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Interior colour rendering of daylight transmitted through a suspended particle device switchable glazing

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Abstract

The colour rendering index (CRI) and correlated colour temperature (CCT) of daylight change upon transmission through a variable transmittance suspended particle device (SPD) switchable glazing. The luminous transmittance of SPD glazing was found to vary from 0.02 to 0.55 in opaque and transparent state respectively. Below 0.14 transmittance, the CRI for a particular SPD glazing was less than 80. No strong correlation was found between CCT and CRI. The CRI of SPD glazing in a transparent state was similar to double panes glazing for SPD glazing transmittance greater than 0.24.

Keywords: ~~adaptive~~Adaptive; ~~switchable~~Switchable; ~~glazing~~Glazing; SPD; CCT; CRI

1 Introduction

The glazed features of a building provide views to the exterior, allow solar heat gain, incur heat losses, provide daylight, can cause glare and are often a conduit for ventilation air. Glazed features include windows roof lights, conservatories and atria. Such glazed elements particularly in non-domestic buildings are frequently an important realization of a design intent to create internal spaces that are visually connected internally with one another and externally to the immediate surroundings [1]. However, in many climates, a certain times incident solar radiation can overheat highly glazed buildings. This can be mitigated by ventilations, storage of heat in the buildings by the appropriate inclusion of thermal mass and design that exploits the variations of glazing transmission with the angular incidence of solar radiation in the specified orientation and inclination of glazing [2]. Overheating may also be inhibited by range of internal and external shading device, or by the use of adaptive variable transmittance glazings. The latter have the potential to minimize the building energy demand by reducing cooling, heating and lighting loads whilst providing daylighting via the various different combinations of attributes illustrated in Fig. 1.

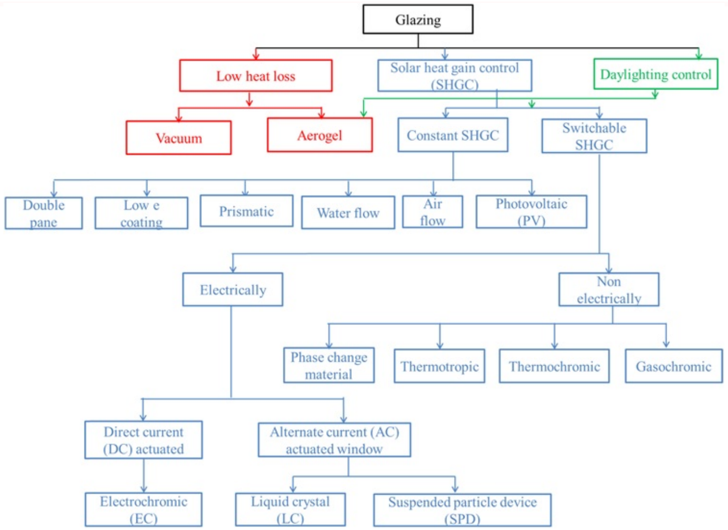

Fig. 1 Indicative taxonomy of selective glazing types.

alt-text: Fig. 1

Solar heat gain control glazings are mainly switchable while low heat loss control glazings have constant transparency [3–10]. Both types have potential to allow daylight. Fig. 1 shows the details of different types of glazing.

Suspended particle device (SPD) glazing is a form of switchable adaptive glazing in which a plastic film sandwiched between two glass panes contains suspended dihydrocinchonidine bisulfite polyiodide or heraphathite SPD particles [11–13]. The particles may be needle-shaped, rod-shaped, or lath-shaped. In the presence of power supply, the particles are orientated perpendicular to the substrate so that light transmit and without power supplies the particles are oriented randomly due to Brownian movement. Illustration of the operation of an SPD glazing is shown in Fig. 2.

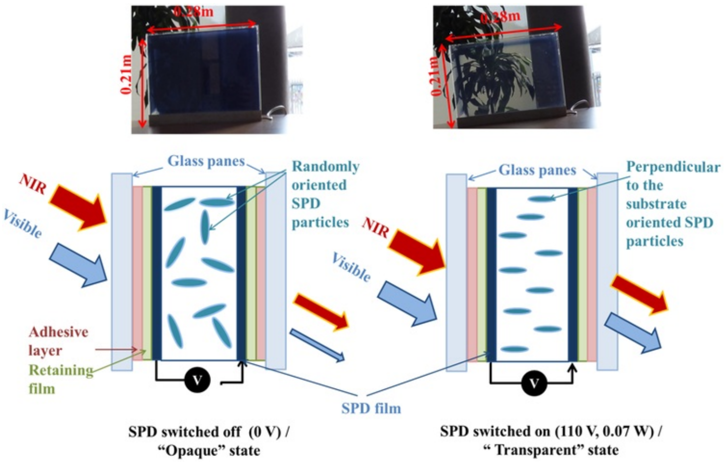

Fig. 2 Viewing through a particular SPD glazing in its opaque and transparent states.

