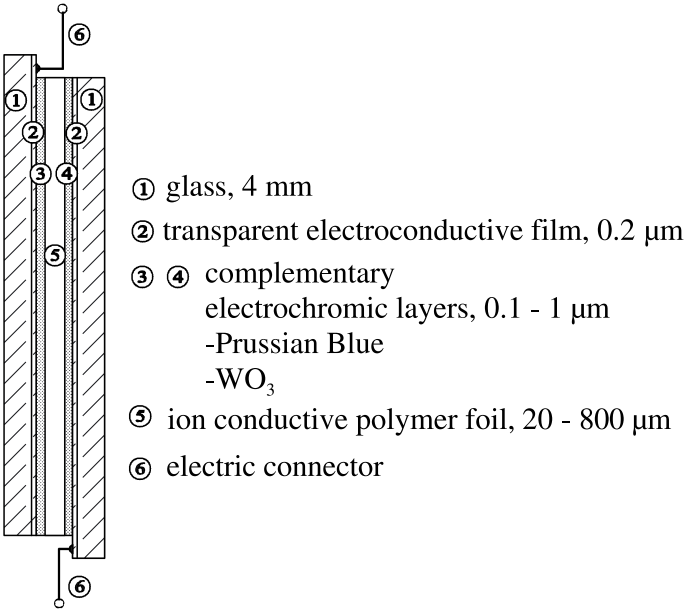

Fig. 2. Composition of the electrochromic glazing.

spectrum between visible light and near-infrared. The Prussian Blue layer becomes colored with oxidation and ion extraction whereas the tungsten oxide layer becomes colored with reduction and ion reception according to the following formulas:

$$\underset{\text{colorless}}{Li_2[Fe^{II}Fe^{II}(CN)_6]} \leftrightarrow \underset{\text{blue}}{Li[Fe^{III}Fe^{II}(CN)_6]} + Li^+ + e^-, \tag{1}$$

$$\underset{\text{colourless}}{WO_3 + xe^- + xLi^+} \leftrightarrow \underset{\text{blue}}{Li_xWO_3}, \quad x < 0.3. \tag{2}$$

The overall cell reaction of the electrochromic system is:

$$\underset{\text{colorless}}{xLi_2[Fe^{II}Fe^{II}(CN)_6] + WO_3} \leftrightarrow \underset{\text{blue}}{Li_xWO_3 + xLi[Fe^{III}Fe^{II}(CN)_6]}, \quad x < 0.3. \tag{3}$$

The system is charged similar to a capacitor in the blue colored state. If the polarity of the applied voltage is reversed, the system discharges and the electrochromic films become transparent. The energy per area necessary for full coloration is only about $200\,J{\cdot}m^{-2}$.

3. SOLAR TRANSMITTANCE

The reflectance and transmittance in the wavelength range of the solar radiation (280 to 2500 nm) at 20 °C were measured using a UV–VIS-NIR spectrometer (Perkin-Elmer Lambda 19). These measurements were performed at the fully bleached and the fully colored state. Results are shown in Figs. 3 and 4. The solar transmittance T_{solar} and reflectance R_{solar}, as well as the visible transmittance T_{vis} and reflectance R_{vis}, were derived from the spectrometer data according to the European standard EN 410 [2].

The time-dependent reflectance and transmittance curves of the glazing in the wavelength range from 380 to 780 nm during a coloring and bleaching cycle were measured by means of a diode-array spectrometer (IKS Optoelektronik GmbH X-dap). Results are shown in the range of 0 to 160 s in time steps of 20 s and 600 s in Figs. 5 and 6, respectively.

