Jiří HABEL, Petr ŽÁK, Jan ZÁLEŠÁK
Czech Technical University in Prague

Determination of luminous flux in conditions of mesopic vision

***Abstract**. The article presents results of applying the newly proposed system for mesopic photometry based on visual performance in practical conditions in the area of public lighting. For a group of nine lamps with different spectral composition was made the analysis of the luminous flux changes, that occur due to the changes in the spectral sensitivity of the human eye in mesopic conditions.*

Streszczenie.** W artykule zaprezentowano praktyczne zastosowanie nowej propozycji mezopowego systemu fotometrycznego opartego na wydolności wzrokowej w warunkach oświetlenia zewnętrznego. Dla dziewięciu lamp o różnym rozkładzie spektralnym promieniowania dokonano analizy strumienia świetlnego, którego zmiany wynikają ze zmieniającej się czułości oka ludzkiego w warunkach widzenia mezopowego. **(Określanie strumienia świetlnego w warunkach widzenia mezopowego)

Keywords: mesopic vision, luminous flux, MES2-system
Słowa kluczowe: widzenie mezopowe, strumień świetlny, system MES2

Introduction

The level of sensitivity of the human vision due to radiation of different wavelengths is determined by level of adaptation luminance. Adaptation depends on the parameters of light environment, which involve indoor and outdoor applications. Transition of visual sensitivity of the human eye goes smoothly between every adaptation level, but time of various transitions can be different due to physical responses. Lower extreme of adaptation is called scotopic vision (nighttime vision) and on the other side of the range is photopic vision (daytime vision).

Photopic vision is mainly associated with the activity of photoreceptors providing color vision – cones, located mainly in the central part of the retina (macula of retina). Terms of daytime vision are the most frequently met by adaptation luminance levels from about more than 5 cd/m^2. This level is not precisely defined, because it depends on many various factors. Scotopic vision is mainly connected to activities of significantly more sensitive photoreceptor - rods, which are located especially around the macula and in the other retinal fields. Night vision correlates to adaptation levels smaller than a few thousandths of cd/m^2.

Between both mentioned types of vision (photopic and scotopic) is a region known as mesopic vision, where both photoreceptors are active in various ratios.

Due to definition of mesopic vision, which is given by cooperating of both types of photoreceptors; there are many problems and complications like in photopic photometry. Difficulty of mesopic photometry is enhanced by a combination of photopic and scotopic systems, and the corresponding luminous efficacy of radiation, which depends on the size and layout of the area of stimulus.

The first approach to solving and description of mesopic vision was based on the assumption that the mesopic vision is provided by both types of photoreceptors and therefore the effect is determined by a combination of photopic and scotopic vision (Palmer). Another method was based on influence of all photoreceptors in the human eye, which means rods and three types of cones (Kokoschka). During the nineties were founds two basic models for describing mesopic photometry. In Europe was created MOVE-system, in America it was USP-system. Both were used for design of two methods MES1 and MES2-system by the technical group TC1-58 International Commission for illumination (CIE). Based on detailed analysis the MES2-system was recommended for practical use by CIE.

Determination of the spectral luminous efficiency of the human vision for luminance in range of mesopic vision

To determine the spectral luminous efficiency of the standard photometric observer in range of mesopic vision is used MES2-system, which is described in the CIE Technical Report [1]. In MES2-system the mesopic vision is defined for luminance in the range from 0,005 cd/m^2 to 5 cd/m^2. Mesopic spectral luminous efficiency function $V_{mes}(\lambda)$ is given by equation (1), where two basic spectral luminous efficiency functions $V(\lambda)$ a $V'(\lambda)$ are represented.

$$(1)\quad \mathrm{V}_{\mathrm{mes,L}}(\lambda)=\frac{\mathrm{mV}(\lambda)+(1-\mathrm{m})\mathrm{V}'(\lambda)}{\mathrm{M}(\mathrm{m})}\qquad \text{for } 0 \le m \le 1$$

where: $M(m)$ - normalizing function such that $V_{mes,L}(\lambda)$ attains a maximum value of „1“, m - coefficient the value which depends on visual adaptation conditions: if $L_{mes,L} \ge 5$ cd/m^2, then m = 1, if $L_{mes,L} \le 0{,}005$ cd/m^2, then m = 0, $V(\lambda)$ - photopic spectral luminous efficiency function, $V'(\lambda)$ - scotopic spectral luminous efficiency function, $V_{mes,L}(\lambda)$ - mesopic spectral luminous efficiency function for particular level of luminance L.

