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Color quality consideration when switching from FL to LED lamps

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Abstract—Fluorescent lamps (FLs) used for general lighting due to European Union legislation will be withdrawn from sale by 2023. The LEDs which are proposed as substitute of FL should provide the same quality of lighting and visual comfort. The research on substituting FL lamps is based on the multi-criteria parameterization. It is indicates that LEDs substituting FLs may not meet the end user expectations due to the Color Preference Criteria. The paper compares a typical FL (4100 K) lamp named by CIE as illuminant FL3.5 with its corresponding LED substitutes available on the market. The LED substitute selection criteria were the value of Corelated Color Temperature (CCT) and chromaticity point which must be within the ellipse provided by the ANSI C78.376 document for 4100 K CCT.

The legal status in the European Union from 2023 prohibits the use of fluorescent lamps in new lighting installations, where the technology promoted due to energy efficiency involves LED sources [1–4]. New and modernized lighting installations should meet the specifications of national standards, where the colorimetric requirements are typically limited to Corelated Color Temperature [5] and General Color Rendering Index (R_a) [6], which is based on a comparison of the length of colour difference vectors in the CIE1964 chromaticity diagram. Research confirms that the R_a measure does not always correlate with the visual assessment of color rendering [7]. The study of the preferred color of white LED light with a similar R_a value, constant CCT and variable distance of the chromaticity point determined by *Duv* (the distance perpendicular to the Planck curve in the CIE1960 *uv* chromaticity diagram, calculated according to [8]), showed that the preferred locations of the light chromaticity point [9] for 3000 K are in value *Duv* –0.02 and –0.03. For light 6500 K *Duv* is with 0.00 and –0.01.

At the publication [10] a synthesis of five studies, conducted on groups of people, was carried out on the basis of which three-stage Color Preference Criteria were presented, which is based on measures calculated according to TM-30-20 [11]: color fidelity (R_f) [12] is based on measuring average colours rendered by the test source and reference source, conducted on 99 Colour Evaluation Samples (CES), gamut area (R_g) [13] is calculated using the CES and describes the average saturation shift of the source compared to the reference source and Local Chroma Shift ($R_{cs,h1}$) [14], which is for nominally reddish objects. Table 1 lists the requirements of classes of Color Preference Criteria from P1 to P3.

Table 1. Color Preference Criteria [10–11]

P1:	„Best”	$R_f \geq 78$, $R_g \geq 95$, $-1\% \leq R_{cs,h1} \leq 15\%$
P2:	„Good”	$R_f \geq 75$, $R_g \geq 92$, $-7\% \leq R_{cs,h1} \leq 19\%$
P3:	„Acceptable”	$R_f \geq 70$, $R_g \geq 89$, $-12\% \leq R_{cs,h1} \leq 23\%$

The LED lighting technology and the well-known phosphors used in white phosphor converting LEDs (pc-WLEDs) make it possible to obtain with variety of Spectral Power Distributions (SPDs). Their optimization is performed based on a number of parameters, including: Luminous Efficacy of Radiation (LER) [15–18], which describes theoretical luminous efficiency of SPD, different colorimetric metrics [19–22], non-image-forming effects of light [22–26]. Research states that it is important to take into account the operating conditions of LED sources, i.e. temperature [27–30] or supply current [31]. These issues are also taken into account during modeling of SPDs [17, 32–33]. The current state of knowledge [10–11] should encourage scientists and producers to take into account also the color preference factor in the SPDs optimization process.

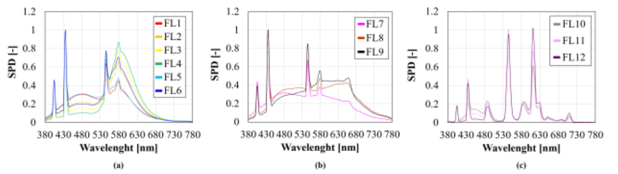

Fig. 1. The CIE fluorescent lamp illuminants: classical FLs (a), broadband FLs (b), narrowband FLs (c).