4. TEMPERATURE FIELDS DUE TO SOLAR IRRADIATION

To estimate critical stress states of the glazing under solar irradiation, the instationary temperature fields for partly shaded test samples with an area of (0.25 × 0.25) m^2 were calculated with help of the finite element analysis software Abaqus Standard [3]. The governing heat conduction equation for the numerical modeling is

$$\rho c \frac{\partial T}{\partial t} = \lambda \left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} \right) + r, \tag{4}$$

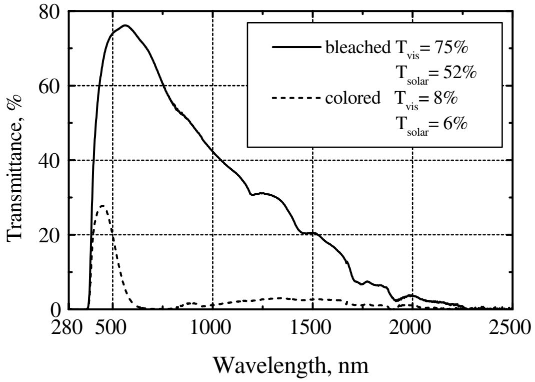

Fig. 3. Transmittance of the electrochromic glazing at the fully bleached and fully colored states. The solar transmittance T_{solar} and the visible transmittance T_{vis} were calculated from the measured spectral data according to the European Standard EN 410 [2].

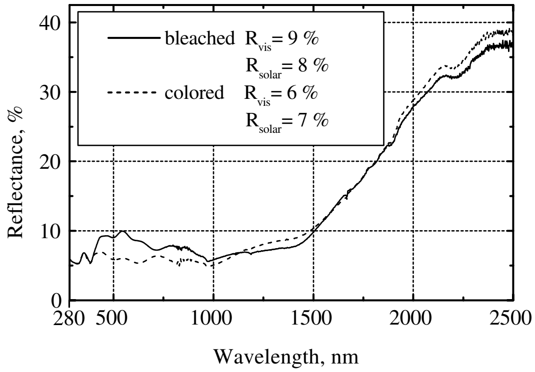

Fig. 4. Reflectance of the electrochromic glazing at the fully bleached and fully colored state. The solar reflectance R_{solar} and the visible reflectance R_{vis} were calculated from the measured spectral data according to the European Standard EN 410 [2].

where T is the temperature, ρ is the mass densitiy, c is the specific heat, λ is the thermal conductivity, t, x, y, z are the time and space coordinates, and r is the heat supplied externally into the body per unit volume and time. One surface of the glazing was subjected to direct solar radiation ramping from 0 to $800\,\text{W}{\cdot}\text{m}^{-2}$ within 600 s. After irradiation for 600 s, the power was decreased to 0 over 600 s. This solar load approximates real

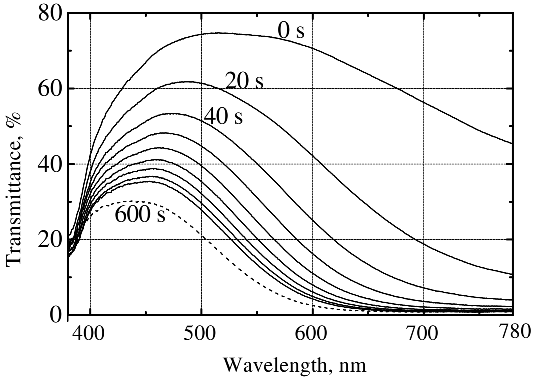

Fig. 5. Time-dependent transmittance of the electrochromic glazing during a complete coloration cycle. The transmittance was measured in time steps of 20 s.