alt-text: Fig. 2

SPD switchable adaptive glazing

- has electrically powered ease of control [14];
- can be connected directly with AC mains power supply without any conversion system (An electrochromic glazing requires an AC to DC inverter to connect with mains) [14];
- can control solar heat gain due to its variable transparency [15];
- facilitates switchable single or double glazing systems [16,17];
- controls glare and facilitating comfortable daylighting [18].

Daylight is the luminance associated with that part of the solar irradiance with a spectral power distribution in the visible range of ~~380~~380–780 nm. The spectral power distribution of natural daylight depends on time of day, season, latitude, weather, and air bound dust and pollutants. Visual comfort in an internal glazed space during the day is influenced by the quality and quantity of transmitted daylight into that space. The spectral transmission properties of a glazing, can be characterized by a correlated colour temperature (CCT) and colour rendering index (CRI).

CRI and CCT are used to characterize the illumination quality of white light [19,20]. A CCT needs to be equivalent to that of a blackbody source at temperatures between 3000 and 7500 K [~~–21~~21,22~~–22~~]. The CCT indicates of whether the light is bluish-white, neutral, or reddish white. The CRI includes spectrally dependent characteristics with CRI values of 95 or higher considered acceptable. A CRI close to 100 indicates an excellent visual quality [23]. Light colour is an influential factor on indoor comfort.

Yellowish and reddish with warm CCT [24,25] have been alleged to produce beneficial psychological effects [26–29] however, the empirical data supporting this is weak [30]. Quantity of light (i.e. illuminance) and the quality of light (i.e. CCT) are used to assess the perceived quality of a lit environment [19]. CRI and CCT have been evaluated for semitransparent PV [31], electrochromic glazing [32] gasochromic glazing and luminescent solar concentrator glazing [33]. For tinted glazings under average daylight (D65) a CRI of 95 and 87 were reported for brown and green glazings, respectively [22].

The spectrum of transmitted daylight changes as an SPD glazing switches from an opaque to transparent state under power supply. Light spectral composition significantly affects the perceived colour and brightness of illuminated objects. CRI and CCT characterization of SPD glazing is required as these parameters assess human response to ~~colors.~~colours.

In this work luminous transmittance, CCT and CRI has been evaluated for the incoming daylight through switchable SPD glazing. CCT and CRI of SPD glazing were compared with those of double paned glazing with air filled and evacuated glazing.

2 Calculation of parameters

2.1 Luminous transmission (τ_v)

Luminous transmittance values τ_v are given by [34].

$$\tau_v = \frac{\sum_{380nm}^{780nm} D_{65}(\lambda) V(\lambda)\, \tau(\lambda)\, \Delta\lambda}{\sum_{380nm}^{780nm} D_{65}(\lambda)\, V(\lambda)\, \Delta\lambda} \quad \textbf{(1)}$$

where τ(λ) is the spectral transmittance of an SPD glazing, D65(λ) is the spectral power distribution of CIE standard illuminant D65, V(λ) is the photopic luminous efficiency function of the human eye and Δλ ~~= 10~~=10 nm. The photopic eye sensitivity to light wavelength is shown in Fig. 3 has maximum sensitivity in the green spectral range at 555 nm, where V (λ) has a value of unity, i.e. V (555 nm) ~~= 1.~~=1.

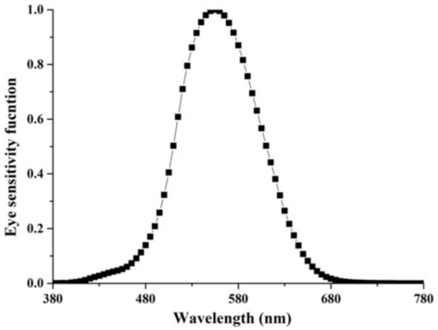

Fig. 3 standardization curve of eye sensitivity to wavelength of light [35].

alt-text: Fig. 3:

2.2 Colour rendering index (CRI)

Colour rendering is defined as “the effect of an illuminant on the colour appearance of objects by conscious or subconscious comparison with their colour appearance under a reference illuminant” [36]. CRI is a numerical measure of how true the ~~colors~~colours look when viewed with the light source. On a space from 0 to 100, with 100 representing true ~~color~~colour reproduction [37,38]. For indoor lighting, a CCT from 3000 K−5300 K and CRI of more than 80 and illuminance between 200 and 750 lx are generally required. The CRI of a warm white fluorescent lamp is about 50 [39].

