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Optimized spectral transmittance of sun protection glasses

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Abstract

A spectral optical transmission function $\tau(\lambda)$ for sun protection insulating glasses is proposed in order to reduce the solar energy load of a building's interior and thus reducing overheating. $\tau(\lambda)$ is based on standard functions such as spectral distribution of solar radiation $S_\lambda(\lambda)$, spectral photopic luminous efficiency $V(\lambda)$, standard illuminant $D_{65}(\lambda)$, and the CIE color-matching functions $\bar{x}_\lambda, \bar{y}_\lambda, \bar{z}_\lambda$. In the framework of the present approach an optimized spectral transmittance $\tau_{\min}(\lambda)$ with a minimal normalized solar energy load (i.e., solar direct transmittance normalized to light transmittance, τ_e/τ_v) has been obtained on the condition of color neutrality of the transmitted light. A comparison with the performance of actual commercial sun protection glasses on the market shows that the present model for an optimized spectral transmittance could reduce the solar energy load by roughly one third for equal light transmittance τ_v.

1. Introduction

Overheating of buildings due to extreme heat loads by solar radiation has become a well-known problem that is caused essentially by architectural preferences for highly glazed façades on one hand and climatic changes on the other hand. A list of measures can be given in order to solve the problem of overheating such as appropriate architectural design, variable shading and blinds or switchable window glazings with variable transmission. The latter approach is technically not yet satisfyingly solved and no product for broad application is available on the market.

With respect to conventional sun protection glasses (SPGs) the question rises whether the optimum performance is already reached in products currently used. In order to answer this question we need the following information: (1) what is the detailed performance of presently used SPGs and (2) what is the theoretical limit for the performance of a SPG? In contrast to point (1) point (2) has not yet been addressed in literature to the best of our knowledge. Though there exist numerous studies on optical data of SPGs all experimental data presented in this work have been measured on the same equipment (Steiner et al., 2005; University of Basel) in order to obtain information on point (1) and to enable a reliable comparison of the data. These data have been obtained by characterizing a broad selection of commercial insulating glass units in terms of optical (Steiner et al., 2005; University of Basel) and thermal (Reber et al., 2005) properties. The as received data include finally the solar direct transmittance $\tau_e(\varphi)$ (determined as a function of the angle of light incidence φ) the light transmittance $\tau_v(\varphi)$ and the total solar energy transmittance factor (solar gain) $g(\varphi)$ as a function of the angle of the incident light φ (for the calculation of one-figure parameters, see e.g. Ref. (European Standard, 1998)). From these parameters the ratio $\tau_e(\varphi)/\tau_v(\varphi)$ (denoted as NEL, normalized energy load, in the present paper) and $g(\varphi)/\tau_v(\varphi)$ are obtained which describe the energy load by solar radiation normalized to the luminous parameter $\tau_v(\varphi)$ (Steiner et al., 2005; University of Basel; Reber et al., 2005).

In order to get information on point (2) we propose in the present paper, a theoretical spectral transmittance $\tau_{\min}(\lambda)$ for sun protection insulating glasses that is minimizing the NEL (at $\varphi = 0$) on the basis of standard spectral

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distribution functions such as solar radiation $S_\lambda(\lambda)$, spectral photopic luminous efficiency $V(\lambda)$, standard illuminant $D_{65}(\lambda)$, and the CIE color-matching functions $\bar{x}_\lambda, \bar{y}_\lambda, \bar{z}_\lambda$ (European Standard, 1998). Thereby, the condition of color-neutrality for the transmitted light has to be fulfilled, i.e., daylight (represented by standard illuminant $D_{65}(\lambda)$) transmitted through the SPG is transformed to an attenuated white light, characterized by $a^* = 0$ and $b^* = 0$ in the CIE Lab color space (see e.g. Berns Roy, 2000). For calculations of color properties, see e.g. references (European Standard, 1998; Berns Roy, 2000; Munsell Color Science Laboratory).

