LIGHTING QUALITY: COLOR RENDERING OF FLUORESCENT LIGHT SOURCES

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Abstract: The Laboratory of Colorimetry and Spectrophotometry (Lacoe) of the Brazilian Institute of Metrology (Inmetro) has developed a high accuracy spectral reference system for the determination of the Color Rendering Index – CRI for light sources. Here is shown the CRI calculation method and the associated uncertainties applied to measurements of a set of commercial fluorescent lamps.

Keywords: CIE color rendering index, chromaticity coordinates, calibration services, correlated color temperature.

1. INTRODUCTION

The Laboratory of Colorimetry and Spectrophotometry (Lacoe) of the Brazilian Institute of Metrology (Inmetro) has developed a high accuracy spectral reference system for the determination of the Color Rendering Index – CRI for light sources. The CRI calibration services now offered by the laboratory will cover the increasing demand by the Brazilian lighting sector.

Color Rendering Index (CRI) is a quantitative measure of the ability of a light source to reproduce the colors of various objects faithfully in comparison with an ideal or natural light source, see figure 1.

Fig. 1: Perception of a color set illuminated by different light sources (photo extracted from: *http:www.nist.gov*).

The specification for the CRI calculation, approved by The International Commission on Illumination - CIE is so far the only internationally-accepted metric for assessing the color rendering performance of light sources and is outlined in reference [1]. The Color Rendering is defined in reference [2] as follows: "*Color rendering*: Effect of an illuminant on the color appearance of objects by conscious or subconscious comparison with their color appearance under a reference illuminant".

To apply the recommended CIE method, the resultant color shifts for suitably chosen test color samples (TCS) must be calculated. A set of fourteen test color samples is specified by the spectral radiance factors in reference [1]. The first eight samples cover the hue circle, are moderate in saturation, and are approximately the same in lightness, as seen in figure 2, numbered from 1 to 8: light greyish red, dark greyish yellow, strong yellow green, moderate yellowish green, light bluish green, light blue, light violet and light reddish purple.

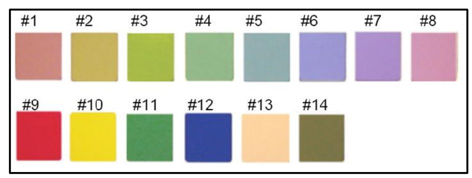

Fig. 2: Reflective test color samples (TCS) taken from Munsell Atlas.

The further test color samples, numbered from 9 to 14, represent a strong red, yellow, green and blue, and represent a human complexion and foliage colors.

2. METHODOLOGY

In the calculation of the CRI, the color appearance of the reflective test color samples (TCS) are simulated when illuminated by a reference source and by the test source. CRI is then calculated with respect to a reference source which is either the blackbody curve below 5000 K or a CIE Daylight source above 5000 K.

The reference illuminant is mathematically defined [3] and has the same Correlated Color Temperature (CCT) [4] as the light source to be tested. Equation (1) shows the reference illuminant for CCT ≤ 5000 K, temperature interval where all the fluorescent lamps fall in, and then for each source sample the CCT is calculated

$$SPD_{\mathrm{Re}f}\left(\lambda\right)=2\pi hc^{2}\left(10^{-9}\lambda\right)^{-5}/\left(e^{\left[\left(hc/k\right)/\left(T_{CCT}\times10^{-9}\times\lambda\right)\right]}-1\right) \qquad (1)$$

Where:

c = 299792458 m/s
h = 6,6260693 x 10^{-34}Js
k = 1,3806505 x 10^{-23} J/K
λ = each wavelength in the measurement range, for example: 380 nm, 384 nm…780 nm.

T_{CCT} = Correlated Color Temperature of the tested source in Kelvin.

After accounting for chromatic adaptation with a Von Kries correction [5], the difference in color appearance under the reference source (suffices *r*) and the test source (suffices *t*) for each sample color (TCS), ΔE_i , is computed in the CIE 1964 W*U*V* Color Space according to equation (2) below:

$$\Delta E_{k,i} = \sqrt{\left(U^*_{r,t} - U^*_{k,t}\right)^2 + \left(V^*_{r,t} - V^*_{k,t}\right)^2 + \left(W^*_{r,t} - W^*_{k,t}\right)^2} \quad (2)$$

The special color rendering index (R_i), i= 1…8, is calculated for each reflective sample by equation (3):

$$R_i = 100 - 4{,}6\Delta E_i \quad (3)$$

The general color rendering index is designated by the letter R_a, equation (4), and is the arithmetic mean of the first eight individual indexes R_i:

$$R_a = \frac{1}{8}\sum_{1}^{8} R_i \quad (4)$$

A perfect score of 100 represents no color differences in any of the eight samples under the test and reference sources.Therefore, light sources that mimic incandescent light or daylight for the eight color samples are, by definition, the ones that will score highest on the CRI. This does not mean that an incandescent lamp is a perfect color rendering light source. It is not. Then, small average differences will result in a higher score, while larger differences give a lower number.