The tristimulus values (X, Y, and Z) are the three-colour perception values of the human eye response and quantify the amounts of red, green and blue in a colour [40]. Tristimulus values X, Y and Z of light transmitted by a glazing are

$$X = \sum_{380nm}^{780nm} D_{65}(\lambda)\,\tau(\lambda)\,\overline{x}(\lambda)\,\Delta\lambda \tag{2}$$

$$Y = \sum_{380nm}^{780nm} D_{65}(\lambda)\,\tau(\lambda)\,\overline{y}(\lambda)\,\Delta\lambda \tag{3}$$

$$Z = \sum_{380nm}^{780nm} D_{65}(\lambda)\,\tau(\lambda)\,\overline{z}(\lambda)\,\Delta\lambda \tag{4}$$

X,Y, and Z can be calculated from the measured SPD transmittance, D_{65} spectral power distribution and the colour matching functions $\overline{x}(\lambda), \overline{y}(\lambda), \overline{z}(\lambda)$ shown in Fig. 4 [41,42].

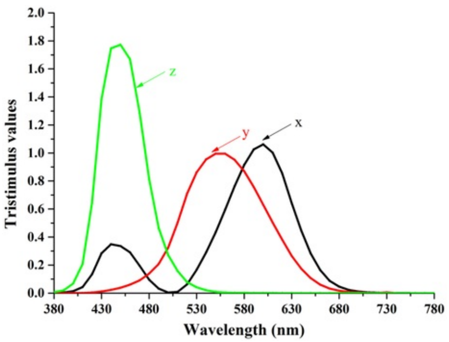

Fig. 4 The spectral response of the colour matching functions $\overline{x}(\lambda), \overline{y}(\lambda), \overline{z}(\lambda)$. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

alt-text: Fig. 4

Tristimulus values of the light transmitted by the glazing and reflected by each of eight test colours are given by [36]

$$X_{t,i} = \sum_{380nm}^{780nm} D_{65}(\lambda)\,\tau(\lambda)\,\beta_i(\lambda)\overline{x}(\lambda)\,\Delta\lambda \quad (5)$$

$$Y_{t,i} = \sum_{380nm}^{780nm} D_{65}(\lambda)\,\tau(\lambda)\,\beta_i(\lambda)\overline{y}(\lambda)\,\Delta\lambda \quad (6)$$

$$Z_{t,i} = \sum_{380nm}^{780nm} D_{65}(\lambda)\,\tau(\lambda)\,\beta_i(\lambda)\overline{z}(\lambda)\,\Delta\lambda \quad (7)$$

where β_i is the spectral reflectance of each test colour i and i=1 to 8

Trichromatic coordinates u_t and v_t for the transmitted reflected light were determined from

$$u_t = \frac{4X}{X + 15Y + 3Z} \text{ and } v_t = \frac{6X}{X + 15Y + 3Z} \quad (8)$$

Each test colour for the light transmitted and reflected is thus given by

$$u_{t,i} = \frac{4X_{t,i}}{X_{t,i} + 15Y_{t,i} + 3Z_{t,i}} \text{ and } v_{t,i} = \frac{6X_{t,i}}{X_{t,i} + 15Y_{t,i} + 3Z_{t,i}} \quad (9)$$

Coordinate correction after distortion by chromatic adaptation is provided by

$$u'_{t,i} = \frac{10.872 + 0.8802\frac{c_{t,i}}{c_t} - 8.2544\frac{d_{t,i}}{d_t}}{16.518 + 3.2267\frac{c_{t,i}}{c_t} - 2.0636\frac{d_{t,i}}{d_t}}, \quad (10)$$

$$v'_{t,i} = \frac{5.520}{16.518 + 3.2267\frac{c_{t,i}}{c_t} - 2.0636\frac{d_{t,i}}{d_t}} \quad (11)$$

where c_t and d_t for transmitted light and $c_{t,i}$ and $d_{t,i}$ for each light transmitted and then reflected by test colour are calculated from

$$c_t = \frac{4 - u_t - 10v_t}{v_t},\ d_t = \frac{1.708v_t + 0.404 - 1.481u_t}{v_t} \quad (12)$$

$$c_{t,i} = \frac{4 - u_{t,i} - 10v_{t,i}}{v_{t,i}},\ d_{t,i} = \frac{1.708v_{t,i} + 0.404 - 1.481u_{t,i}}{v_{t,i}} \quad (13)$$

