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LEDs COLOURS MIXING USING THEIR SPD AND DEVELOPING OF THE MATHEMATICAL MODEL FOR CCT CALCULATION

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ABSTRACT

Light is a condition that human beings are subjected to in nature. Light is not only a physical parameter but also an important factor, which is affecting the mental and cognitive performance of the person. For this reason, in recent years, many researchers and scientists have been working on and exploring this direction of light. The spectral structure of light in the natural environment shows a continuous change. We can define this natural environment as the spectral transformation of daylight in open air. Thus, people who remain in closed environments during the day are living under unfavourable conditions, such as constant colour temperatures and luminous flux of illumination. The studies aimed at reducing this harmful effect the most. These studies are based on the principle that all intermediate colours are obtained by blending the light in 2 different colours (usually one is very warm white and the other is very cold white) and that the intermediate colours are timed within a certain scenario and illuminated indoors to simulate the outside environment. In this study, the mixture of light sources in different colours was mathematically modelled in computer environment and the CCT in K of the mixture was calculated. It is also optimized to obtain the mixture colour with least mistakes of the mixture functions by comparing with the actual measurement results.

Keywords: light emitting diode (LED), spectral power distribution (SPD), correlated colour temperature (CCT)

1. INTRODUCTION

During the day, the relationship between our biological rhythm and the day's cycle of circulation has led to the emergence of the concept of "Biodynamic Lighting". Biodynamic illumination, which allows people to control the light towards their own desires, can be described as creating a natural lighting environment by following the rhythm of daylight. Thus, the effects of daylight on people are also utilized in working and living spaces. Variable seasons and weather conditions, the day-and-night cycle creates ever-changing light scenarios throughout the day. Therefore, in the biodynamic illumination, the lighting level, colour temperature and light colour vary, not constant. Illumination control systems, such as DALI designed for automation systems or lighting control, and control options provided by these systems can be used to create biodynamic lighting that requires varying levels of illumination or is energy-saving to take advantage of daylight.

Ceiling-recessed LED biodynamic luminaires with dimensions of 600mm×600mm×120mm was designed by LITPA to show the influence of LED biodynamic luminaires with three different lighting scenarios on human performance, Fig.1.

2. SPECTRAL POWER DISTRIBUTION (SPD)

This spectral structure of the light rays determines all the characteristics of the light. This is called spectral power distribution (SPD) and pre-

Table 1. Measuring Data of 2200 K CCT LED & 7000 K CCT LED

2200K LED Measuring Data		
WL(nm)	PL	PE(mW/nm)
360	0,0059	0,2323
361	0,0091	0,3548
362	0,0067	0,2611
363	0,0074	0,2892
364	0,0061	0,2387
365	0,0048	0,188
366	0,0054	0,2124
367	0,0043	0,1667
368	0,0023	0,0915
369	0,003	0,1175
370	0,0044	0,1712
:	:	:
820	0,0121	0,473
821	0,0113	0,4412
822	0,0119	0,4681
823	0,0111	0,4367
824	0,0107	0,4182
825	0,0111	0,4365
826	0,01	0,3916
827	0,0095	0,3706
828	0,0095	0,3732
829	0,0095	0,3731
830	0,0092	0,3624

7000K LED Measuring Data		
WL(nm)	PL	PE(mW/nm)
360	0,0034	0,2717
361	0,0048	0,3859
362	0,001	0,0774
363	0,0041	0,3302
364	0,0059	0,4741
365	0,0025	0,2034
366	0,0047	0,375
367	0,0037	0,2945
368	0,0031	0,2512
369	0,0045	0,3584
370	0,0041	0,3314
:	:	:
820	0,0017	0,136
821	0,0022	0,1753
822	0,0017	0,1338
823	0,0019	0,1505
824	0,002	0,1602
825	0,0013	0,1018
826	0,0018	0,1456
827	0,0015	0,1204
828	0,0015	0,1197
829	0,0015	0,1174
830	0,0016	0,1303

sented in Fig. 2 for worm-white and cold-white LED.

The wavelength that the human eye can perceive is usually given in the range of (380–780) nm. Spectral measuring instruments can perform a wider range of measurements. The Everfine HAAS-1200, we use in this study, can measure from 350 to 1000 nm. However, because of *V(λ)*, we used range (360–830) nm in our measurements and calculations. In the spectral chart, the vertical (y) axis is the spectral flux value at each wavelength of the wavelength range. We measure this value by the spectroradiometric device in [mW / nm].

Fig.1. The biodynamic LED luminaire

3. LABORATORY MEASUREMENTS

Our laboratory measurements consist of two steps. In the first step, we can calculate the spectral power distribution data of the radiation in two different light colours. In the second stage, it was done to find out, which currents of intermediate colours were obtained by driving both colour LEDs at different driving currents and to verify and optimize the calculations according to these measurements.