The values of CCT and CRI for a light source are obtained from spectral power distribution measurements. Experience has shown that the most significant factor which affects the value of CRI is the precise determination of the spectral power distribution of the light source samples. In this work, attention has been paid to determine the uncertainty in CRI according to such factor.

2.1. Experimental setup and measurements

A CCD spectroradiometer measuring the spectral distribution in 4 nm interval from 380 nm to 780 nm was mounted firmly onto a rotating arm with the axis of rotation being coincident with the vertical central line of the white tile and is focused onto the center of the white tile. This setup, figure 3, allows for spectral radiance measurements over a continuous range of observation angles and for the fine adjustment of the angle with respect to the illuminant.

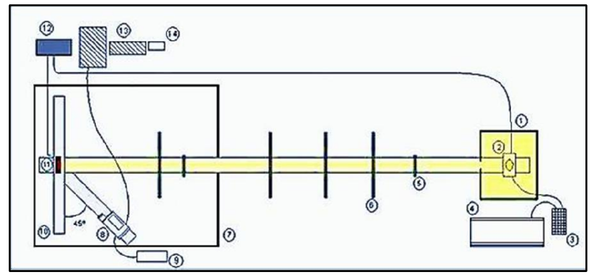

Fig3. Experimental set-up; (1),(2),(3),(4): "housing" and light source, standard resistence. (5), (6), (7): optical accessories and baffles. (8),(9),(10),(11): spectroradiometer, positioners, white tile. (12),(13),(14): computer, system measurements.

Spectral power distribution (SPD) measurements were carried out in the standard 0°:45° illumination observation geometry.The distance between the plate and the source can be changed to adjust the irradiance pattern on the white tile surface.The ambient conditions, temperature and relative humidity, were maintained at (23 ± 3) ºC and (50 ± 10) %.

The color rendering uncertainties have been obtained applying the ISO Guide Method [6] and reference [7] to derive analytical expressions for the uncertainties in CRI. The mathematical derivation of the equations for the CRI is not straightforward, and one should attempt to the correlations among the chromaticity coordinates.

A sequence of derivations must be carried out to obtain the uncertainty in the color rendering indexes [8]. A brief outline of the expressions considered is shown below. The uncertainties in the special and general color rendering indexes are given by equations (5) and (6):

$$U_c\left(R_{k,t}\right) = 4,6 \cdot U_c\left(\Delta E_{k,t}\right) \quad (5)$$

$$U_c\left(R_a\right) = \frac{1}{8}\sum_{i=1}^{8} U_c\left(R_{k,t}\right) \quad (6)$$

Where the equations above depend on the expression (7);

$$\begin{aligned} U_c^2\left(\Delta E_{k,t}\right) = & \left(\left(\frac{\partial \Delta E_{k,t}}{\partial U^*_{k,t}}\right)^2 U_c^2\left(U^*_{k,t}\right)\right) \\ & + \left(\left(\frac{\partial \Delta E_{k,t}}{\partial V^*_{k,t}}\right)^2 U_c^2\left(V^*_{k,t}\right) + \left(\frac{\partial \Delta E_{k,t}}{\partial W^*_{k,t}}\right)^2 U_c^2\left(W^*_{k,t}\right)\right) \\ & + \left(2r_{U^*,V^*}\frac{\partial \Delta E_{k,t}}{\partial U^*_{k,t}} \cdot \frac{\partial \Delta E_{k,t}}{\partial V^*_{k,t}} \cdot U_c\left(U^*_{k,t}\right)U_c\left(V^*_{k,t}\right)\right) \\ & + \left(2r_{U^*W^*}\frac{\partial \Delta E_{k,t}}{\partial U^*_{k,t}} \cdot \frac{\partial \Delta E_{k,t}}{\partial W^*_{k,t}} \cdot U_c\left(U^*_{k,t}\right)U_c\left(W^*_{k,t}\right)\right) \\ & + \left(2r_{V^*W^*}\frac{\partial \Delta E_{k,t}}{\partial V^*_{k,t}} \cdot \frac{\partial \Delta E_{k,t}}{\partial W^*_{k,t}} \cdot U_c\left(V^*_{k,t}\right)U_c\left(W^*_{k,t}\right)\right) \end{aligned} \quad (7)$$

Where $U_c(U^*)$, $U_c(V^*)$, $U_c(W^*)$ are the coordinate uncertainties in the CIE 1964 W*U*V* Color Space and

$r_{U^*V^*}, r_{U^*W^*}, r_{V^*W^*}$ are the correlation factors between the coordinates.