Then subjectively perceiving luminance is calculated by equation (2):

$$(2)\qquad L_{mes}=\frac{683}{V_{mes,L}(\lambda_0)}\int V_{mes,L}(\lambda)L_{e,\lambda}(\lambda)d\lambda$$

where: $V_{mes,L}(\lambda_0)$ - value of the spectral luminous efficiency for particular level of luminance L at wavelength of λ_0 = 555 nm, $L_{e,\lambda}(\lambda)$ - is spectral radiance density (Wm^{-2}sr^{-1}nm^{-1})

Coefficient m is calculated by iterative approach [2]:

$$(3)\qquad L_{mes,n}=\frac{m_{(n-1)}L_p+\left(1-m_{(n-1)}\right)L_sV'(\lambda_0)}{m_{(n-1)}+\left(1-m_{(n-1)}\right)V'(\lambda_0)}$$

m_0 = 0,5; for λ_0 = 555 nm: $V'(\lambda_0)$ = 683 / 1699

$$(4)\qquad m_n=0{,}7670+0{,}3336\cdot log_{10}\left(L_{mes,n}\right)$$

where: L_p - photopic luminance (cdm^{-2}), L_s - scotopic luminance (cdm^{-2}) from equation:

$$(5)\qquad L_S=L_P\left(S/P\ ratio\right)$$

$$(6)\qquad \left(S/P\ ratio\right)=\frac{K'_m\int_0^\infty \Phi_{e\lambda}(\lambda)V'(\lambda)d\lambda}{K_m\int_0^\infty \Phi_{e\lambda}(\lambda)V(\lambda)d\lambda}$$

where: K_m = 683 lm/W - maximum value of the luminous efficacy of radiation for photopic vision, K'_m = 1699 lm/W - maximum value of the luminous efficacy of radiation for scotopic vision, $V(\lambda)$ - spectral luminous efficiency function for photopic vision, $V'(\lambda)$ - spectral luminous efficiency function for scotopic vision, $\Phi_{e\lambda}(\lambda)$ - spectral density of compound radiant flux $\Phi_e(\lambda)$.

If the $\Phi_e(\lambda)$ describes spectral composition of the radiant flux, then the $\Phi_{e\lambda}(\lambda)$ is calculated from equation:

$$\Phi_{e\lambda}(\lambda) = \left(\frac{d\Phi_e(\lambda)}{d\lambda}\right)_\lambda \tag{7}$$

This methodology was used for calculation spectral luminous efficiency functions of human vision in range of mesopic vision for determination $V''(\lambda)$ of particular selected values of mesopic luminance. These functions together with $V'(\lambda)$ and $V(\lambda)$ are displayed in figure 1.

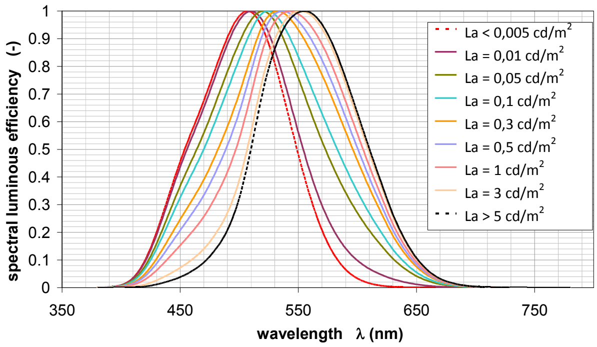

Fig. 1 Spectral luminous efficiency functions for selected luminances

In SI units the photometric quantities are derived from the luminous intensity expressed in candela. The candela is the luminous intensity, in a given direction, of source that emits monochromatic radiation of frequency $540 \cdot 10^{12}$ Hz a that has a radiant intensity in that direction 1/683 Wsr^{-1}. The value 1/683 Wsr^{-1} is important constant, which connects the physical photometry and the optical radiometry. Main consequence of luminous intensity definition is, that luminous efficacy of radiation at value 555 nm is K = 683 $lm\mathrm{W}^{-1}$. This applies for photopic K_m(555), scotopic K'_m(555) and also for mesopic vision, when any curve luminous efficacy of radiation have the same value of K''_m(555), see equation (8).