3.1. Luminaire used in Measurements

The luminaires used in the measurements are Biodynamic and are made with LEDs of both colours at 2200 K and 7000 K CCT values. In addition, the driver output currents can be programmed via the DALI interface by dimming at desired dim levels. There are 90 pieces of 2200 K LEDs and 90 pieces of 7000 K LEDs in the luminaire. LED chips are placed next to each other in order to optimize

Table 2. Meaning of Terms Used in Equation 1

λ	A series from 360 nm to 830 nm (If we take the starting value 0, a series of up to 470)
$W(\lambda)$	(mW/nm) Warm White SPD data
$C(\lambda)$	(mW/nm) Cold White SPD data
$M(\lambda)$	(mW/nm) Mixed SPD data

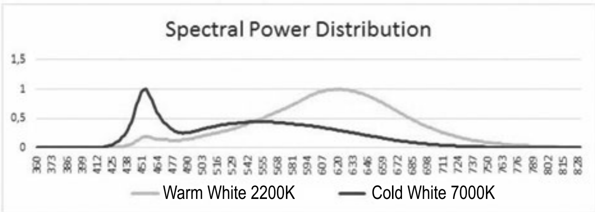

Fig. 2. LEDs Spectral Power Distribution

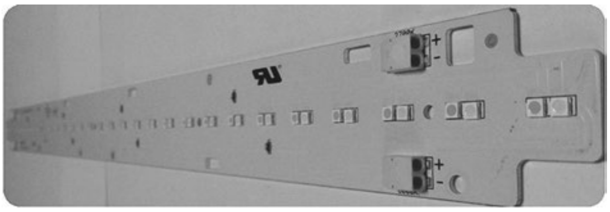

Fig.3. PCB of Biodynamic LED luminaire

the colours (Fig. 3) and a special diffuser (Fig. 4) is used in the luminaire;

90 units of 2200 K LEDs are the 1st group with its own driver. The other 90 LEDs are 7000 K and this 2nd group of LEDs is also driven by a 2nd driver. Both groups have a maximum 500 mA driving current. Output currents in the range of 0 to 500 mA are obtained by dimming via DALI protocol or completely turning OFF the drivers. Linear dimming is used as a method of dimming in operation. When 50 % dimming is done, 250 mA value of max current of 50 % will be taken as output current. Each of the 90 LED circuits in two groups consists of 6 serial 5 parallel circuit connections. Thus, when the driver is supplied with 500 mA, an LED is driven with 100 mA. The dimming ratio from 0 to 100 on the DALI means to drive the LED from 0 to 100 mA current.

3.2 Experimental Study

In two-stage measurements, the dim ratio of 2200 K LEDs in 1 step is set to 100 %, 7000 K LEDs are turned OFF and the spectral data is taken. In the same way, the dimming rate of 7000 K LEDs is adjusted to 100 % and 2200K LEDs are turned on OFF position, and the spectral data of 7000K LEDs are also taken (Table 1).

4. MATHEMATICAL MODEL OF COLOUR MIX

The spectral data are of two types and the first type is the amount of energy flux possessed per wavelength. These sizes constitute the characteristic of the light colour. The second type is the case where the energy value of the wavelength having the maximum value in the collection of these energy values is taken as 1 and the energy values of the other wavelengths are normalized by proportioning accordingly (Figs. 4–5). We can say, the normalization coefficient to the energy value of the maximum value. The normalization coefficient is a special value that is unique to the light source to which it is concerned. Each light source, each different colour and each light form has its own specific normalization coefficient. Therefore, when calculating the mixture colour, we must use the first type data and go through the actual energy values.

To calculate the colour that will result in a colour mixture result, we sum the spectral data of each of the two ranks. In other words, we create the mixture

Fig.4. Special diffuser of Biodynamic LED luminaire

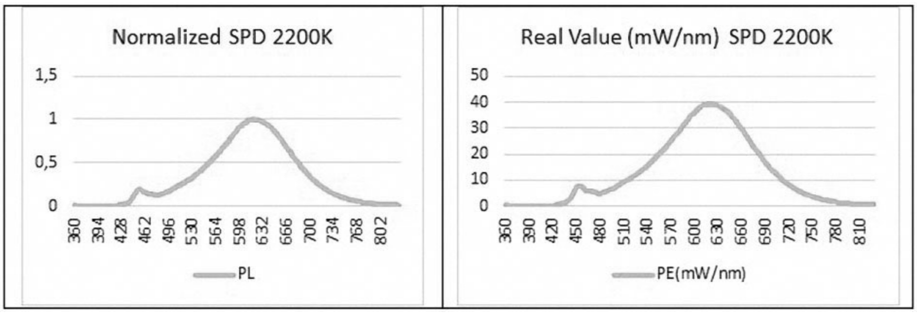

Fig.5. SPD of Light Source at CCT 2200 K

colour by summing the real luminous values of the same wavelengths (Equation 1);

