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Colour rendition quality of typical fluorescent lamps determined by CIE Colour Fidelity Index and Colour Rendering Index

***Abstract**. This paper describes how CIE colour fidelity index R_f values are correlated with CIE R_a colour rendering index values for typical FL fluorescent lamps. The results shows that for broad band FL lamps R_f doesn't introduce drastically changes in relation to R_a values. The other situation is with narrow band FL lamps whose spectral power distribution was designed for achieving of high R_a value. At that case there is no correlation between R_a and R_f.*

***Streszczenie.** W artykule przedstawiono badania nad zależnością wskaźnika wierności barwy CIE R_f od wskaźnika oddawania barw CIE R_a dla standardowych lamp fluorescencyjnych (świetlówek) FL. Wyniki pokazują, że dla szerokopasmowych świetlówek, wskaźnik R_f nie wprowadza drastycznych zmian w stosunku do wartości R_a. W przypadku wąskopasmowych lamp FL, tj. takich których rozkład widmowy został zaprojektowany w celu osiągnięcia wysokiej wartości R_a pomimo faktu iż wizualnie ich światło nie oddaje perfekcyjnie barw, wartość wskaźnika Rf nie koreluje z Ra. (**Jakość oddawania barw współczesnych lamp fluorescencyjnych określona zdefiniowanym przez CIE wskaźnikiem wierności barwy oraz wskaźnikiem oddawania barw**).*

Keywords: colorimetry, colour rendering index, colour fidelity index, CIE illuminants.
Słowa kluczowe: kolorymetria, wskaźnik oddawania barw, wskaźnik wierności barwy, iluminanty CIE.

Introduction

The assessment of artificial lamp colour rendition quality is one of the key technical and scientific issue which appeared with beginning of designing and manufacturing of electrical lamps. The mathematical parameters whose can be used as colour quality metrics are under continuously development up to these days. The most recent internationally recognized document about this subject was published in April 2017 by International Commission on Illumination CIE as Technical Report 224:2017 entitled "Colour Fidelity Index for accurate scientific use" [1]. In this document is defined general colour fidelity index R_f of light sources and descried how to calculated it. Before that CIE recommendation, there had been a lot of proposals of lighting metrics for describing colour rendering of light sources (Fig.1). The broader interpretation of colour quality index calculations were made in several publications [2,3,4,5,6,7]. However only one from all of proposals got international approval by CIE. This new R_f measure is an additional to described in the 60's, also by CIE, Colour Rendering Index R_a. The CIE said that introduction of the new CIE R_f index does not either replace the CIE R_a index for the purpose of product evaluation and specifications or meet regulatory requirements but aims at introducing an additional measure in light sources specifications that may has possibility to become the main parameter which describes the light's colour quality in the future [1]. CIE colour fidelity index R_f eliminates many of the errors highlighted in the CIE CRI system because is based on higher number of colour test samples and more homogeneous colour space (CAM02-UCS) than CRI method.

Furthermore, the CIE defined the terms, "colour rendering" and "colour fidelity", as a similar meaning to be distinguished it from the other aspects of colour quality [1]. Despite that, CIE document 13.3-1995 said that colour quality assessment for whole range available lamps can be done by CRI R_a method, however, the research carried out indicates that this method should not be used for white LED light sources [3,4,7,8]. In 2015 the North American Illuminating Engineering Society (IES) introduced and recommended for use in the United States new measures for lamps colour quality assessment known as TM 30-15 method. This new IES method introduced two colour rendering indicators – the colour fidelity index R_f as equivalent to the CIE 13.3-1995 CRI R_a and the colour gamut index, i.e. the index referred to the Gamut Area Index [2]. In June 2018 IES [9] in IES TM-30-18 document presented a revision of TM-30-15 method. The TM-30-18 method contains three modifications in relation to TM-30-15 method. Those modifications were made to achieve consistency with publication CIE 224:2017. Both indices (CIE 224:2017 R_f and IES-TM-30-18 R_f) have been harmonized. There is no difference between CIE R_f and IES TM R_f in value. In spite of that, currently only CIE R_a and CIE R_f indicators are internationally recognized for describing colour quality of light sources. Therefore, it is interesting to examine whether there is any dependency between the values of these indicators and whether or not it can be described numerically.

In this paper authors are focused to compare the CIE R_a and CIE R_f indices in assessing light colour quality of the group of well known typical fluorescent lamps.

