Luminous efficacy of white LED in the mesopic vision state

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The traditional eye sensitivity function based on photopic vision is not applicable in the mesopic vision state. The mesopic vision is studied by using the photopic and scotopic vision state sensitivity functions. And the model which links the mesopic sensitivity with the photopic and scotopic states is built. Based on the model, the luminous efficacy of mesopic vision is calculated and applied to the spectrum distribution of LED light sources. The results show that the luminous efficacy of a commercial YAG phosphor converted white LED is up to 172.7 lm/W at mesopic vision, which is 67.2% higher than that of photopic vision state. We also conclude that the optimal spectral power distribution of the LED will greatly increase the mesopic luminous efficacy.

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The human eyes have different visual responses at different ambient light conditions, where mesopic lighting condition falls between 0.001 cd/m^2 and 3 cd/m^2[1]. The outdoor lighting generally falls into the mesopic vision region[2, 3]. To date, the CIE has not formulated the photometry standard for the mesopic vision[4]. All the illumination testing instruments available in the market are based on the photometric standard $V(\lambda)$ of the photopic state, which can not accurately reflect the complexity of human eyes. Therefore, more precise luminous efficiency calculations are required to reflect the human perception of the light sources at different lighting conditions.

The LED solid state lighting is a new type of highly efficient solid light source[5-7]. In this paper, based on the mesopic vision models and the experimental data[8-11], the LED spectral luminous efficacy for the mesopic vision is calculated, and the best mesopic spectral luminous efficacy is obtained by optimizing the LED spectral distribution, which will be crucial for the effective illuminations at night.

In both photopic and scotopic luminance states, the models of spectral response are rather complete[12]. However, under mesopic lighting conditions, both the rods and cones on the retina are, and active their ratio varies with the background luminance. Therefore, the luminous efficacy also changes.

The European Union MOVE project team[8] studied the reaction time, contrast threshold and other experimental results, and proposed a mesopic luminous efficiency model related to the photopic and scotopic states functions, as shown in eq.(1).

$$M(x)V_{\text{mes}}(\lambda,x)=xV(\lambda)+(1-x)V^{'}(\lambda)\ , \qquad (1)$$

where $V_{\text{mes}}(\lambda, x)$ is the spectral luminous efficacy function at mesopic lighting conditions, $V(\lambda)$ and $V'(\lambda)$ are the spectral luminous efficacy functions in the photopic and scotopic states resp-ectively, $M(x)$ is the normalization factor to keep the maximum of $V_{\text{mes}}(\lambda, x)$ at 1.

The x parameter value, ambient brightness L_b and the light source S/P are related. The S/P is the ratio of the light effective flux at photopic and scotopic lighting conditions. Because of photoreceptors' different response characteristic in retina, the S/P reflects the ratio of rods and cones which can be stimulated by the light spectrum[13].

From the experimental data from Rea MS. and the European Union MOVE project group[107], the relations between x and S/P for various background luminances (L_b) are shown in Fig.1.

In the mesopic state, the luminous efficiency can be determined for each x as shown in Fig.2.

In Fig.2, at $x = 0$, the curve corresponds to the scotopic spectral luminance efficacy, where the sensitivity peaks at 507 nm with the maximum visual efficacy of 1700 lm/W; At $x = 1$, the curve corresponds to the photopic spectral luminance efficacy, where the sensitivity peaks at 555 nm with the maximum efficacy of 683 lm/W. For x values in the range of 0 to 1, the curve corresponds to the mesopic vision, and

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its peak sensitivity wavelength and related luminous efficacy are between that of the photopic and scotopic states.

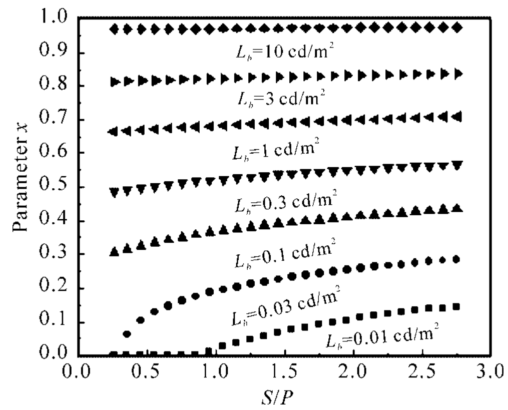

Fig.1 The *x* parameter dependence on L_b and *S/P*.