3. RESULTS

To facilitate comparison of our results, figure 4 presents the CCT and the values of special color rendering indexes for each of the FCLs samples. All the color rendering indexes from 1 to 7 had similar performance, despite the CCT differences between the lamps.The prediction of the color rendering properties of FCLs by the CIE CRI method presents a problematic behavior as can be seen for the TCS 09, a strong red color, which results in a negative value for the ninth special color rendering.

The color differences in all tested samples, on average, allowed a high score for the final CRI, despite the poor reproducibility of some colors. Two lamp colors can have the same Color Temperature, but render colors very differently. The CCT does not define how natural or unnatural the colors of objects will appear when lighted by the source.

Our visual experience can give us the prediction of a color rendering as good or not according to our judging. Thereby, we can perceive an extraordinary color difference comparing a red color sample illuminated by lamps A and F, and thus for us a bluish color lamp (F) is preferable to a yellow one (A). A scene containing spectral reflectances such as that of CIE TCS 09S is not expected to have its actual (visual) color rendering described by a color rendering index based on an average color difference value.

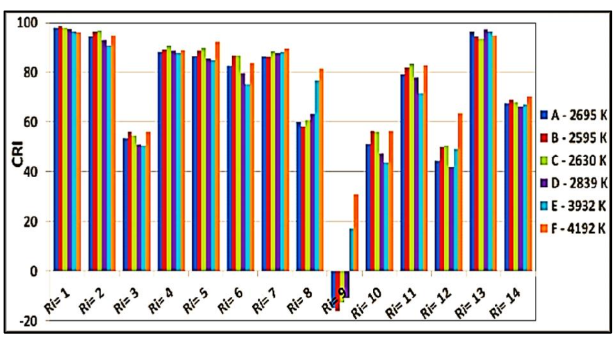

Fig.4. Set of fluorescent lamps of different color temperatures sampled in CRI, according the CIE standard in use [1].

Table 1 gives, for the first eight TCS, the special color rendering indexes (R_i) of the fluorescent compact lamps A, B, C, D, E and F. The variations in the special indices R_i for the light samples are remarkably uniform; the *light reddish purple* (TCS 08) in particular, presents a greater variation between the lamp group (A, B, C, D) and (E, F).

Table 2 presents the calculated uncertainties for special color rendering indexes $U_c(R_i)$ of TCS under the fluorescent compact lamps A,B,C, D, E and F. We apply the equation (5) to obtain the uncertainty in each of the special color rendering indexes. The higher values appear for the TCS 03 and TCS 08.

Table 1. Rounded values of the special color rendering indexes R_i(i=1..8) of TCS under fluorescent compact lamps A,B,C, D, E and F.

	A	B	C	D	E	F
Munsellsamples						
TCS 01	98,5	98,0	96,9	98,0	97,1	94,7
TCS 02	94,9	96,6	97,2	93,5	91,5	95,5
TCS 03	53,8	56,2	55,0	51,2	50,7	56,1
TCS 04	88,3	89,1	90,7	88,9	88,3	88,6
TCS 05	87,3	89,4	90,5	86,2	85,9	93,2
TCS 06	83,6	87,6	87,8	80,4	76,1	84,6
TCS 07	86,6	86,4	88,6	88,1	88,4	89,7
TCS 08	60,3	58,8	61,2	64,0	77,7	82,5

Table 2. Rounded values of uncertainty for special color rendering indexes $U_c(R_i)$ of TCS under tested fluorescent compact lamps A,B,C, D, E and F.

	A	B	C	D	E	F
Munsellsamples						
TCS 01	0,9	3,1	3,6	1,6	2,1	3,3
TCS 02	3,0	2,2	2,3	3,3	3,0	2,7
TCS 03	4,0	4,0	4,1	4,0	3,6	3,5
TCS 04	0,8	1,1	1,8	0,8	1,6	2,2
TCS 05	3,2	3,2	3,2	3,3	2,8	2,3
TCS 06	3,2	3,1	3,2	3,2	2,7	2,6
TCS 07	1,8	2,2	2,2	1,4	1,7	1,7
TCS 08	3,7	3,8	3,9	3,6	2,7	2,7

Table 3 presents the general color rendering index R_a and the calculated uncertainty of special color rendering indexes $U_c(R_a)$ of TCS under fluorescent compact lamps A, B, C, D, E and F. All samples presented CRI $\geq$ 80 and the value $U_c(R_a) \approx 3$.