Differences in the assessment of the colour quality of individual indicators

Most metric which were proposed for assessing the colour quality of the light source are based on the evaluation of the differences occurring in the appearance of colour test samples illuminated by reference source and lamp under evaluation [7].

In comparison with the CIE R_a method (described at CIE 13.3-1995 document) in CIE R_f calculations the number of colour samples is changed from 8 to 99. Those set of the colour samples were designed to reliably uniform the colour distribution in the colour space. This enlarged set of test samples compare to 8 CIE CRI method test colour samples has some advantages. Those samples uniformly distributed both in terms of saturation and brightness. Their spectral coefficients uniformly fill the spectral space.

To eliminating the discontinuity of scale occurring for CIE R_a calculations [3,4,5,6,7] in CIE R_f method the reference light source is changed. As the reference source for the lamps under assessment whose correlated colour temperature (CCT) is less than 4500K, in CIE R_f calculations the spectral power distribution (SPDs) of Planck's radiator (Fig. 2) is taken under consideration. For tested lamps with CCT above 5000K the SPDs of illuminant D50 is chosen as reference light source (Fig. 3).

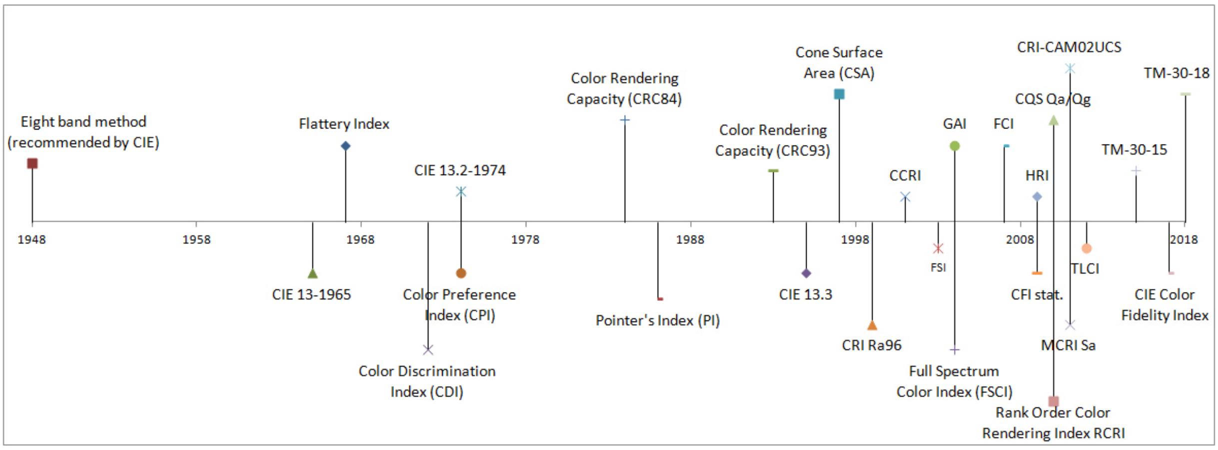

Fig. 1 The timeline of proposed metrics for light color quality assessment

In the range from 4500K to 5000K, the SPDs of light source which is a linear combination of the spectral distribution of the Planck radiator and of a daylight (Fig.2, Fig.3) has been introduced. A change in those ranges causes small differences in the R_f value – usually less than 1 for the general index and from 2.5 to 6.5 for the special indices determined for each R_f method colour sample. Despite the small differences, this is a significant change that eliminates the imperfections in the CIE R_a calculation method and allows for a reliable assessment of light sources in the full range of colour temperatures.