$$M(\lambda)=W(\lambda)+C(\lambda). \quad (1)$$

4.1 Colour Matching Functions

To calculate the CCT values of the colours from the spectral diagram data, we need three main colour spectral value tables. These values are defined in CIE1931 as 2 ° colour equalization functions. (Colour-matching functions for CIE2° Standard Observer (1931)) [1].

Among the colours, red, green, and blue colours are generally regarded as the three main colours of light. The reason for this is that our eyes are sensitive to these three primary colours and the eye contains three types of cones (colour sensors) that are sensitive and allow colour perception. According to the 1931 Standard Observer's definition of CIE [1], Fig. 9 shows spectral sensitivity curves corresponding to the human eye. These are called colour matching functions. It has a high sensitivity in the red, green and blue wavelength regions.

4.2 Calculation of Tristimulus Values

Tristimulus values, which are determined based on colour matching functions and defined by the CIE in 1931, are also referred to as 2 ° *XYZ* tristimulus values. When evaluating the brightness of the colours relative to each other, people see the light in the green parts of the spectrum brighter than the red or blue light of equal power. For this reason, we take the *Y* value representing green light as 100 and form the *K* coefficient and the reduced tristumulus values for *X* and *Z*. [3], see also Table 3.

Calculation of the Tristimulus values using the colour matching functions for CCT 2200 K:

$$X1 = K1\times\int_{360}^{830} W(\lambda)\times\bar{X}(\lambda)\times R(\lambda)\times d\lambda. \quad (2)$$

$$Y1 = K1\times\int_{360}^{830} W(\lambda)\times\bar{Y}(\lambda)\times R(\lambda)\times d\lambda. \quad (3)$$

$$Z1 = K1\times\int_{360}^{830} W(\lambda)\times\bar{Z}(\lambda)\times R(\lambda)\times d\lambda. \quad (4)$$

$$K1 = \frac{100}{\int_{360}^{830} W(\lambda)\times\bar{Y}(\lambda)\times R(\lambda)\times d\lambda}. \quad (5)$$

Calculation of the Tristimulus values using the colour matching functions for 7000 K:

$$X2 = K2\times\int_{360}^{830} C(\lambda)\times\bar{X}(\lambda)\times R(\lambda)\times d\lambda. \quad (6)$$

$$Y2 = K2\times\int_{360}^{830} C(\lambda)\times\bar{Y}(\lambda)\times R(\lambda)\times d\lambda. \quad (7)$$

$$Z2 = K2\times\int_{360}^{830} C(\lambda)\times\bar{Z}(\lambda)\times R(\lambda)\times d\lambda. \quad (8)$$

$$K2 = \frac{100}{\int_{360}^{830} C(\lambda)\times\bar{Y}(\lambda)\times R(\lambda)\times d\lambda}. \quad (9)$$

We calculate the tristimulus values using the matching functions for the mixture colour:

$$X3 = K3\times\int_{360}^{830} M(\lambda)\times\bar{X}(\lambda)\times R(\lambda)\times d\lambda. \quad (10)$$

$$Y3 = K3\times\int_{360}^{830} M(\lambda)\times\bar{Y}(\lambda)\times R(\lambda)\times d\lambda. \quad (11)$$

Table 3. Meaning of Terms Used in Formulas

λ	Wavelength (array with increment 1 from 360nm to 830nm)
$W(\lambda)$	SPD for 2200 K
$C(\lambda)$	SPD for 7000 K
$M(\lambda)$	SPD for mixture
$\bar{X}(\lambda)$	CIE1931 standard observer colour equalization function (for Red Main Colour)
$\bar{Y}(\lambda)$	CIE1931 standard observer colour equalization function (for Green Main Colour)
$\bar{Z}(\lambda)$	CIE1931 standard observer colour equalization function (for Blue Main Colour)
$R(\lambda)$	Spectral reflectance ratio (We assume as 1)
K1,K2,K3	Reduction coefficient (Calculated based on Y = 100)
X1,Y1,Z1	Tristimulus values for 2200 K
X2,Y2,Z2	Tristimulus values for 7000 K
X3,Y3,Z3	Tristimulus values for mixture
$X1_T, Y1_T, Z1_T$	Reduced tristimulus values relative to Y1 =100 for 2200K
$X2_T, Y2_T, Z2_T$	Reduced tristimulus values relative to Y2 =100 for 7000K
$X3_T, Y3_T, Z3_T$	Reduced tristimulus values relative to Y3 =100 for Mixture
$X1_X, Y1_Y$	Tristimulus values for 2200 K
$X2_X, Y2_Y$	Tristimulus values for 7000 K
$X3_X, Y3_Y$	Tristimulus values for mixture

