Quality of LED Based Daylight Simulators

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Abstract

A light source capable of simulating CIE D Illuminants was developed based on different coloured LEDs. A model was also devised to construct the spectral power distribution (SPD) of a CIE illuminant by mixing different coloured LEDs at different intensities. The performance of the LED simulators, was evaluated in terms of correlated colour temperature (CCT), colour rendering index (CRI), metamerism index (MI) and stability.

Introduction

The colour appearance of an object varies according to the composition and amount of the light reflected from its surface, which enters the observer's eyes. This is governed by two factors: the spectral reflectance of the sample and the composition and intensity of the light falling on it. However, arguably the most widely used light source, daylight, varies significantly and thus there is no light source available to simulate the daylight. These limitations have motivated a long search for a source to closely simulate CIE illuminants by means of existing sources such as tungsten lamps, xenon lamps and fluorescent lamps. More recently, a new source based on Light Emitting Diodes (LEDs) is available, which has longer life span, higher luminous efficacy, more energy saving, and more friendly environmental influence than the other sources.

A spectrally tunable light-source utilising LED technology for radiometric, photometric, and colorimetric applications was introduced by Eppeldauer *et al*[1]. It included 40 LEDs with 10 different spectral distributions which were mounted in an integrating sphere, and were controlled independently by a voltage-to-current circuit. Their results showed that the source can actually approximate the spectra power distribution (SPD) of CIE illuminants over the visible spectral ranged from 380 nm to 780 nm. The tunable LED source can also simulate spectral distributions of special sources such as discharge lamps and CRT or LCD displays..

With this in mind, a viewing cabinet was built to accommodate different coloured LEDs and to measure the SPD and luminance for each LED. A mathematical model was developed to choose a set of coloured LEDs by achieving the least spectral difference between the target illuminant and the LED simulators. The aim of this study is to investigate the number of LEDs required to provide a successful light source capable of simulating CIE D illuminants. The predicted SPD was reconstructed and measured to compare with those predicted by the model. The performance of the LED source, in terms of the correlated colour temperature (CCT), colour rendering index (CRI), metamerism index (MI) and stability, were investigated.

Experiment

Setup

Sixty different types of LEDs including eight whites were accumulated. All of the coloured LEDs were 3 mm or 5 mm discrete LEDs with the peak wavelength ranging from 370 nm to 700 nm. The eight white LEDs were InGaN plus yellow phosphor 5 mm throughhole LEDs with different colour temperatures and luminance levels. The spectral half-width for each LED varies from 15 to 50 nm with an average spectral half-width around 35 nm. A viewing cabinet including ten channels was specially built for this study as shown in Figure 1. Up to ten LEDs of the same type were placed in the same channel of the cabinet. For each LED, the radiance power was regulated by adjusting the electrical current through a control box. Moreover, an electrical fan was installed to stablise the LED's junction temperature. A diffuser was used for mixing the light emitted from LEDs, and a barium sulphate tile was used to reflect the light for colour measurement. The characteristics of LEDs were specified in terms of the CIE 1931 chromaticity coordinate (x,y), the luminance (cd/m^2) and the SPD from 400 nm to 700 nm, which were measured by a Minolta CS1000 tele-spectroradiometer (TSR). The illumination geometry of the measurement was 0/45. All measurements were conducted inside the viewing cabinet in a dark room.

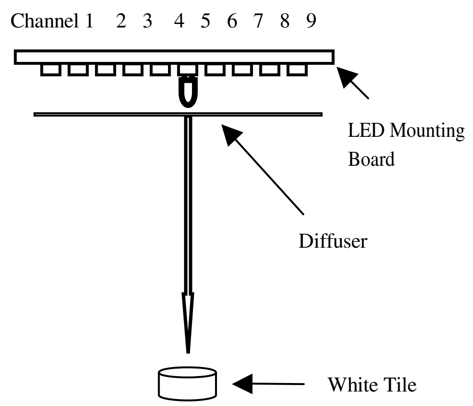

Figure 1 *Experiment setup*

Characteristics of coloured LEDs

Five minutes were taken for warming up before the measurement of each LED. The chromaticity results are plotted in CIE 1931 chromaticity diagram as shown in Figure 2. It can be seen that the colours of the LEDs covered a large scope of colour gamut. The SPDs of all LEDs are also plotted in Figure 3. For each type of LED, five different luminance levels were measured to establish the relationship between the electrical current and luminance output.