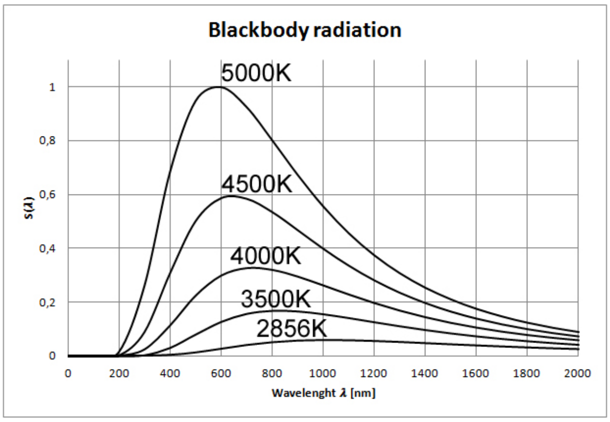

Fig. 2 Spectral power distribution of blackbody radiation

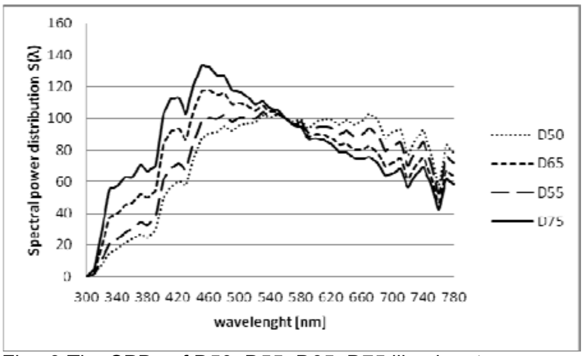

Fig. 3 The SPDs of D50, D55, D65, D75 illuminants

The calculation of the colour fidelity index R_f is made with the scaling factor (eq. 1).

(1) $$R_f' = 100 - 6,37\left(\frac{1}{99}\sum_{i=1}^{99}\Delta E_{Jab,i}\right)$$

where: $\Delta E_{Jab,i}$ – difference between the correlate of the perceived colour of a test sample illuminated by test and reference light source (CAM02UCS colour space).

In the CIE 224 R_f method the scaling factor is selected so that the values of R_f and R_a were similar for 187 SPDs of lamps (i.e 36 fluorescent lamps, 14 discharge lamps, 129 LED sources with phosphor and 9 hybrid LED sources) [2].

Comparison of the colour rendering indicates

Twelve CIE FL illuminants (fluorescent lamps) and fifteen additional illuminants shown in the CIE 2004 Colorimetry technical report, were used to calculate the CIE R_a and CIE R_f colour rendering indices [9,10,11]. This group of light sources was selected to represent the range of spectral power distributions (SPD) which are possible to be achieved in this construction. The same representation is a good choice to check what influence of changes that were introduced in the colour fidelity calculation is in comparison to the colour rendering index according to CIE 13.3-1995 [11]. The standard SPDs measurement interval was defined by the CIE and it is 5 nm, the same interval is used in the calculation of the colour quality indicates. The differences in the SPD measurements between different certificated laboratories were checked and do not showed significant influence on the value of the colour quality indicates [12].

For the first group are selected classic fluorescent light sources (fluorescent lamps) which in their power spectral distribution (SPD) have two broad bands of continuous spectrum and are characterized by a lack of radiation in the range corresponding to the red colour (Fig.4).

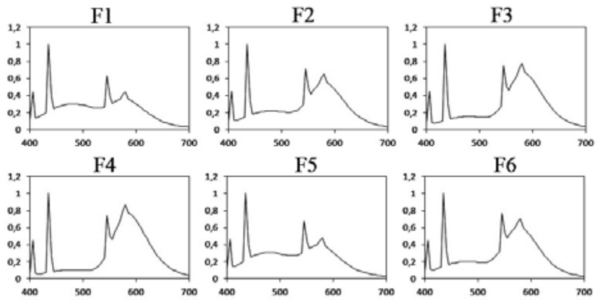

Fig. 4 The SPDs of classic fluorescent light sources defined by CIE as standard illuminant F1, F2, F3, F4, F5, F6

The second group consists of FL lamps that have been designed to obtain the highest values of R_a colour rendering index (Fig.5).

The third group includes three-band fluorescent lamps which in their spectral power distribution have three characteristic narrow bands (Fig.6). These light sources are characterized by very high efficiency and good colour rendering index R_a.

Another group (Fig. 7) are halophosphate phosphor based fluorescent lamps (second generation of fluorescent lamps). Among the sources investigated there were also Deluxe fluorescent light sources, i.e. those that offer the same colour temperature as previous designs but have better colour rendering (Fig.8).

The next group of lamps shown in Fig.9 includes the representation of three-band fluorescent lamps (FL 3.7 - FL 3.11) and fluorescent lamps with a multi-band phosphor (FL 3.12 - FL 3.14). The last source is a fluorescent light source that simulates the D65 (FL 3.15).