2. Theoretical model for $\tau_{\min}(\lambda)$

2.1. Neglecting color neutrality

In a first step we restrict the spectral transmittance $\tau(\lambda)$ of the SPG as much as possible to the wavelength range for which the spectral photopic luminous efficiency $V(\lambda) > 0$ (see Fig. 1). If we neglect the requirement of color neutrality (as defined above) we may set the spectral transmittance $\tau(\varphi)$ of the SPG

$$\tau(\lambda) = c \cdot V(\lambda) \tag{1}$$

where c is an appropriate constant in order to scale the maximum of $\tau(\lambda)$ to a value <1.

This spectral transmittance function $\tau(\lambda)$ would yield in fact a very low NEL parameter however at the expense of missing color neutrality:

spectral transmittance: $\tau(\lambda) = c \cdot V(\lambda)$

NEL: $\boldsymbol{\tau_e/\tau_v = 0.231}$

color of transmitted D_{65}-light: $a^* = -44$(*green*), $b^* = 93$ (*yellow*).

If $\tau(\lambda)$ is normalized to *1* at $\lambda = 555$ nm, we obtain a value of $\tau_v = 0.723$.

2.2. Taking color neutrality into account

Color neutrality can be obtained by taking into account in addition the CIE 2° color matching curves $\bar{x}_\lambda, \bar{y}_\lambda, \bar{z}_\lambda$ shown in Fig. 2 and we start with the following ansatz (that has to be justified by the final result below):

$$\tau(\lambda) = V^\delta[\alpha \cdot \bar{x} + \beta \cdot \bar{y} + \gamma \cdot \bar{z}] \tag{2}$$

The weighting coefficients α, β and γ have to be determined in such a way that color neutrality is obtained for the transmitted D_{65}-*light*. It is evident that the coefficients α, β and γ cannot be <0. These values are determined by solving a linear system of three equations that are obtained by calculating the color coordinates X, Y and Z (European Standard, 1998)

$$\begin{aligned} \vec{\tau} \cdot [\vec{\bar{x}} . \cdot \vec{D}_{65}] &= X \\ \vec{\tau} \cdot [\vec{\bar{y}} . \cdot \vec{D}_{65}] &= Y \\ \vec{\tau} \cdot [\vec{\bar{z}} . \cdot \vec{D}_{65}] &= Z \end{aligned} \tag{3}$$

The vector notation represents the wavelength dependent functions as vectors with n components, n corresponding to the number of discrete wavelengths. The expression $[\vec{a} . \cdot \vec{b}]$ represents a vector obtained by multiplying corresponding components of $\vec{a}$ and $\vec{b}$. $\tau(\lambda)$ is therefore represented by

$$\vec{\tau} = [\alpha \cdot \vec{\tau}_x + \beta \cdot \vec{\tau}_y + \gamma \cdot \vec{\tau}_z]$$

with

$$\vec{\tau}_x = \vec{\bar{x}} . \cdot \vec{V}^\delta, \vec{\tau}_y = \vec{\bar{y}} . \cdot \vec{V}^\delta \text{ and } \vec{\tau}_z = \vec{\bar{z}} . \cdot \vec{V}^\delta$$