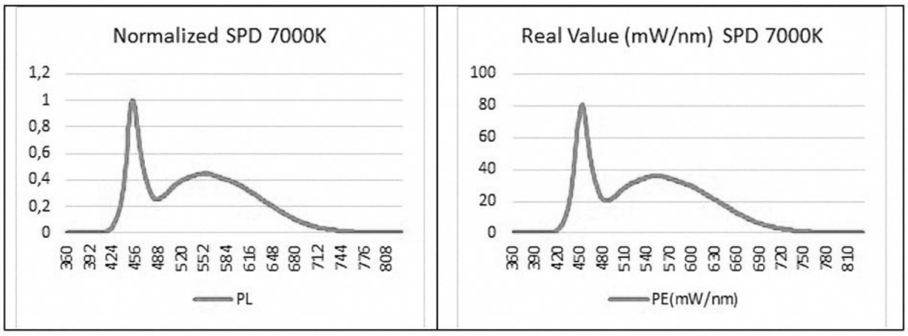

Fig. 6. SPD of Light Source at CCT 7000 K

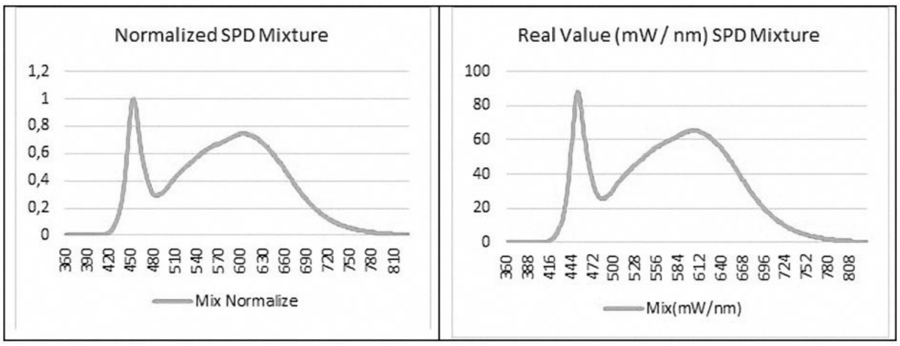

Fig.7. SPD of Mixed Light Source

$$Z3 = K3 \times \int_{360}^{830} M(\lambda) \times \bar{Z}(\lambda) \times R(\lambda) \times d\lambda. \quad (12)$$

$$K3 = \frac{100}{\int_{360}^{830} M(\lambda) \times \bar{Y}(\lambda) \times R(\lambda) \times d\lambda}. \quad (13)$$

4.3. Calculation of Chromaticity Coordinates

The chromaticity coordinates (*x, y*) are based on standard tristimulus (*XYZ*) values. These standards have been established by (CIE) [3]. From the obtained tristimulus values, we calculate the *x* and *y* coordinates of the light colour in CIE1931 colour space with the following formulas;

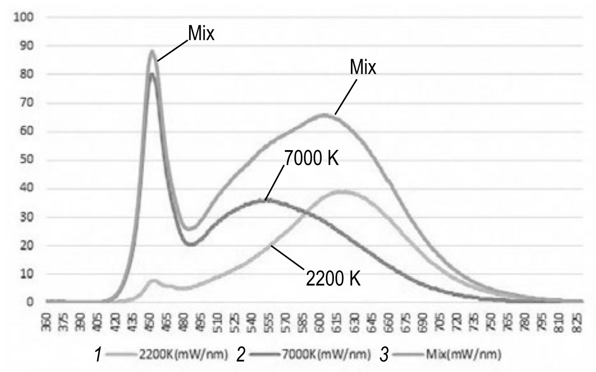

Fig.8. CCT 2200K and CCT 7000K, and their SPD data mixture

$$x = \frac{X}{\left(X + Y + Z\right)}. \quad (14)$$

$$y = \frac{Y}{\left(X + Y + Z\right)}. \quad (15)$$

4.4. Calculation of CCT

Using the McCamy formula [4], calculate the CCT values in Kelvin using the *x* and *y* coordinates:

$$N = \frac{\left(x - 0.33320\right)}{\left(0.1858 - y\right)}. \quad (16)$$

$$CCT = 449 \times N^3 + 3525 \times N^2 + \\ + 68253.3 \times N + 5520.33. \quad (17)$$

5. VERIFICATION OF MEASURED VALUES IN THE EXPERIMENT

First we calculate the tristimulus values using the spectral data, then we calculate the chromaticity coordinates, finally we calculate the CCT (Fig. 10).