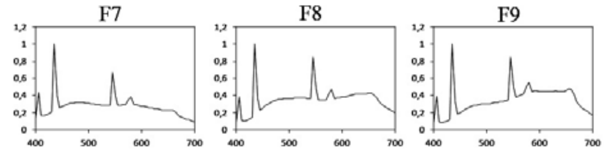

Fig. 5 The SPDs of broadband fluorescent light sources with high Ra, defined by CIE as standard illuminant F7, F8, F9

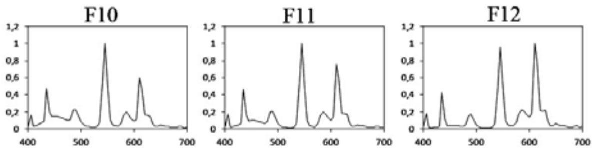

Fig. 6 The SPDs of three-band fluorescent light sources

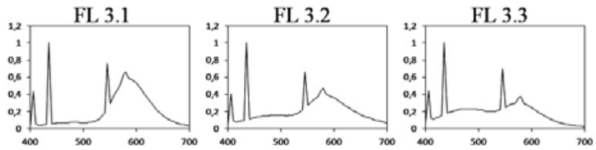

Fig. 7 The SPDs of second generation fluorescent standard illuminants FL3.1, FL3.2, FL3.3

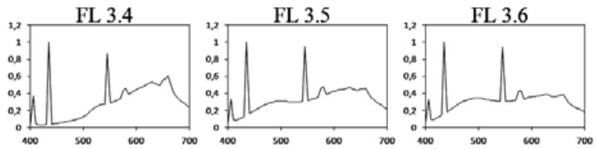

Fig. 8 The SPDs of deluxe fluorescent standard illuminants

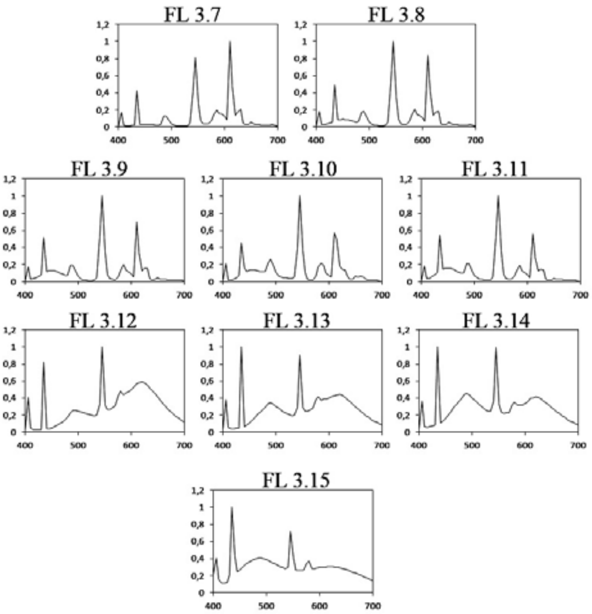

Fig. 9 The SPDs of multi-band phosphor fluorescent standard illuminants FL3.7 to FL3.15

The values of FL lamp colour quality indices CIE R_a and R_f are shown in the tables (Table 1, Table 2). The comparison of R_a and R_f values is shown on the Fig. 10.

Table 1. The CIE colour quality indices of fluorescent lamps recommended by CIE as standard illuminants F1-F12

Iluminant CIE	Parameters		
	Colour Temperature	Index CIE	
		R_a	R_f
F1	6428	76	81
F2	4224	64	71
F3	3446	57	63
F4	2938	51	57
F5	6345	72	78
F6	4148	59	67
F7	6495	90	92
F8	4997	96	96
F9	4149	90	91
F10	4998	81	80
F11	3999	83	80
F12	3000	83	78

Table 2. The CIE colour quality indices of fluorescent lamps recommended by CIE as standard illuminants FL 3.1-FL 3.15

Iluminant CIE	Parameters		
	Colour Temperature	Index CIE	
		R_a	R_f
FL 3.1	2932	51	55
FL 3.2	3965	70	74
FL 3.3	6280	72	77
FL 3.4	2904	86	80
FL 3.5	4086	96	96
FL 3.6	4894	96	97
FL 3.7	2979	81	76
FL 3.8	4006	80	79
FL 3.9	4852	80	78
FL 3.10	5000	88	86
FL 3.11	5853	78	78
FL 3.12	2984	93	91
FL 3.13	3896	96	96
FL 3.14	5044	95	94
FL 3.15	6508	98	99