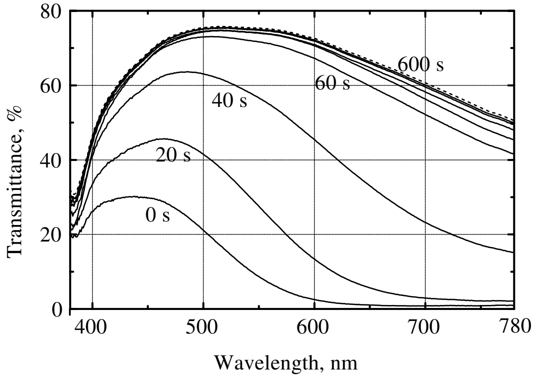

Fig. 6. Time-dependent transmittance of the electrochromic glazing during a complete bleaching cycle. The transmittance was measured in time steps of 20 s.

conditions. Obviously, the highest thermal stresses will be developed when the system is in its fully colored state. In this case the solar reflectance is taken as R_{solar}= 0.07 and the solar transmittance $T_{solar} = 0.06$. Consequently, a maximum heat flux density of 696 W·m^{-2} is absorbed. Neglecting absorption within the first glass pane, which is less than 5%, this leads to a heat source r of $3.48 \times 10^6\,\mathrm{W \cdot m^{-3}}$ within the layers between the glass panes with a thickness of 200 μm. The heat contributed by the dc current to the system is less than 5×10^3 W·m^{-3}. This is about 3 orders of magnitude less than the solar heat and therefore also negligible. The surfaces of the glazing are considered to radiate to ambient temperatures of 10 and 20 °C, respectively, with a hemispherical emissivity of 0.84 [4]. The heat exchange to the ambient air is governed by Newton's law of cooling with heat transfer coefficients of $\alpha = 23.0\,\mathrm{W \cdot m^{-2} \cdot K^{-1}}$ for one and $\alpha = 8.0\,\mathrm{W \cdot m^{-2} \cdot K^{-1}}$ for the other surface and the edge of the glazing system. The initial temperature of the whole glazing system is 20 °C. The material data used for the instationary temperature field calculations are shown in Table I.

A variety of cases were examined. The cases corresponding to the shadings depicted in Fig. 7 will be discussed. In each case the resulting three-dimensional temperature field is shown 20 min after the onset of irradiation. The maximum temperature difference of approximately 15 K between the warm and cold regions of the glazing is attained after 20 min. At any time during irradiation, the temperature gradient normal to the surface is less than 3 K over the 4.2 mm pane thickness. Obviously, an electrochromic glazing at controlled states with solar transmittances higher than 0.06 is expected to exhibit lower temperature differences.

5. MECHANICAL STRESSES DUE TO SOLAR IRRADIATION

At any time of the transient irradiation period, the three-dimensional temperature-induced displacement and stress states were calculated. An elastic material model with the material constants listed in Table I is considered. The linear thermal expansion coefficient of the glass was measured by means of a push-rod dilatometer (Netzsch DIL 402). The maximum principal stresses according to the temperature fields are illustrated in Fig. 7.

Table I. Material Data for the Instationary Temperature Field and Thermal Stress Calculations

Quantity	Unit	Glass	Polymer foil
Mass density ρ	$\mathrm{kg \cdot m^{-3}}$	2350^{b}	900^{b}
Thermal conductivity λ	$\mathrm{W \cdot m^{-1} \cdot K^{-1}}$	0.81^{b}	0.25^{b}
Specific heat capacity c_p	$\mathrm{kJ \cdot kg^{-1} \cdot K^{-1}}$	0.72^{a}	1^{c}
Young's modulus E	$\mathrm{N \cdot m^{-2}}$	$7.0 \times 10^{10\,b}$	$1.5 \times 10^{6\,b}$
Poisson's ratio ν	–	0.23^{c}	0.49^{c}
Coefficient of linear thermal expansion α	$\mathrm{K^{-1}}$	$8.2 \times 10^{-6\,a}$	$120 \times 10^{-6\,b}$

[a] Measurements from this study.
[b] Ref. 5.
[c] Estimation.