Colour space system $W^*_{t,i}$, $U^*_{t,i}$, $V^*_{t,i}$ are given by

$$W^*_{t,i} = 25\left(\frac{100Y_{t,i}}{Y_t}\right)^{1/3} - 17 \quad (14)$$

$$U^*_{t,i} = 13W^*_{t,i}\left(u'_{t,i} - 0.1978\right) \quad (15)$$

$$V^*_{t,i} = 13W^*_{t,i}\left(V'_{t,i} - 0.3122\right) \quad (16)$$

The total distortion ΔE_i is determined from

$$\Delta E_i = \sqrt{(U^*_{t,i} - U^*_{r,i})^2 + (V^*_{t,i} - V^*_{r,i})^2 + (W^*_{t,i} - W^*_{r,i})^2} \quad (17)$$

The special colour rendering index R_i for each colour sample is given by

$$R_i = 100 - 4.6\Delta E_i \quad (18)$$

The general colour rendering index (CRI) is thus given by

$$CRI = \frac{1}{8}\sum_{i=1}^{8} R_i \quad (19)$$

2.3 Correlated colour temperature (CCT)

CCT was calculated from McCamy's equation [43]

$$CCT = 449n^3 + 3525n^2 + 6823.3n + 5520.33 \quad (20)$$

where $n = \frac{(x-0.3320)}{(0.1858-y)}$

in which $x = \frac{X}{X+Y+Z}$ and $y = \frac{Y}{X+Y+Z}$

3 Experiment

One SPD glazing from smart glass international was employed in this experiment. A Griven INSE 1200 MSR metal halide lamp was used as solar simulator. An AvaSpec-ULS2048 spectrometer was employed to measure transmission of SPD glazing. Details of glazings are listed in Table 1. Fig. 5 shows the indoor set up for spectral measurements. Variable voltage was applied to the SPD glazing to obtain variable transmittance.

Table 1 Details of glazings.

alt-text: Table 1:

		Dimensions (mm × mm)	Power supply	Supplier
Glazing	SPD	280 × 210	110 V (50 Hz AC sinusoidal signal); (Transparent)	Smart Glass International, Dublin
			0 V (Opaque)	
	Vacuum	350 × 200	Not required	NSG
	Double	280 × 210		Pilkington, UK

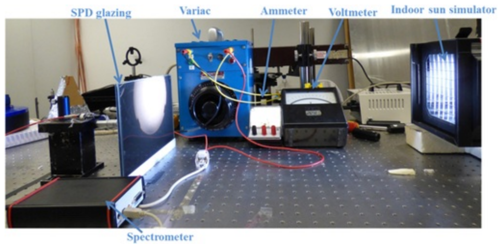

Fig. 5 SPD glazing luminous transmittance measurement.

alt-text: Fig. 5:

4 Results ~~&Discussion~~and discussion

4.1 CCT and CRI for SPD glazing

Light filtered by switchable SPD glazing is characterized by variables luminous transmittance, CCT and CRI. Luminous transmittance of SPD glazing for different applied voltages is shown in Fig. 6. Luminous transmittance was calculated by Eq. (1) using illuminant D65(λ) spectral power distribution and the photopic luminous efficiency function V(λ). Overall luminous transmittance for different power and applied voltage is also shown in Fig. 6.

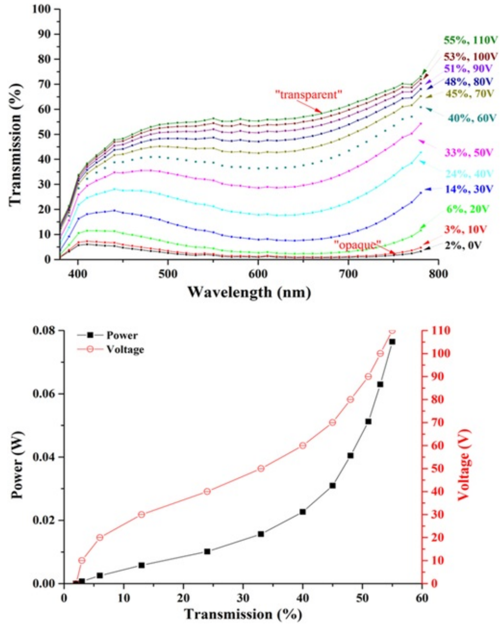

Fig. 6 Luminous transmittance of a SPD glazing for ~~0~~0-110 V selected switching states by wavelength (upper graph) and overall (lower graph).