We calculate the tristimulus values using the SPD data for the *W (λ)* sequence measured for 2200 K CCT with taking into account Equations 2,3,4,5.

$$X1 = \sum_{\lambda=360}^{830} \bar{X}(\lambda) W(\lambda),\ Y1 = \sum_{\lambda=360}^{830} \bar{Y}(\lambda) W(\lambda),$$

$$Z1 = \sum_{\lambda=360}^{830} \bar{Z}(\lambda) W(\lambda),$$

$$K1 = \frac{100}{Y1},$$

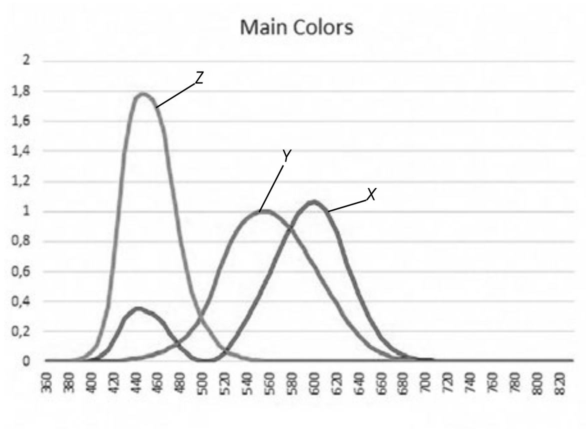

Fig.9. $\bar{X}\bar{Y}\bar{Z}$ colour matching functions

$$X1_T = K1 \times X1\ \ Y1_T = K1 \times Y1\ \ Z1_T = K1 \times Z1.$$

Chromaticity coordinates for 2200 K CCT have been calculated based on Equations 14 & 15;

$$X1_X = \frac{X1_T}{X1_T + Y1_T + Z1_T},$$

$$Y1_Y = \frac{Y1_T}{X1_T + Y1_T + Z1_T}.$$

CCT calculation for 2200 K has been performed based on Equations 16 & 17;

$$N1 = \frac{X1_X - 0.332}{0.1858 - Y1_Y}$$

$$CCT1 = 449 \times N1^3 + 3525 \times N1^2 + \\ + 6823.3 \times N1 + 5520.33.$$

$CCT1 = 2260\,K$ (The measured value by the device is 2277K, difference rate is the 0.7465 %)

We calculate the tristimulus values using the SPD data for the *C (λ)* sequence measured at 7000 K based on Equations 6,7,8,9:

$$X2 = \sum_{\lambda=360}^{830} \bar{X}(\lambda) C(\lambda),\ Y2 = \sum_{\lambda=360}^{830} \bar{Y}(\lambda) C(\lambda),$$

$$Z2 = \sum_{\lambda=360}^{830} \bar{Z}(\lambda) C(\lambda).$$

$$K2 = \frac{100}{Y2},$$

$$X2_T = K2 \times X2,\ Y2_T = K2 \times Y2,$$

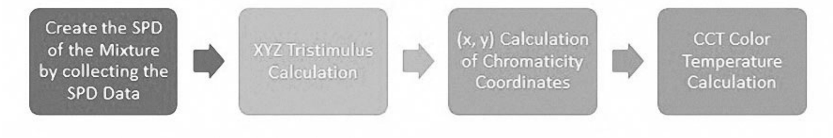

Fig. 10. Flow chart of Verification of Measured Values

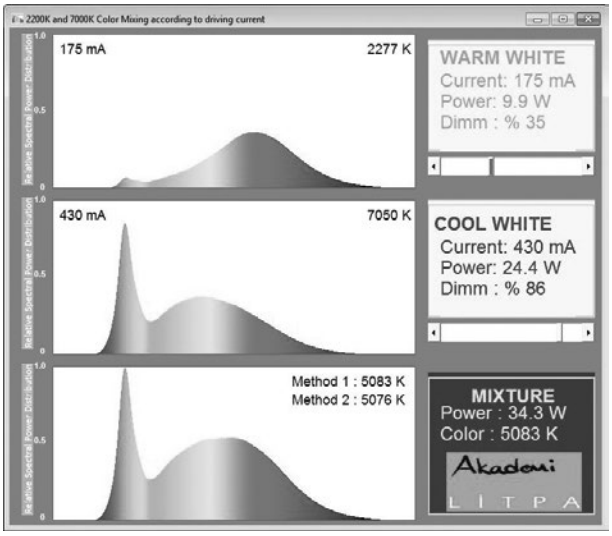

Fig.11. Screenshot of the Software

$$Z2_T = K2 \times Z2$$

Chromaticity coordinates for CCT 7000 K have been calculated based on Equations 14 & 15;