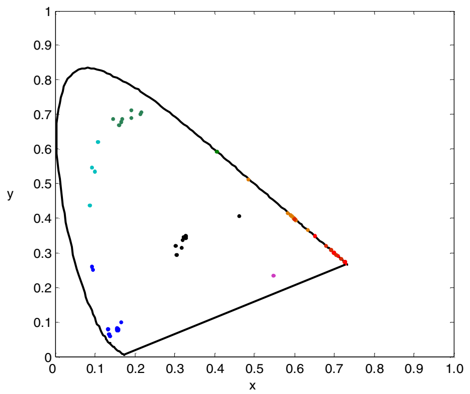

Figure 2 *the CIE 1931 chromaticity coordinates of LEDs*

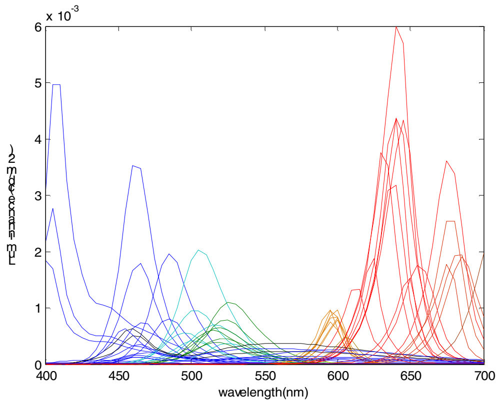

Figure 3 *SPDs of LED samples*

Mathematical model

An algorithm was developed to simulate the SPD of a CIE illuminant by various LEDs. In the optimisation, the values of coefficients k_i , $i = 1 \ldots n$ for the n LEDs were determined by achieving the smallest root-mean-square (RMS) value between the target source and the LED simulator.

$$S_{LED}(\lambda) = k_1 S_{LED1}(\lambda) + k_2 S_{LED2}(\lambda) + \ldots\ldots + k_n S_{LEDn}(\lambda) \quad (1)$$

$$RMS = \sqrt{\frac{\sum_{\lambda=400}^{700} (S_{LED}(\lambda) - S_{Target}(\lambda))^2}{N}} \quad (2)$$

The CCT,[2] CRI [2] and MI [3] values were also calculated from the predicted S_{LED} for the LED simulators to indicate the quality of the source.

The CCT is the temperature corresponds to the Planckian radiator whose perceived colour most closely resembles the colour of a stimulus of equal brightness. The recommended method for calculating the CCT of a stimulus is to determine on the u,v chromaticity diagram the temperature corresponding to the point on the locus of Planckian radiators that is nearest to the point representing the stimulus..

The CRI values can be calculated by equation 3

$$R_i = 100 - 4.6\overline{d_i} \quad (3)$$

where d_i is the distance in the CIE1964 U*V*W* space between the points representing the colour concerned when illuminated by the test source and by a CIE D illuminant closest in the CIE u,v chromaticity diagram, and $\overline{d_i}$ is the mean values of d_i .

The metamerism index can be calculated by equation 4

$$MI' = mean\ (\Delta E) \quad (4)$$

where ΔE is the average ΔE^*_{ab} of the five metameric pairs illuminated by the mixed light. In fact, the *MI* defined by the CIE should be reported in terms of grades (A-E) based on the calculated values (*MI'*)..

Different constitutions of LEDs were tried in order to achieve the CRI values over 90 and MI values in the Category A (which is under 0.25) for the LED simulator according to equation 1. Finally, eight LEDs, including seven coloured LEDs and one white LED, were selected for simulating a range of D illuminants. For different D illuminants simulator, different coefficient k_i (i=1……8) were calculated from equation 1 to compute the SPD for each simulator. The corresponding CCT, CRI and MI values were also reported.

Results and Discussion

According to the predicted results, the eight selected LEDs were placed in the viewing cabinet, controlled by different electrical current to achieve the target light source and measured by TSR. The SPDs of the real simulators were recorded and the RMS values, the CCT, CRI and MI values for each simulator were computed and listed in Tables 1 to 4.

Table1. D50 simulation results

	CCT	x	y	CRI	MI	RMS
Predict	4968	0.3463	0.3556	98.4	0.13	9.8
Measured	4977	0.3462	0.3563	98.4	0.14	10.2

Table2. D55 simulation results

	CCT	x	y	CRI	MI	RMS
Predict	5459	0.3334	0.3445	98.2	0.11	9.3
Measured	5475	0.3331	0.3452	98.2	0.14	9.8

Table3. D65 simulation results

	CCT	x	y	CRI	MI	RMS
Predict	6435	0.3145	0.3260	97.6	0.12	9.2
Measured	6401	0.3149	0.3270	97.5	0.09	9.4

Table4. D75 simulation results

	CCT	x	y	CRI	MI	RMS
Predict	7438	0.3009	0.3117	97.2	0.14	9.1
Measured	7486	0.3004	0.3111	96.3	0.18	9.6

It is obvious that there is a good agreement between the predicted and measured measures CCT, CRI and MI, i.e. within the ranges of 48, 0.9 and 0.04, respectively.

Furthermore, for each simulator, the CRI value was greater than 96 and has an MI of Category A. This means that the light source can satisfactorily simulate D illuminants.

The SPD of the measured light against the predict light and target source are plotted in Figures 4 to 7, for D50, D55, D65, D75, respectively.

