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The colour rendering index and correlated colour temperature of dye-sensitized solar cell for adaptive glazing application

Aritra Ghosh*, Prabhu Selvaraj, Senthilarasu Sundaram, Tapas K. Mallick*

Environment and Sustainability Institute (ESI), University of Exeter, Penryn Campus, TR10 9FE, United Kingdom

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ABSTRACT

The colour rendering index (CRI) and correlated colour temperature (CCT) of transmitted daylight through a DSSC glazing is an essential parameter for building interior space comfort. Six small-scale dye-sensitized solar cells (DSSCs) were fabricated by varying TiO_2 electrode thickness, which offered luminous transmittance between 0.19 and 0.53. Below 0.5 transmittance, the CRI for this TiO_2 electrode based DSSC glazing was less than 80. A strong linear correlation was found between CCT and CRI. The CRI of 53% transparent DSSC glazing had only 2.7% lower CRI than 77% transparent double glazing and 72% transparent vacuum glazing.

1. Introduction

Buildings consume 40% of energy worldwide due to heating, cooling and lighting (Sudan et al., 2015; Sudan and Tiwari, 2016, 2014) load demand (Al Dakheel and Tabet Aoul, 2017; Hee et al., 2015). Mitigation of this energy demand is possible by introducing new zero energy building or retrofits the building envelope using energy efficient material. Windows are the weakest part of a building as it allows 40% of total building energy losses. Thus, replacing of low energy efficient window with smart, energy efficient, adaptive glazing is essential (Ghosh, 2014; Ghosh et al., 2017a, 2017b; Ghosh and Norton, 2017a). Moreover, for retrofit application, replacement of windows is easier than any other part of the building (Ghosh et al., 2016a, 2015).

Currently adaptive glazing systems are in research interest for building window applications as they have potential of lighting demand reduction of building and introduce comfortable daylight into space (Jelle et al., 2012; Rezaei et al., 2017; Skandalos and Karamanis, 2015). These glazing systems are mainly switchable (Ghosh et al., 2018a, 2018b; Ghosh and Mallick, 2018) and non-switchable (Ghosh et al., 2016b, 2016c; Ghosh et al., 2018b). Switchable has potential to change its transparency based on occupant demand and comfort (Ghosh et al., 2016). However, for large-scale application this electrically switchable glazing can increase the building switching energy demand (Ghosh et al., 2016d). Photovoltaic (PV) glazing is advantageous over any other smart adaptive glazing as they can control energy losses and generate clean energy (Cuce, 2016; Ng and Mithraratne, 2014; Skandalos and Karamanis, 2015).

In a PV glazing, PV devices are sandwiched between two glass panes (Cuce, 2016; Favoino et al., 2015). These devices can be crystalline silicon (Si) (Park et al., 2010), amorphous Si (Miyazaki et al., 2005), CIGS (Wei et al., 2014), CdTe (Shen et al., 2016), perovskite (Cannavale et al., 2017) or dye-sensitized type solar cells (DSSC) (Kang et al., 2013; Yoon et al., 2011). Compared to other type of PV cells, DSSCs have below attributes, which make them advantageous

- DSSCs are insensitive to environment contaminants, which offer them to prepare under ambient temperature. Thus, easier fabrication process can be adopted such as roll-to-roll, which involves continuous, low-cost manufacturing method to print dye-sensitized solar cells on flexible substrates (Gong et al., 2017, 2012; Grätzel, 2003).
- DSSCs work even in low light conditions. Thus for northern latitude area where diffuse sun lights are majority over direct sunlight, DSSC based windows are excellent choice for building applications (Gong et al., 2017, 2012; Grätzel, 2003; Sharma et al., 2017; Upadhyaya et al., 2013).
- DSSCs are superior than a-Si:H based PV as the transparency can be increased by making use of highly transparent photoanodes and

* Corresponding authors.
E-mail addresses: a.ghosh@exeter.ac.uk (A. Ghosh), t.k.mallick@exeter.ac.uk (T.K. Mallick).

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Nomenclature

CIE	Commission Internationale de l'Eclairage
CCT	correlated color temperature
CRI	colour rendering index
D65	CIE standard illuminant
ΔE_i	color difference between the color coordinates determined for the same test color samples illuminated by test and the reference illuminants
i	number of test color
R_i	special color rendering index
u_t, v_t	user coordinates system (UCS) or trichromatic coordinate for test illuminant
$W_{t,i}$, $U_{t,i}$, $V_{t,i}$	UCS chromaticity coordinates of test color samples under test illuminant
$W_{r,i}$, $U_{r,i}$, $V_{r,i}$	UCS chromaticity coordinates of test color samples under reference illuminant
X, Y, Z	CIE tristimulus values of test color samples
x, y	chromacity coordinates of test illuminant
$\bar{x}(\lambda)$,$\bar{y}(\lambda)$,$\bar{z}(\lambda)$	color matching functions of 1931 CIE 2°standard observer

counter electrodes. Selecting proper dyes for these devices can provide low eye sensitive factor (Kumara et al., 2017; Richhariya et al., 2017; Shalini et al., 2015).
- DSSCs have positive temperature effect (Berginc et al., 2007; Parisi et al., 2017).