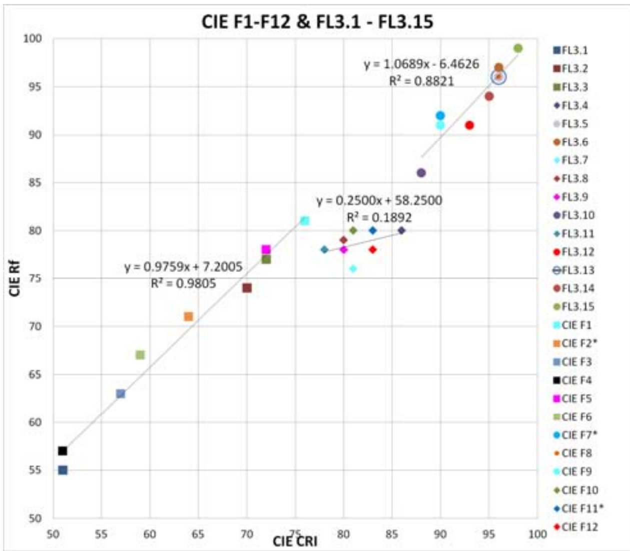

Fig. 10 The relationship between CIE R_f and CIE R_a for CIE defined standard illuminants F1 to F12 and FL3.1 to FL3.15

The results presented on Fig. 10 showed that there is strong correlation between R_a and R_f colour quality metrics (coefficient of determination R^2=0.9805) for classical fluorescent lamps (F1÷F6) and (FL3.1÷FL3.3). Those FL lamps having rich light spectrum in yellow and orange-yellow regions but poor representation of red and greens lights.

For lamps with broadband spectrum (F7÷F9), deluxe type lamps (FL3.5÷FL3.6) and multi-band fluorescent lamps (FL3.12÷FL3.15) and one three-band FL there is still some correlation between old and new lamp colour quality metrics (R^2=0.8821).

The most interesting result is for (F10÷F12), (FL3.7÷FL3.9 and FL3.11) lamps which contain the narrow spectral lines (strong orange-red lines at around 611 nm and green band around 542 nm and weaker band in blue-green region). The FL3.4 deluxe lamp also belongs to this group. For this group of lamps there is no correlation between R_a and R_f (the coefficient of determination is R^2=0.1892). Furthermore the R_f index is lower in value than R_a. This fact can be interpreted as proof of the fact that the new measure identifies the problem of high CRI and poor colour perception. For the other hand it can be interpreted as sign that there are some number of ambiguities connected with new R_f measure. Firstly the same value of the R_f index (different R_a) is assign to more than one light source. We can notice that fact on two groups of lamps – (F10, F11, FL3.4) and (FL3.11, FL3.9, F12). Similar situation occurred when we analyse the same R_a value but different R_f – there are three groups of lamps – (FL 3.8, FL 3.9), (FL3.7, F10) and (F11, F12). Based on this observation is possible to say that interpretation which index (R_a or R_f) works better can't be assess on such a small group of light sources and in the future this kind of research have to be done for large number of lamps having different SPDs . The other issue is that the difference which is possible to be perceived by the human eye in CIE R_a is 5 in value [3]. This number should not be broadened to the CIE R_f because the research about that issue hasn't been done yet.

Conclusions

The research presented in the article was aimed at presenting the possibilities of interpreting the lamp's colour quality index R_f. The data provided in this paper were used for assessing the differences which occurring when comparison of CIE R_f to CIE CRI R_a index were done. The data presented has confirmed that the CIE Colour Fidelity Index R_f compared to the CIE CRI (R_a) doesn't introduce drastic changes in index interpretation for some of the commonly used fluorescent lamps. Nevertheless for the narrow-band FL light sources, which spectral power distribution was designed only to achieve high values of the colour rendering index R_a, scored drastically different values of the colour fidelity index R_f. According to this fact is possible to say that the R_f method is smarter than R_a. This situation is good from the point of view of the average user of those indicators. It means that the new R_f index did not destroy any requirements at lighting standards which are describing lighting quality parameter when traditional light sources are applied. The other good thing is that R_f method is able to detect the creativity which was done for narrowband lamp's SPDs made to achieve only high value of R_a however in user opinion their colour quality was not high - but up to now there was lack of index which was able to describe this fact. The value of R_f index is lower than R_a for this kind of light sources. Base on this fact the user of those lamps may pay attention that this type of light source could render colours much more different than in reality. The investigation which was made in this article pointed the research area which should be taken into consideration for the broader studies of CIE 224:2017.

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