$$X2_X = \frac{X2_T}{X2_T + Y2_T + Z2_T},$$

$$Y2_Y = \frac{Y2_T}{X2_T + Y2_T + Z2_T}.$$

CCT calculation for 7000 K is based on Equations 16 & 17;

$$N2 = \frac{X2_X - 0.332}{0.1858 - Y2_Y}$$

$$CCT2 = 449 \times N2^3 + 3525 \times N2^2 + \\ + 6823.3 \times N2 + 5520.33$$

$CCT2 = 7049\,K$ (The measured value by the device is 7052K, difference rate is the 0.0425 %)

We first calculate the tristimulus values for the mixture colour using the *M (λ)* sequence (SPD Data) calculated by Equation 1 based on Equations 10,11,12,13:

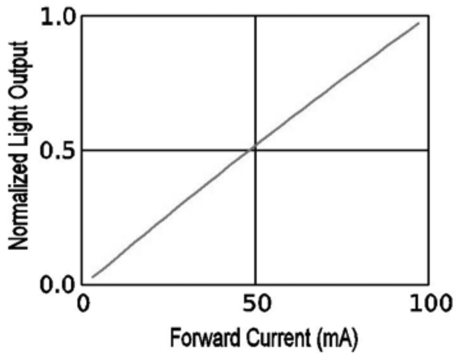

Fig. 12. Current vs. light output diagram

$$X3 = \sum_{\lambda=360}^{830} \bar{X}(\lambda) M(\lambda),\ Y3 = \sum_{\lambda=360}^{830} \bar{Y}(\lambda) M(\lambda),$$

$$Z3 = \sum_{\lambda=360}^{830} \bar{Z}(\lambda) M(\lambda).$$

$$K3 = \frac{100}{Y3}$$

$$X3_T = K3 \times X3,\ Y3_T = K3 \times Y3,$$

$$Z3_T = K3 \times Z3.$$

Chromaticity coordinates of colour mixture were calculated based on Equations 14 & 15:

$$X3_X = \frac{X3_T}{X3_T + Y3_T + Z3_T},$$

$$Y3_Y = \frac{Y3_T}{X3_T + Y3_T + Z3_T}.$$

CCT calculation for Colours Mixture were calculated based on Equations 16 & 17:

$$N3 = \frac{X3_X - 0.332}{0.1858 - Y3_Y}$$

$$CCT_{MIX} = 449 \times N3^3 + 3525 \times N3^2 + \\ + 6823.3 \times N3 + 5520.33.$$

$CCT_{MIX} = 4042\ K$ (The measured value by the measurement device is the 4033K, difference rate is the 0.0425 %)

Table 4. Comparison of Laboratory Measurement Data with Mathematical Model

Dim ratings,%		Current, mA		Measured CCT, K	Mathematical model, K	Difference rate,%	Optimized mathematical model, K	Difference rate, %
7000 K	2200 K	7000 K	2200 K					
100	0	500	0	7052	7050	-0,028	7071	0,27
100	10	500	50	6378	6356	-0,345	6356	-0,35
100	20	500	101	5839	5898	1,01	5817	-0,38
100	30	500	151	5428	5496	1,25	5411	-0,31
100	40	500	199	5112	5178	1,29	5101	-0,22
100	50	500	247	4860	4911	1,05	4849	-0,226
100	60	500	300	4624	4664	0,87	4623	-0,022
100	70	500	351	4432	4463	0,699	4433	0,023
100	80	500	402	4272	4290	0,42	4274	0,045
100	90	500	449	4149	4152	0,072	4146	-0,072
100	100	500	500	4033	4021	-0,298	4021	-0,297
90	100	448	500	3913	3891	-0,562	3898	-0,38
80	100	401	500	3798	3765	-0,87	3780	-0,47
70	100	350	500	3661	3619	-1,15	3643	-0,49
60	100	297	500	3505	3455	-1,4	3489	-0,456
50	100	252	500	3361	3305	-1,67	3347	-0,417
40	100	198	500	3164	3113	-1,61	3160	-0,126
30	100	150	500	2985	2930	-1,84	2977	-0,268
20	100	100	500	2766	2727	-1,41	2765	-0,036
10	100	52	500	2540	2518	-0,87	2541	0,0394
0	100	0	500	2277	2277	0	2270	-0,307
10	10	52	52	4062	4021	-1,01	4021	-1,01
20	20	101	101	4021	4021	0	4021	0
30	30	151	151	4021	4021	0	4021	0
40	40	199	199	4019	4021	0,0497	4021	0,05
50	50	253	253	4019	4021	0,0497	4021	0,05
60	60	298	298	4021	4021	0	4021	0
70	70	352	351	4026	4024	-0,0497	4024	-0,05
80	80	404	403	4026	4024	-0,0497	4024	-0,05
90	90	452	449	4028	4029	0,025	4013	-0,37
100	100	500	500	4033	4021	-0,297	4021	-0,298
50	100	255	500	3362	3315	-1,398	3357	-0,149
50	90	255	449	3453	3412	-1,187	3452	-0,029
50	80	256	402	3549	3522	-0,761	3557	0,225
50	70	257	351	3678	3666	-0,33	3692	0,38