DSSCs were first reported by O'Regan and Grätzel in 1991 (O'Regan and Gratzel, 1991) and the maximum efficiency of 13% was recorded in 2014 (Mathew et al., 2014). The recent progress of DSSC offers it to consider for glazing applications. Fig. 1 shows the different components of a typical liquid electrolyte DSSC for glazing application.

First ever DSSC glazing was fabricated by series connected 9 unit ($80 \times 80\,mm^2$ active area) solar cells which offered 60% average transmission between 500 and 900 nm (Kang et al., 2003). Thermal and optical characteristics of double glazed DSSC window were investigated using WINDOW software where DSSCs were fabricated using green (33% transparent) and red (28% transparent) dyes (Kang et al., 2013). This glazing was able to reduce 60% entering solar heat gain. In an another work, thermal, optical and electrical performance of DSSCs inside a patented glass block were also investigated using COMSOL Multiphysics, WINDOW and Zemax (Morini and Corrao, 2017).

Spectral power distribution (SPD) of solar radiation in the visible range of 380–780 nm is considered as daylight. SPD of natural daylight changes with local latitude, weather, season, time of day, air bound dust and pollutant (Ghosh and Norton, 2017b). SPD of transmitted light into the interior of a room influence the visual comfort and color perception. Glazing transparency, thickness, solar heat gain coefficient and overall heat transfer coefficient are the most common investigated parameters while color properties such as correlated color temperature (CCT) and color rendering index (CRI) evaluations are often overlooked. Colour of transmitted daylight through glazing is an influential factor on indoor comfort. Correlated color temperature (CCT) and color rendering index (CRI) are the two major components to understand the SPD of transmitted light through glazing (Davis and Grinthner, 1990; Luo, 2011). CCT and CRI are the most aesthetic criteria as they show whether the spectrum coming inside through the glazing is suitable for occupant or cross the comfort level. They are used to characterize the illumination quality of white light (D'Andrade and Forrest, 2004). Good quality lighting is an important feature, as the quantity and quality of lights are required for wellbeing, health, interpersonal relationships and aesthetic taste (Bommel and Beld, 2004; Webb, 2006). CRI of a glazing indicates the color of entering daylight into an interior before and after placing a glazing. CRI values can be from 0 to 100 (Gunde et al., 2005) where between 80 and 90 are considered to be acceptable (Chain et al., 2001). CRI close to 100-represents true color perception inside the building, thus, indicates perfect visual quality (Gong et al., 2005; Niu et al., 2006). A CCT needs to be equivalent to that of a blackbody source at temperatures between 3000 and 7500 K (Hernández-Andrés et al., 1999). CCT offers to understand whether light is neutral, bluish white or reddish white. CCT for various daylight sources are listed in Table 1.

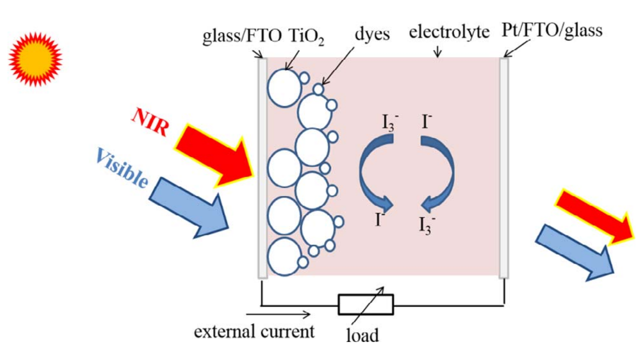

Fig. 1. Schematic illustration of a DSSC glazing. Entering visible light can be changed by tuning TiO_2 thickness, dyes and electrolyte.

CCT and CRI evaluation for PV glazing is rare. CRI for semi-transparent PV module using a-Si PV cells was the only reported work of PV glazing (Lynn et al., 2012). No CCT values were calculated for this type of glazing.

The spectrum of transmitted daylight into an interior space changes due to the presence of DSSC glazing. CRI and CCT characterization of DSSC glazing is required as these parameters assess human response to colors (Ghosh and Norton, 2017b).

In this work, different thickness of DSSCs was realized to evaluate luminous transmittance, CCT and CRI for the incoming daylight through DSSC glazing. CCT and CRI of DSSC glazing were compared with air filled double pane glazing and evacuated (vacuum) glazing.

2. Experiment

2.1. DSSC manufacturing

Six different titanium dioxide (TiO_2) layers (as listed in Table 2) were prepared for DSSCs using screen-printing method in order to measure its solar to electrical efficiency and thermo-optical properties for glazing applications at our solar energy lab, University of Exeter. The thickness of the TiO_2 electrodes was measured using Dektak 8

Table 1
Correlated color temperatures for various daylight sources of Washington DC USA (Mardaljevic, 2014).

Daylight source	CCT
Sunlight – sunrise or sunset	2000 K
Sunlight – one Hour After Sunrise	3500 K
Sunlight – early Morning	4300 K
Sunlight – late Afternoon	4300 K
Overcast sky	6000 K
Summer skylight	9500–30,000 K