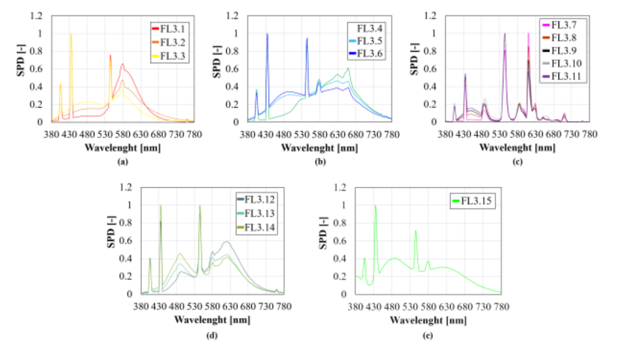

Fig. 2. The CIE fluorescent lamp illuminants: second generation classical FLs (a), deluxe FLs (b), three-band FLs (c), multi-band phosphor FLs (d), simulated the spectrum of Daylight 6504 K (e).

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The most frequently used spectral distributions of fluorescent lamps are shown in Figs. 1÷2. The FL3.5 illuminant was selected since it represents typical FL lamps with 4000 K/4100 K.

It was decided to verify how the replacement of fluorescent lamps (CCT ~ 4100 K) with pc-WLED light sources available on the market will affect the Color Preference Criteria. From among the LED sources available in the world presented in the article [34], 6 SPDs (S1÷S6) were selected which met the criteria:

• similar value of the CCT illuminant FL3.5 (4086 K) (Fig. 3),

• location of the the chromaticity point within the 5-steps MacAdam Ellipse from the 4000 K/4100 K/Cool White chromaticity point given by ANSI C78.376-2014 [35],

• *Duv* (closest to the illuminant value).

Figure 3 shows the SPDs of the FL3.5 illuminant and six selected commercial LEDs and location of their chromaticity points. Figure 4 shows the quality values of the analyzed light sources, on the sub-figures (e), (f), (g) are outlined the boundaries of classes P1, P2, P3 of Color Preference Criteria according to Table 1.

All LEDs (S1÷S6) are characterized by a higher LER value than the fluorescent illuminant FL3.5. LED S2 and FL3.5 have similar LER and R_a values, and also belong to the P1 class according to the Color Preference Criteria. The remaining LEDs (S1, S3÷S6) meet only the typical requirements for indoor lighting installations $R_a \geq 80$ and belong to the P3 class of the Color Preference Criteria scale, or fall outside the three-tier scale (P-). It is worth noting that the value of the *Duv* parameter is very similar for FL3.5 and LED S3 (Fig. 4 (c)) but according to the Color Preference Criteria such type of lighting installation replacement would lead to worse lighting conditions and decrease lighting classification from P1 to P3 (see Table 1).