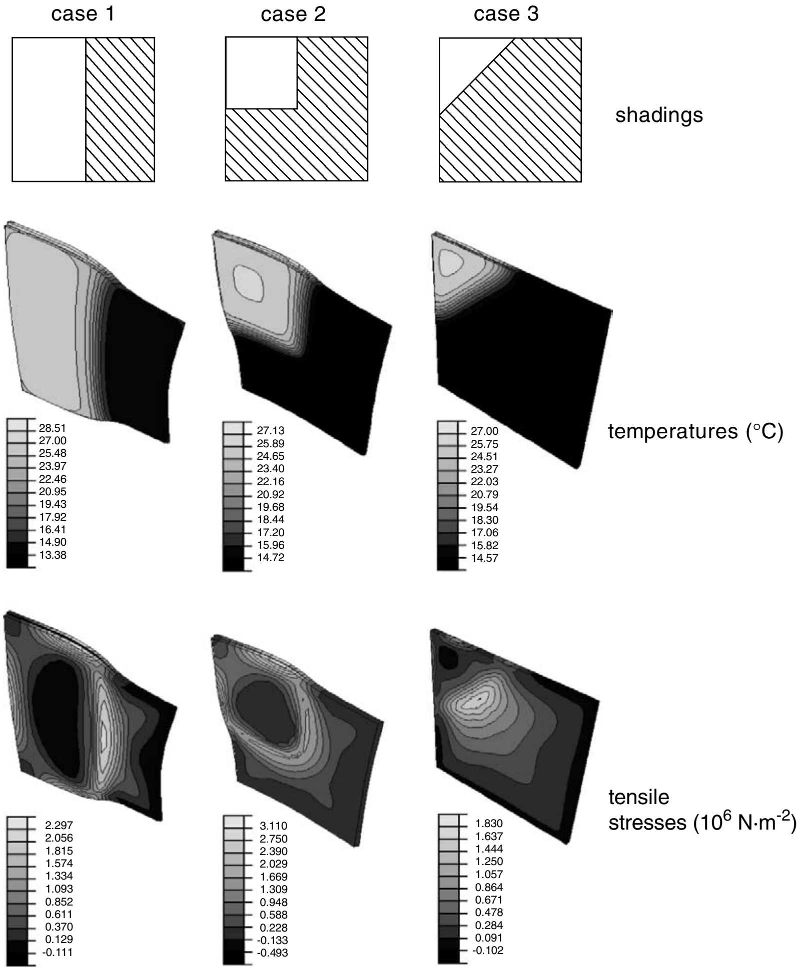

Fig. 7. Partly shadowed electrochromic glazings with corresponding temperature fields and tensile stresses due to solar irradiation of $800\,\mathrm{W \cdot m^{-2}}$.

The maximum tensile stresses occur both at the edges of the glass pane and near the shadow borderline. The stress direction lies in the glass plane. For the estimation of crack development potential, only tensile stresses are important. A value of $3.11 \times 10^6\ \mathrm{N \cdot m^{-2}}$ appears in case 2 with a quarter of the glass area irradiated. In cases with a straight shadow borderline, the maximum tensile stresses are smaller. In either case the tensile stresses are less than the glass tensile strength of $30 \times 10^6\,\mathrm{N \cdot m^{-2}}$. For a better visualization the deformation is displayed with a scale factor of 2000 (cases 1 and 2) and 150 (case 3).

6. CONCLUSIONS

Transmittance and reflectance data in the wavelength range from 280 to 2500 nm of an electrochromic glazing with voltage controlled transmittance are presented. The fully colored and bleached states were measured. We found a maximum change of 46% for the solar transmittance as well as 69% for the visible transmittance. The time dependent transmittance and reflectance at 380 to 780 nm during a coloring and bleaching cycle were measured.

Based upon the data, the instationary temperature fields due to transient solar irradiation were calculated. Several cases with partly shadowed glass pane areas were considered. The temperature induced stresses were computed. In no case did the maximum tensile stresses exceed the tensile strength of the glass material. The maximum tensile stresses are an order of magnitude less than the tensile strength. Consequently, the electrochromic glazing system is expected to operate damage-free under the considered irradiation conditions.

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