Dim ratings,%		Current, mA		Measured CCT, K	Mathematical model, K	Difference rate,%	Optimized mathematical model, K	Difference rate, %
7000 K	2200 K	7000 K	2200 K					
50	60	257	298	3846	3847	0,026	3860	0,36
50	50	257	253	4021	4040	0,47	4039	0,448
50	40	257	199	4306	4338	0,74	4317	0,255
50	30	257	151	4644	4691	1,01	4653	0,19
50	20	257	101	5149	5193	0,85	5143	-0,117
50	10	257	53	5850	5880	0,51	5837	-0,22
50	0	257	0	7021	7050	0,41	7090	0,98
0	50	0	254	2274	2277	0,13	2264	-0,44
10	50	53	253	2753	2747	-0,218	2766	0,47
20	50	103	253	3137	3133	-0,127	3164	0,86
30	50	154	254	3482	3474	-0,23	3501	0,55
40	50	203	254	3754	3762	0,21	3777	0,61
50	50	257	253	4021	4040	0,47	4039	0,448
60	50	304	254	4206	4242	0,86	4230	0,57
70	50	359	254	4400	4453	1,20	4419	0,43
80	50	410	254	4561	4623	1,36	4576	0,33
90	50	458	254	4691	4765	1,58	4709	0,38
100	50	500	247	4860	4911	1,049	4849	-0,226

6. SOFTWARE THAT CALCULATES MIXTURE VALUES FOR DIFFERENT DIM RATIOS

By using these two data at hand, we calculated the colour of the mixture when mixing 100 % of both colors, using only the warm white spectral data and the cold white spectral data. So, to calculate what the mixture will be at different mixing ratios, we calculate the mixture after mixing the two SPD values of the two colours with the dim ratio in %.

Our new mixture formula is as follows:

$$M(\lambda) = Dim1 \times W(\lambda) + Dim2 \times C(\lambda). \quad (18)$$

With this software spectral data of CCT 2200 K LED and spectral data of CCT 7000 K LED are visualized, and the mixture colour is calculated by two different methods depending on the desired dim ratio. For the representation of the spectral data, the values are normalized by assuming a maximum value of 1, which is the value of the sequence, and the spectrum chart is formed in this way. The dim ratio determined by the scrolling bars of both colours enlarges the spectral ratio from 0 to 100 as a multiplier of the spectral power values at all wavelengths between 360 nm and 830 nm. This change affects the spectral data sequence with a maximum value of 1 in proportionately. The sum of the two colours is calculated based on the dim ratio and the spectral data of the mixture is displayed simultaneously. Two different calculation methods are used in this software. First method is the McCamy method, which is the calculation method we use in our article. The second method is the CIECAM02 based calculation method. This calculation method will not be examined in this article.

7. LABORATORY MEASUREMENTS AND VERIFICATION

All intermediate values can be calculated with the software. A number of laboratory measurements