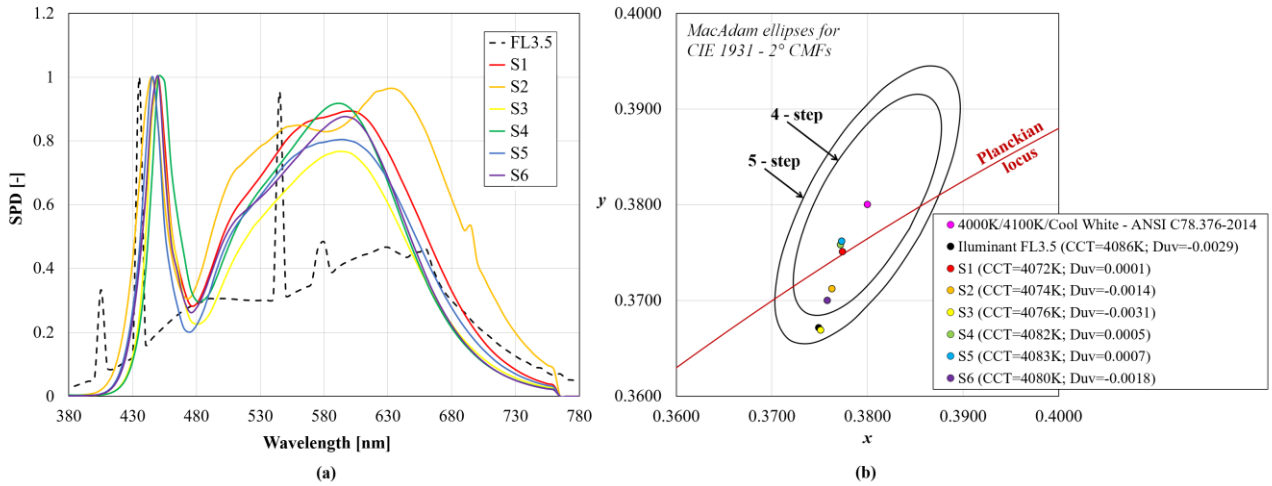

Fig. 3. Information about SPDs and *xy*: (a) the normalized spectral power distributions (SPDs) of the FL3.5 illuminant, LED sources and (b) the corresponding chromaticity points at CIE1931 (*x,y*) chromaticity diagram.

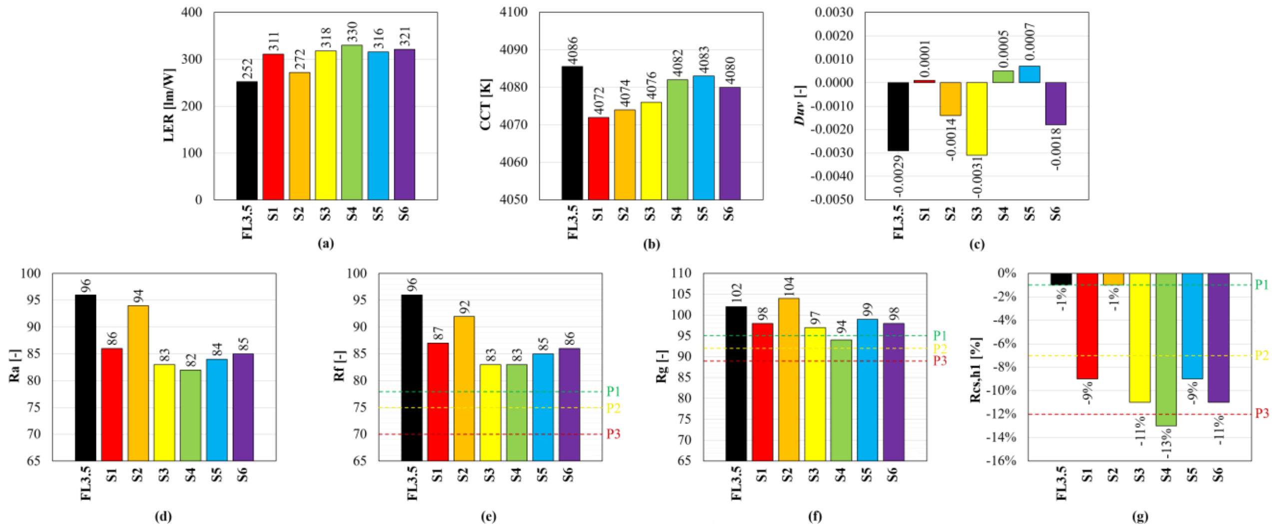

Fig. 4. Value of the parameters: LER, CCT, *Duv*, R_a, R_f, R_g , $R_{cs,h1}$ of the FL3.5 illuminant and the LED used as substitutes.

Research has shown that the modernization of the fluorescent installation (~4100 K) by LED allows to maintain similar colorimetric parameters, light efficiency and Color Preference Criteria by using LED sources available on the market. However, the probability of encountering such a source on the basis of CCT and chromaticity point alone is not obvious.

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