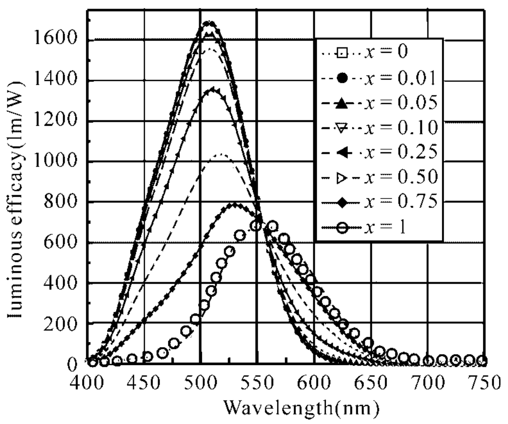

Fig.2 The luminous efficacy characterized by *x* parameter

The *S/P* value of LED can be obtained by calculating its luminous efficacies in photopic and scotopic states. The *x* parameter can be determined according to the background luminance, and further the luminous efficacy response curve $V_{mes}(\lambda, x)$ can be obtained as shown in Fig.2. Rewriting eq.(1) as eq.(2), we can express the mesopic luminous efficacy as a linear combination of photopic and scotopic state luminous efficacy.

$$k_m(x)V_{mes}(\lambda,x) = xk_pV(\lambda) + (1-x)k_sV'(\lambda) \quad , \qquad (2)$$

where $V_{mes}(\lambda, x)$ is the mesopic luminous efficacy response function, $k_m(x)$ is the maximum luminous efficacy with unit of lm/w, k_p is the maximum luminous efficacy of photopic vision, which equals to 683 lm/w, k_s is the maximum luminous efficiency of scotopic vision, which equals to 1700 lm/W. The *x* parameter characterizes the mesopic state and determines the $k_m(x)$, which is its maximum luminous efficacy.

The spectral power distribution of LED light sources $S(\lambda)$ is given, and the LED luminous efficacy of mesopic vision $L_{mes}(x)$ can be derived as follows,

$$L_{mes}(x) = k_m(x)\int S(\lambda)V_{mes}(\lambda,x)\,d\lambda \,, \qquad (3)$$

where $L_{mes}(x)$ is the LED mesopic luminous efficacy, the unit is lm/W.

The *x* parameter is the key one for the mesopic vision response function $V_{mes}(\lambda, x)$, which is determined by the source *S/P* value and the background luminance. We study three types of white LEDs, which are Cree XLamp® XR-E series with radiant flux of 350 mW at 350 mA. Light source A: The cool white, XREWHT-L1-0000-00C01, color temperature 8000 K; Light source B: The neutral white, XREWHT -L1-0000-00BE4, color temperature 4500 K; Light source C: The warm white, XREWHT-L1-0000-009E7, color temperature 3500 K. Fig.3 is the normalized spectral power distribution of these three LEDs.

From the LED spectral distributions and radiant flux, the conversion efficiency (η) of the phosphor is estimated to be 86%, 80% and 76% for A, B and C, respectively. Along with η and LED spectral power distribution, we can obtain the *S/P* value and the luminous efficacy of the photopic (L_p) and scotopic state (L_s), as follows,

$$S/P = \frac{L_S}{L_P} = \frac{\int_{400}^{750} k_s V'(\lambda)S(\lambda)\,d\lambda}{\int_{400}^{750} k_p V(\lambda)S(\lambda)\,d\lambda} \quad . \qquad (4)$$

The units of L_p and L_s are all lm/W. Based on the spectral power distribution $S(\lambda)$ and above equations, the results are shown in Tab.1.

Tab.1 The photopic and scotopic luminous efficacy for LEDs

LED type	Photopic luminous efficacy (lm/w)	Scotopic luminous efficacy (lm/w)	S/P
A (cool white)	93.3	200.5	2.01
B (natural white)	92.2	142.9	1.52
C (warm white)	84.2	112.2	1.39

From the *S/P* in Tab.1 and background luminance (L_b), the *x* parameter can be determined for each light source as shown in Fig.1. Tab.2 lists the *x* parameter for the L_b at 0.03 cd/m², 0.10 cd/m² and 0.30 cd/m².