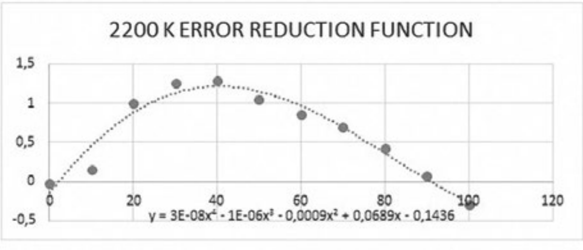

Fig. 13. Difference reduction function diagram for 2200 K CCT

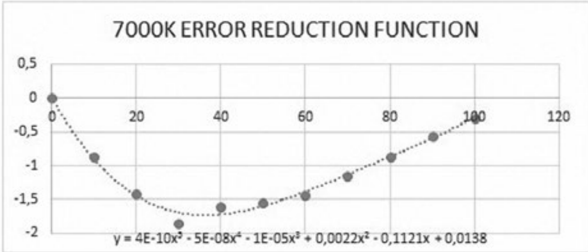

Fig. 14. Difference reduction function diagram for CCT 7000 K

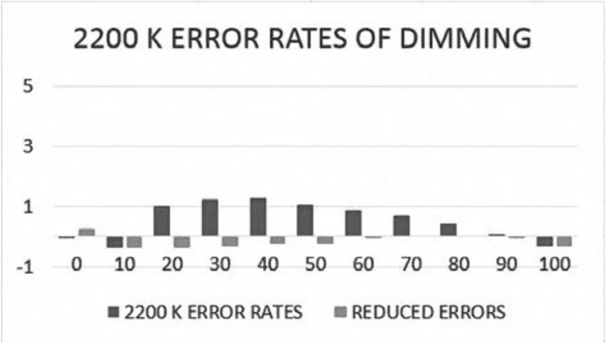

Fig. 15. CCT 2200 K difference rates in dependence of dimming

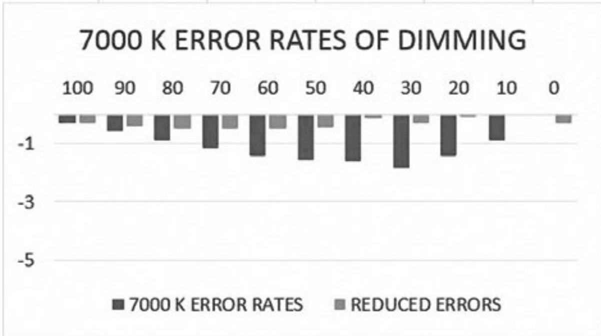

Fig.16. CCT 7000 K difference rates in dependence of dimming

are needed to verify the mathematical model. For the verification of calculations and software outputs, laboratory measurements were made at the following dim ratios and the deviation ratios were determined by comparing, Table 4.

8. IMPROVING DIFFERENCE REDUCTION FUNCTION AND RE-VERIFYING BY APPLYING TO CALCULATIONS

Calculated values show up to 1.5 % deviations. The regions where these deviations are generated are those where one of the colours is at the maximum level, while the other colour is at 30 %, 40 %, 50 %, 60 % dim levels. This is because the variation of the luminous flux of the LED is not directly proportional to the dim levels. We can see this clearly in the graph of luminous flux change according to the dim levels given in the LED datasheet.

Fig. 13 shows the difference ratios for 2200K LEDs from 0 % to 100 % for each dim level with 10 % increase when the 7000K LED is at 100 % dim. From this graph y = 3E-08x4–1E-06x3–0,0009x2 + 0,0689x – 0,1436 difference reduction function is obtained.

Fig. 14 shows the difference ratios for CCT 7000 K LEDs from 0 % to 100 % for each dim level with 10 % increase when the 2200K LED is at 100 % dim. From this graph y = 4E-10x5–5E-08x4–1E-05x3 + 0.0022x2–0.1121x + 0.0138 difference reduction function is obtained.

When we apply the curved functions of the polynomial structure of the 4th and 5th grades obtained from these graphs to the dim ratio of our mixture formula:

$$Dim1Fix = 3 \cdot 10^{-8} \cdot Dim1^4 - 10^{-6} \cdot Dim1^3 - 0.0009 \cdot Dim1^2 + 0.0689 \cdot Dim1 - 0.1436. \quad (19)$$

$$Dim2Fix = 4 \cdot 10^{-10} \cdot Dim2^5 - 5 \cdot 10^{-8} \times Dim2^4 - 10^{-5} \cdot Dim2^3 + 0.0022 \cdot Dim2^2 - 0.1121 \cdot Dim2 + 0.0138. \quad (20)$$

$$M(\lambda) = Dim1Fix \times W(\lambda) + Dim2Fix \times C(\lambda), \quad (21)$$

we get the final mixture formula.

After applying the difference reduction functions to the main formula, the differences rates have changed by decreasing as seen in the graphs (Figs. 15–16).

9. CONCLUSIONS & DISCUSSION

In order to calculate the mixture colour, it is possible to apply the side sum method of wavelengths we have used here for more than one colour. What we initially need for this is only the spectral data of the primary colours. Using the spectral data of the main colours, we can calculate the CCT of the mixture and the spectral data of the mixture colour by mixing the desired number of different colours mathematically. When we place our mixing ratios as a Dim coefficient before the spectral data of each colour in the total formula:

$$Mix(\lambda) = Dim1 \times Colour1(\lambda) + Dim2 \times \times Colour2(\lambda) + \ldots + DimN \times ColourN(\lambda), \quad (22)$$

and compare the results of the calculations from the software with the measured values again, they are significantly improved and reduced to less than ± 0.5 %, especially at the difference rate of 30 %, 40 %, 50 %, 60 % dim.

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