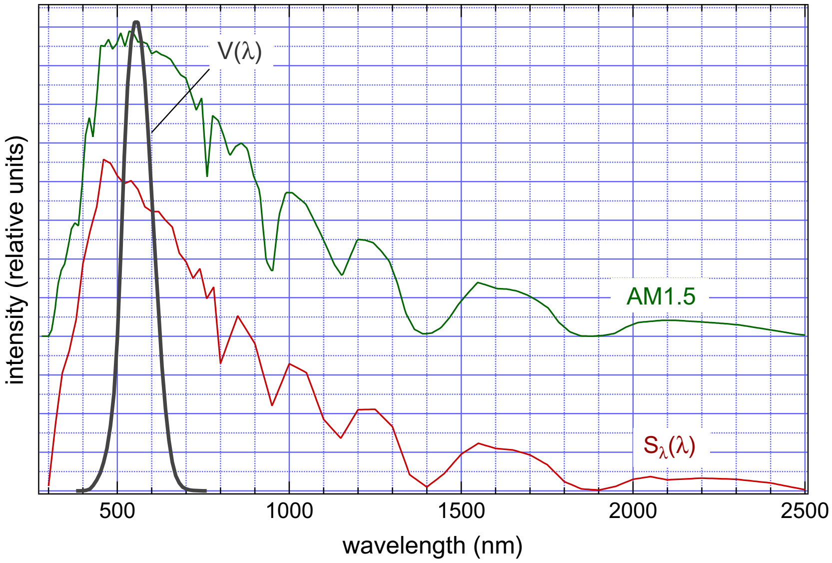

Fig. 1. Spectral distribution of solar radiation $S_\lambda(\lambda)$, solar radiation AM1.5 spectrum (vertically shifted) and photopic spectral luminous efficiency $V(\lambda)$ (European Standard, 1998).

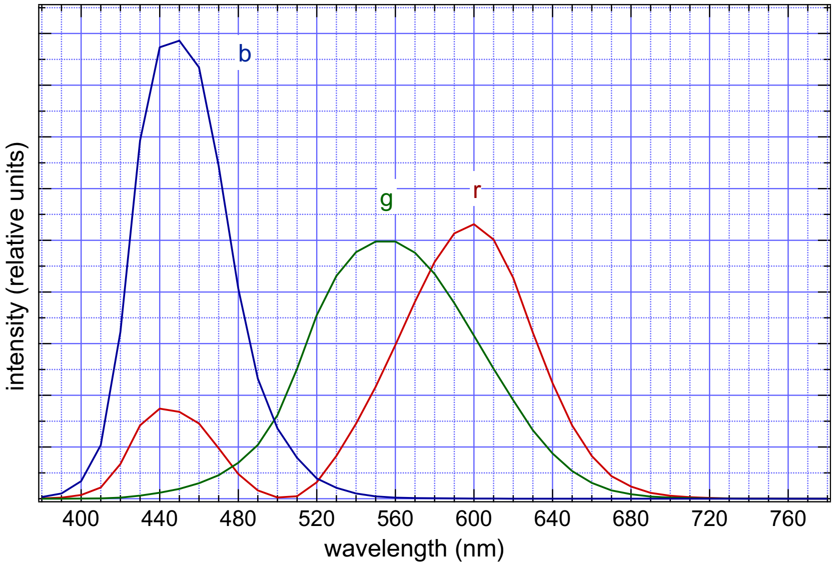

Fig. 2. Color matching curves $\bar{x}_\lambda$ (r), $\bar{y}_\lambda$ (g), $\bar{z}_\lambda$ (b) of the CIE Lab 2° color space corresponding to red, green and blue tristimulus functions (data in 10 nm steps according to (European Standard, 1998)). (For interpretation of the references to colour this figure legend, the reader is referred to the web version of this article.)

If we insert for X, Y and Z the coordinates for white light, 95.047, 100 and 108.883, respectively (e.g. Berns Roy, 2000) in formula (3) we can determine α, β and γ by solving the equation system for a given δ. For $\delta = 1$, only a mathematical solution exist for α, β and γ with $\beta < 0$. Physical solutions exist for

$$0 \leqslant \delta < 0.85$$

Since function $V(\lambda)$ takes values between $0 \leqslant \mathrm{V}(\lambda) \leqslant 1$, the width of curve $V(\lambda)$ is increased with decreasing δ and as a consequence the width of the transmitted wavelength range is increased. Fig. 3 shows the $\mathrm{NEL} = \tau_e/\tau_v$ parameter as a function of δ that reveals a flat minimum close to 0.33. Therefore, we choose $\delta = 1/3$ in Eq. (3). Along with the parameters α, β and γ we obtain for $\tau_{\min}(\lambda)$

$$\tau(\lambda) = \tau_{\min}(\lambda) = V^{1/3}[\alpha \cdot \bar{x} + \beta \cdot \bar{y} + \gamma \cdot \bar{z}] \tag{4}$$