alt-text: Fig. 6:

Fig. 7 shows the CRI and CCT for different luminous transmissions was calculated using Eqs. (19) and (20) respectively. A CRI greater than 90 indicates a ‘very good’ ~~color~~colour rendering while a CRI greater than 80 indicates a ‘good’ ~~color~~colour rendering. As the bleaching of the switchable device increases, the τ_v and CRI increases, while the CCT decreases. It can be seen that transmittance lower than 14% the CRI falls below 80.

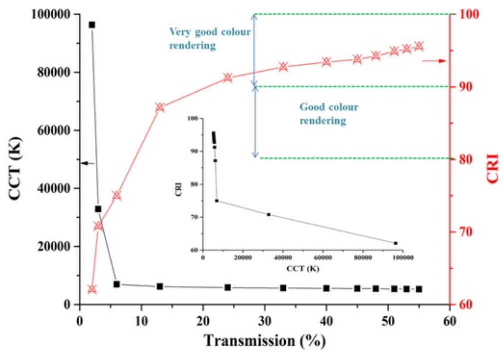

Fig. 7 Relationship between CRI, CCT and glazing luminous transmission for an SPD glazing and (inset) CRI and CCT at same transmittance of an SPD glazing. (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.)

alt-text: Fig. 7

4.2 CCT and CRI for evacuated (vacuum) and double glazing

The CCT and CRI of an SPD glazing of transparent state was compared double paned glazing with and air filled gap and (i.e double glazing) and an evacuated gap (i.e. vacuum glazing). These two glazing types were selected for comparisons as vacuum glazing and double glazing represent typical contemporary and indicative future glazing system respectively. Details of vacuum and double-glazing are well documented [44]. Fig. 8 shows the luminous spectrum for vacuum glazing, double-glazing and a 55% transparent SPD glazing. Overall luminous transmission for vacuum glazing was 72% and for double-glazing was 77%.

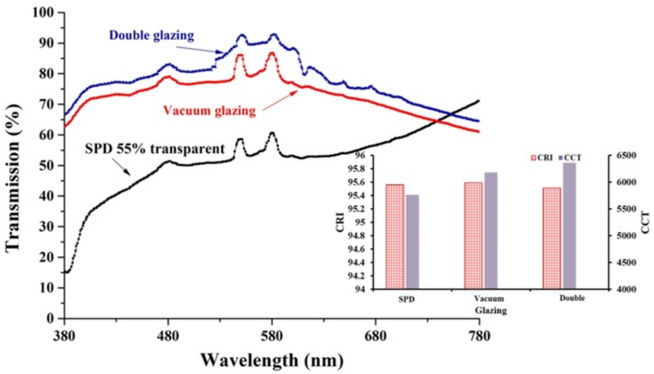

Fig. 8 Luminous transmission CRI and CCT of double-glazing, vacuum glazing and (55%) transparent SPD glazing.

alt-text: Fig. 8

CRI for vacuum, double and 55% transparent SPD glazing were 95.59, 95.51 and 95.56 respectively and CCT for vacuum, double and 55% transparent SPD glazing were 6178 K, 6360 K and 5762 K respectively as shown in Fig. 8. Average transmittance value of vacuum and double-glazing was 30% and 40% higher than the SPD glazing in a transparent state but the CRI values were similar for all three glazings. Above 0.24 transmittance, the SPD glazing had a CRI of up to 91.

5 Conclusions

The daylighting properties of a switchable SPD glazing in the opaque and transparent states, has been examined. ~~Color~~Colour rendering properties of the interior daylight can be greatly affected by transparency of switchable SPD glazing. From results, it is evident that SPD when opaque state does not satisfy standard CRI and CCT requirements. SPD glazing with transmission above 14% is able to provide CRI above 80.

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Highlights

- CRI and CCT of SPD glazing was ~~calculated,~~calculated.
- CRI and CCT of SPD glazing was compared with double and evacuated ~~glazing,~~glazing.
- SPD transmittance below 0.14 offers CRI below 80.

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