Tab.2 The *x* parameters for white LEDs under various background luminance

LED type	x(0.03 cd/m²)	x(0.10 cd/m²)	x(0.30 cd/m²)
A (cool white)	0.259	0.415	0.560
B (natural white)	0.230	0.398	0.540
C (warm white)	0.218	0.385	0.535

The mesopic luminous efficacy response function, $V_{mes}(\lambda, x)$, is determined for a given *x* parameter. Fig.3 plots the spectral power distribution and luminous efficacy for LED (A, B, C) for L_b at 0.10 cd/m². The corresponding luminous efficacies are shown in Tab.3, where the three white LEDs' mesopic luminous efficacies are respectively 67.2%, 33.1% and 20.5% higher than that of photopic states. Under the mesopic vision, the LED luminous efficacy is higher than that of photopic vision, and the peak spectrum response shifts to the shorter wavelength. By calculating the testing light source spectral power distribution, the difference between the photopic luminous efficacy and that of mesopic vision is obvious. Since light meters and photometric devices are generally calibrated to the photopic response, direct extension of the photopic measurement and design methodology to the mesopic vision condition are not applicable.

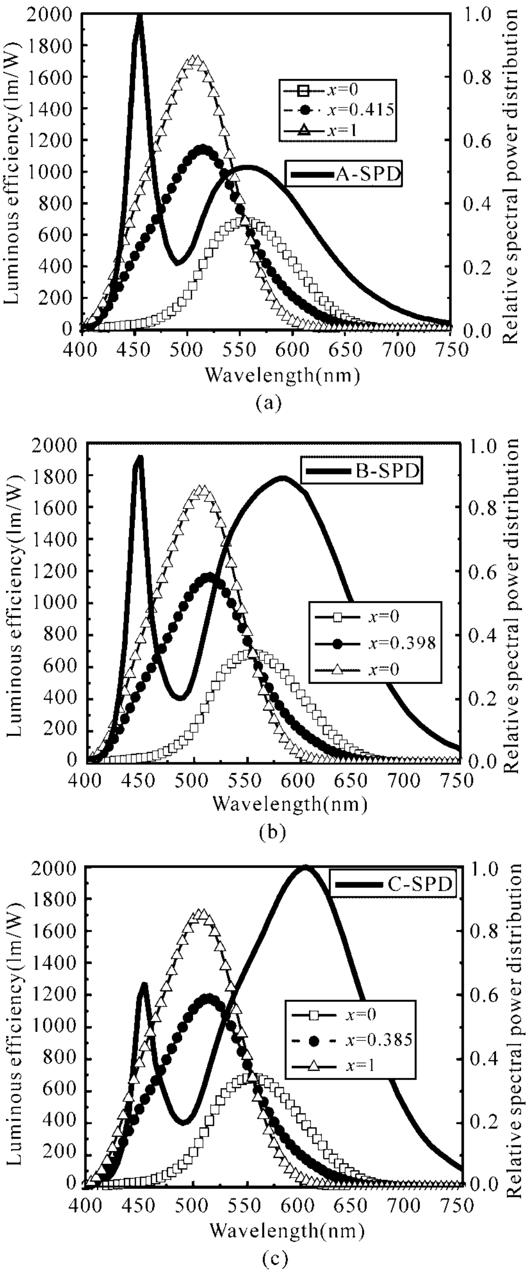

Fig.3 The spectral power distribution and the luminous efficacy for LEDs (A, B, C)

Tab.3 Luminous efficacy of LED light sources (A, B, C) in mescopic vision

LED type	background luminance (cd/m^2)	x	mesopic luminous efficacy (lm/W)	photopic luminous efficacy (lm/W)
A (cool white)		0.415	156.0	93.3
B (natural white)	0.1	0.398	122.7	92.2
C (warm white)		0.385	101.5	84.2

As seen in Tab.3, in the mesopic vision state at 0.10 cd/m^2, the luminous efficacy of a cool white LED is 53% higher than that of a warm white LED. The white LEDs here are made by converting part of the blue light (450 nm) through YAG phosphor to a broad yellow light spectrum. The cool white LED (A) may be regarded as natural white LED (B) with more blue content or less yellow spectrum conversion, while the warm white LED (C) is considered to be more yellow and red spectrum.

Since eyes are more sensitive at blue-green region in mesopic vision, we can optimize LED spectrum to get optimized luminous efficacy and color rendering index for a given illuminance. Lemnis lighting Inc. has designed their outdoor lighting products based on the *S*/*P* value for higher luminous efficacy[13].

In conclusion, in the outdoor lighting, the human eyes are in the mesopic vision state, the application of photometry system for the photopic state will fail to the actual eyes' perception. This work shows that both background luminance and spectrum distribution can affect the mesopic luminous efficacy. With certain background luminance, the optimal luminous efficacy can be realized by changing the spectral distribution of LED sources.

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