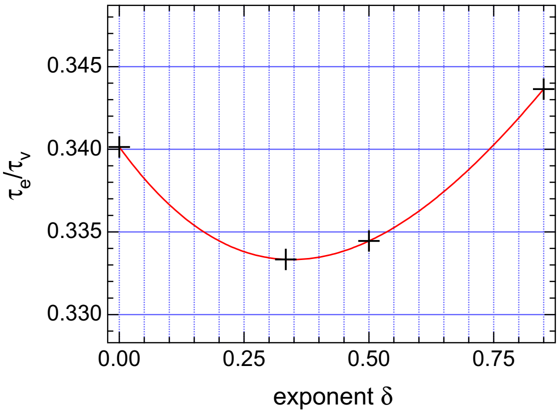

Fig. 3. τ_e/τ_v as a function of the exponent δ. Crosses represent calculated values for τ_e/τ_v under the condition of color neutrality (see text). The full line shows a polynomial fit curve.

with $(\alpha, \beta, \gamma) = (0.4544, 0.4501, 1.000)$. For $\tau_{\min}(\lambda)$ as obtained in (4) we obtain the following parameters:

NEL : $\boldsymbol{\tau_e/\tau_v = 0.3341 \approx 1/3}$

> *color neutrality of transmitted* D_{65}*-light*: $a^* = 0$, $b^* = 0$. If $\tau_{\min}(\lambda)$ is normalized arbitrarily to *0.95* at $\lambda = 575$ nm we obtain a value of $\tau_v = 0.693$.

Fig. 4 shows $\tau_{\min}(\lambda)$ along with the color matching curves $\bar{x}_\lambda, \bar{y}_\lambda, \bar{z}_\lambda$. The $\tau_{\min}(\lambda)$-function reveals a camelback shape. Due to partly suppressing light intensity near 420 nm (blue) and 640 nm (red), light intensity in the central part of the transmitted band (green-blue) has to be suppressed as well in order to achieve color neutrality. For the design of $\tau_{\min}(\lambda)$

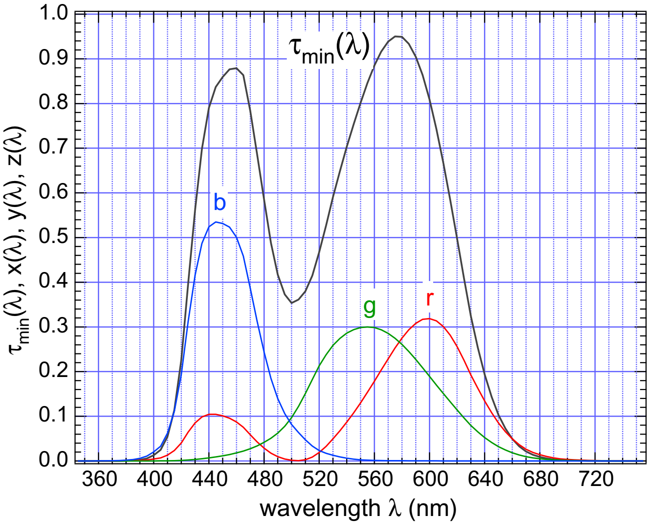

Fig. 4. $\tau_{\min}(\lambda)$ and color matching curves $\bar{x}_\lambda(r), \bar{y}_\lambda$ (g), $\bar{z}_\lambda$ (b). Data are shown here in 5 nm steps (Munsell Color Science Laboratory).