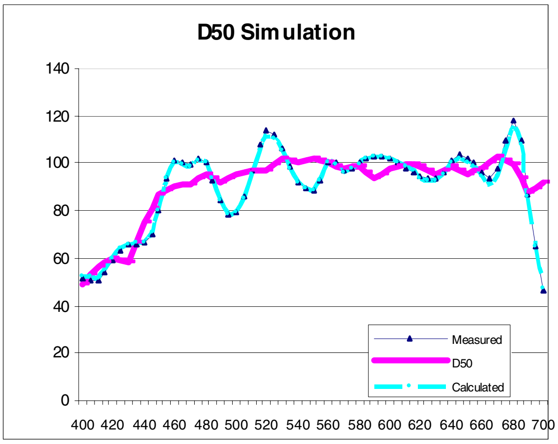

***Figure 4** D50 simulation*

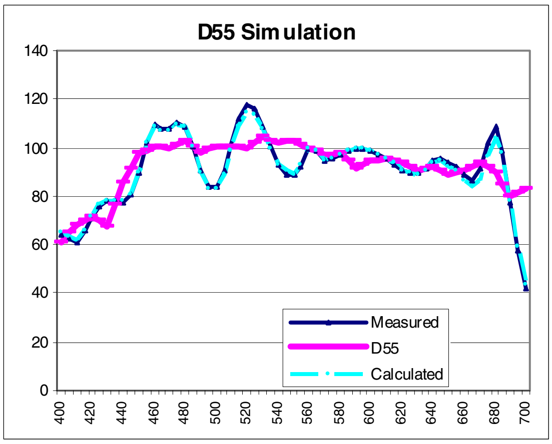

***Figure 5** D55 simulation*

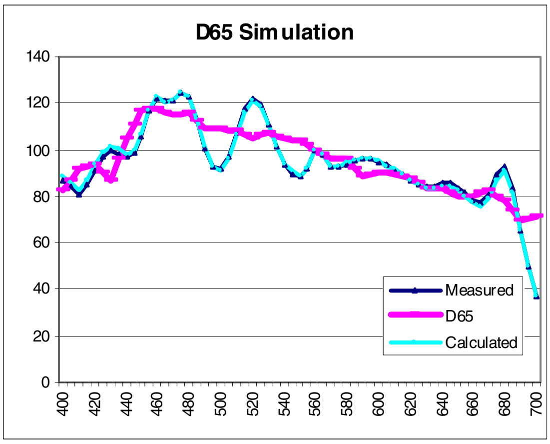

***Figure 6** D65 simulation*

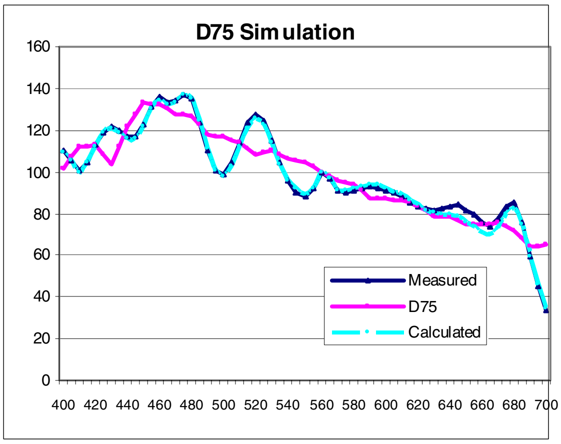

***Figure 7** D75 simulation*

Finally, the stability of the LED simulator was also investigated. The luminance output of the D65 simulator was measured by the TSR at a 2-minutes interval for 2 hours including 61 measurements, from which almost no change in the luminance measured. The CIELAB colour difference was calculated between each measurement and the first measurement. The average ΔE^*_{ab} was 0.23, which indicates a highly stable LED source..

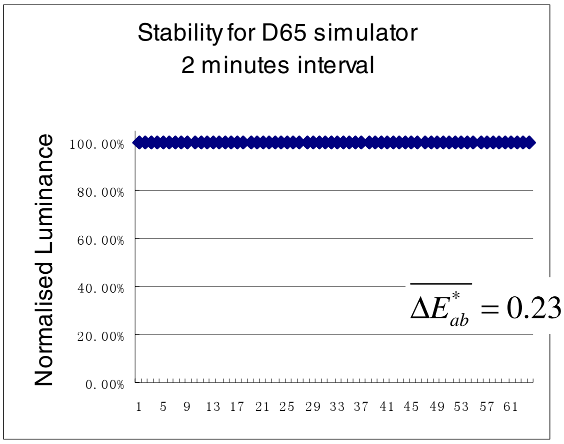

***Figure 8** Stability for D65 simulator*

Conclusion

Different combinations of LEDs were selected to approximate CIE D illuminants by minimising the RMS values between the predict light and target light source. Eight LEDs were selected and were constructed. The difference between the predicted and the measured SPD was investigated, which shows that they match almost excellently. For each simulator, the CRI values are greater than 96 and the MI are all in Category A, which means a highly satisfactory D illuminants simulator.

References

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Author Biography

Cheng Li received his B.Eng. degree in Optical Engineering from Zhejiang University (China) in 2004. He has been a PhD student at the Colour & Imaging Group at the University of Leeds (UK) since 2004. His research interests are the development of the LED light source. This work is collaborated with the VeriVide Limited, U