The uncertainty budget was elaborated and one can observe that the greatest contribution comes from $U_c(R_a)$. The calculated coverage factor is $k = 2$ and the final calculated expanded uncertainty is $U = 5$.

Table 3. Rounded values of general color rendering index R_a and uncertainties $U_c(R_a)$ of fluorescent compact lamps A, B, C, D, E and F .

	A	B	C	D	E	F
R_a	81,7	82,8	83,5	81,3	81,9	85,6
$U_c(R_a)$	2,6	2,8	3,0	2,6	2,5	2,6

3.1. Color Rendering Index vs. Color Quality

Looking at the "spikes" in the spectral power distribution (SPD) for a fluorescent light source, for example the lamp F in figure 5, one can observe that shifting the emission wavelengths, the CRI score may drop significantly, this way, some narrowband features of light spectra can improve or degrade the color appearance of objects significantly, what is not addressed in the current standard CIE color rendering method.

If the color difference ΔE_i is higher than a maximum value, obtained from equation (1), one should expect a negative color rendering value as can be seen in figure 4. Figure 5 gives the CIE spectral reflectance curves, TCS 09 and TCS 12, as examples, together with the relative spectral power distribution of the tested sources A and F.

The maximum color difference value is $\Delta E_{U^*V^*W^*} = 25$ for source A, for CIE TCS 09, and it is $\Delta E_{U^*V^*W^*} = 14$ for the light source F. For the TCS 12, $\Delta E_{U^*V^*W^*}$ = 8 for the light source F and $\Delta E_{U^*V^*W^*}$ =12 for the light source A.

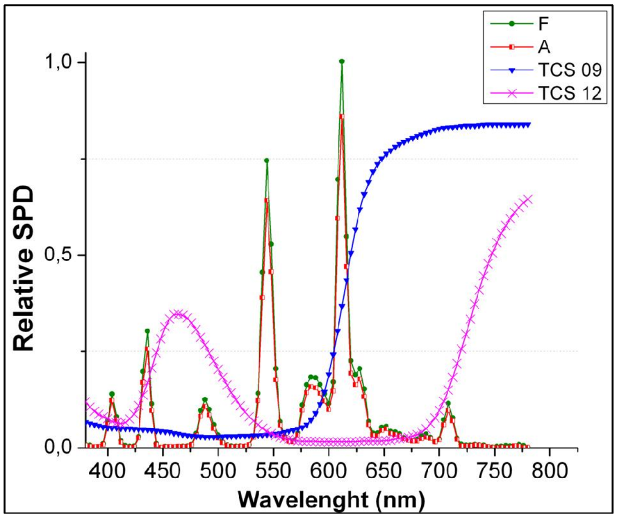

Fig.5.Spectral reflectance curve of CIE TCS 09 and relative SPD of test sources A and F.

4. CONCLUSIONS

To help indicate how colors will appear under different light sources, a system was devised by the CIE that mathematically compares the change in chromaticity of a number of test colors illuminated alternately by the test source and by a reference source. If there is no change in appearance, the source in question is given a CRI of 100 by definition. An incandescent lamp has a Color Rendering Index (CRI) close to 100. This does not mean that an incandescent lamp is a perfect color rendering light source. It is not. It is very weak in blue, as anyone who has tried to sort out navy blues, royal blues and black under low levels of incandescent lighting.

CRI is useful in specifying color but must be used within its limitations. Possible reason may include the use of a single number of test color samples and the use of an unsuitable color difference metrics. At the same time, the colors lighted by sources with characteristic line spectra may actually look better than their CRI would indicate. However, some exotic fluorescent lamp colors may have very high CRI's, while substantially distorting some particular object color.It may be the aim of further studies whether and how the CRI impacts other sources like LEDs and OLEDs, and accomplish the discussion about a new CRI method under discussion at CIE TC 1-69 [9].

In this work a set of commercial FCLs was measured and for each of them the value of CRI and its associate uncertainties were calculated. Some aspects about the actual rendering of source light samples were discussed too.

The colorimetric system developed and implemented by the Colorimetry and Spectrophotometry Laboratory at Inmetro – Lacoe – will represent the first reference system in Brazil for CCT and CRI measurements of light sources and will permit calibration services for industrial and testing laboratories. A complete automation of the measurement system is in progress.

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