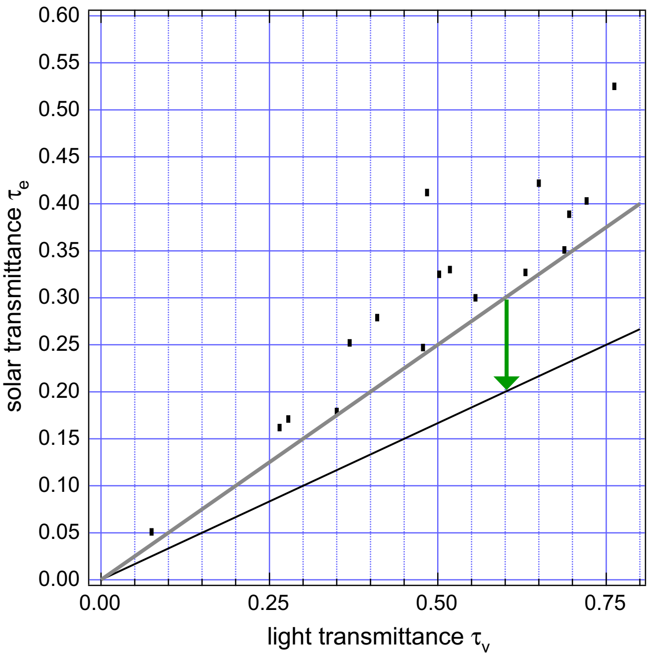

Fig. 5. τ_e vs. τ_v graph showing a selection of commercial sun protection glasses revealing color neutrality (black squares). All data points lie above the line $\tau_e = \tau_v/2$ (gray line). The absolute error of both the τ_e and τ_v values amounts $\leqslant 0.02$. The thin black line represents the theoretical limit of the solar energy load $\tau_e = \tau_v/3$ of $\tau_{min}(\lambda)$-glasses and the arrow indicates the improvement potential of commercial SPGs.

as described above $S_\lambda(\lambda)$, $V(\lambda)$, $D_{65}(\lambda)$, and the CIE 2° color-matching functions $\bar{x}_\lambda, \bar{y}_\lambda, \bar{z}_\lambda$ have been taken from *Munsell Color Science Laboratory, Rochester Institute of Technology*(Munsell Color Science Laboratory).

3. Discussion

We do not claim that the model for $\tau_{min}(\lambda)$ described above is strictly yielding the theoretical minimum for τ_e/τ_v. A slightly lower value might be obtained by a more sophisticated theory. However, we have to keep in mind that the model described above is not based on exact preconditions but on empirical functions such as the spectral luminous efficiency $V(\lambda)$ and the CIE color-matching curves $\bar{x}_\lambda, \bar{y}_\lambda, \bar{z}_\lambda$. The former function has been established in 1924, the latter ones in 1931 (see e.g. Berns Roy, 2000). These functions cannot be *measured quantitatively* but are rather based on standard observers and are therefore an unavoidable source of tentativeness.

The question rises how the solar energy load of a SPG with a $\tau_{min}(\lambda)$ transmission function compares with current commercial SPGs. As mentioned above a series of sun protection glasses have been characterized optically and thermally (with respect to the solar gain factor) in the author's laboratory (Steiner et al., 2005; University of Basel; Reber et al., 2005). In Fig. 5 a selection of commer-

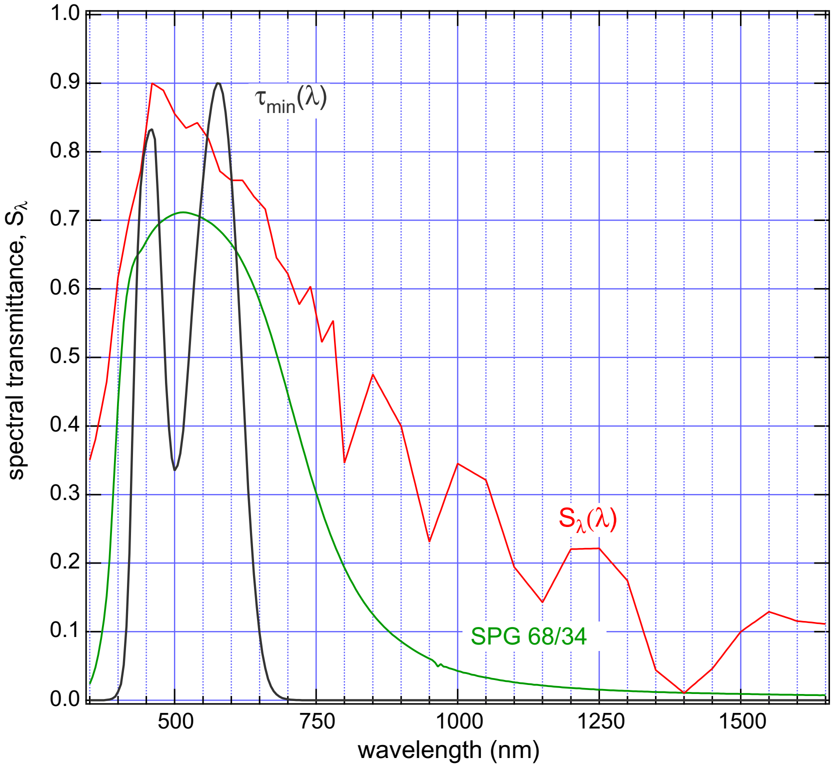

Fig. 6. Comparison of $\tau_{min}(\lambda)$ with a SPG transmission function (data from reference (Steiner et al., 2005; University of Basel), Pilkington Insulight^{TM} Sun Neutral 68/34 (Pilkington, 2003)) and solar spectrum $S_\lambda(\lambda)$ (European Standard, 1998).

cial SPGs with acceptable color neutrality is displayed by black squares in the $\tau_e - \tau_v$ plane (data taken from (Steiner et al., 2005; University of Basel)). All data points are located above the line $\tau_e = \tau_v/2$ (gray line). SPGs with a $\tau_{\min}(\lambda)$ transmission function would lie on the line $\tau_e = \tau_v/3$ (thin black line). The arrow in Fig. 5 represents the improvement potential of current commercial SPGs by one third of the solar energy load.

It has to be pointed out that there exist some commercial glasses with NEL values slightly below 0.5 (Glassdbase; University of Basel); however, these glasses do not exhibit color neutrality, especially at oblique angles of incidence. If we would relax the condition of color neutrality in our model for $\tau_{\min}(\lambda)$, an even lower NEL (below 1/3) could be obtained and therefore the improvement potential would be about 1/3 also in these cases.

As an example we show in Fig. 6 a comparison of a typical SPG (*Pilkington Insulight^{TM} Sun Neutral 68/34* (Pilkington, 2003)) with $\tau_{\min}(\lambda)$ along with the solar spectrum. The SPG has a $\tau_e/\tau_v = 0.510$ as compared to 0.334 of $\tau_{\min}$. From Fig. 5 we can see that the $\tau_{\min}(\lambda)$-glass significantly reduces the transmittance in the near infrared wave length range (between 650 and 1200 nm) with respect to the SPG 68/34 resulting in a distinctly lower τ_e/τ_v value.

4. Conclusion

The above proposed spectral transmittance function for sun protection glasses reveals a potential for solar energy load reductions by roughly one third as compared with (the best) current commercial SPGs. The benefits of such new sun protection glasses are evident: they would reduce the interior temperature rise in a (highly glazed) building significantly and could reduce energy costs for air conditioning.

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References

Berns Roy, S., 2000. Principles of Color Technology, third ed. John Wiley & Sons, Inc.

European Standard EN 410, Glass in Building – Determination of Luminous and Solar Characteristics of Glazing, December 1998 (German edition).

Glassdbase – The Independent and Comprehensive Database for Building Glass, University of Basel, Basel, Switzerland. <http://www.glassdbase.unibas.ch/>.

Munsell Color Science Laboratory, Rochester Institute of Technology<http://www.cis.rit.edu/mcsl/online/>.

Pilkington Insulight^{TM} Sun Neutral 68/34 delivered by Pilkington (Switzerland) AG, Zentrumstrasse 2, 4806 Wikon, Switzerland, September 2003.

Reber, G., Steiner, R., Oelhafen, P., Romanyuk, A. In: Proceedings of CISBAT 2005 Conference, LESO–EPFL, September 28–29, 2005, pp. 173–178.

Steiner, R., Oelhafen, P., Reber, G., Romanyuk, A. In: Proceedings of CISBAT 2005 Conference, LESO–EPFL, September 28–29, 2005, pp. 441–446.