$$K(555) = K'(555) = K''(555) = 683\ lm/W \tag{8}$$

To calculate maximum value of the luminous efficacy of radiation for mesopic vision K''_m for different adaptation luminance can be used the definition of the spectral luminous efficiency:

$$V'(\lambda) = \frac{K'(\lambda)}{K'_m(\lambda)} \text{ resp. } V''(\lambda) = \frac{K''(\lambda)}{K''_m(\lambda)} \tag{9}$$

Then for K'_m, respectively K''_m and wavelength λ = 555 nm following equations can by used:

$$K'_m = \frac{683}{V'(555)} \text{ resp. } K''_m = \frac{683}{V''(555)} \tag{10}$$

The values of the spectral luminous efficiency $V'(\lambda)$, respectively $V''(\lambda)$ for wavelength λ = 555 nm determinate from the curves of spectral luminous efficiency $V'(\lambda)$, respectively $V''(\lambda)$ (see fig.1). For instance the value of K'_m, when the $V'(555)$ = 0,40176 [7] is:

$$K'_m = \frac{683}{V'(555)} = \frac{683}{0{,}40176} = 1700\ lm/W \tag{11}$$

The same procedure is valid for determination of mesopic $K''_{m,L}$. For example, for adaptation level 0,1 cd/m^2, the value of spectral luminous efficiency on wavelength λ = 555 nm is $V''(555)$ = 0,78492 and the value of maximum of luminous efficacy of radiation is:

$$K''_{m,L=0,1} = \frac{683}{V''_{L=0,1}(555)} = \frac{683}{0{,}78492} = 780\ lm/W \tag{12}$$

From values of the spectral luminous efficiency $V''(\lambda)$ and from maximum of luminous efficacy of radiation $K''_{m,L}$ it is possible to calculate the spectral distributions of luminous efficacy of radiation $K''(\lambda)$ from the following equation:

$$K''(\lambda) = K''_{m,L} V''(\lambda) \tag{13}$$

In fig.2 are shown the spectral distributions of luminous efficacy of radiation for selected adaptation luminance in the mesopic range.

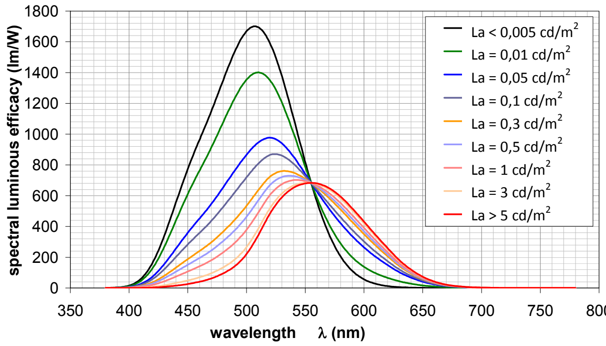

Fig. 2 Spectral luminous efficacy of radiation for selected luminances

Application of the MES2-system

Obtained curves of luminous efficacy of radiation were used for the calculation of luminous fluxes of luminaires used in public lighting in different adaptation conditions. For comparison were used one luminaire for high pressure sodium lamp (type I) and eight luminaires for LED (type A – H). Basic parameters of selected luminaires are summarized in tab. 1.

Table 1. The parameters of selected luminaires

type	lamp	P_{lu} (W)	Φ_{lu}□ (□lm)	Φ_{lu} (lm/W)	T_{cp} (K)	R_a (-)
A	LED	106	5 053	48	4 960	72
B	LED	141	6 011	43	5 100	72
C	LED	118	8 400	71	6 870	73
D	LED	110	6 417	59	6 010	69
E	LED	22	1 080	48	3 090	93
F	LED	130	6 716	52	3 900	81
G	LED	47	3 206	68	7 480	80
H	LED	204	12 300	60	5 690	69
I	HST	150	12 000	80	2 000	20

For each luminaire was measured the curve of the radiant flux spectral distribution in step of 1 nm. From the measured data the values of correlated colour temperature (T_{cp}) and the CIE 1974 general colour rendering index (R_a) were calculated.

From curves of luminous efficacy of radiation for given mesopic luminance and curves of the radiant flux spectral distribution were calculated luminous fluxes for each luminaire (see table 2 and 3).

From the obtained luminous fluxes for all luminaires and for selected adaptation luminances (see tab.2) were calculated the relative luminous fluxes Φ_L''/Φ which allow mutual comparison between luminaires. The results are shown in figure 3.

Table 2 Luminous flux of selected luminaires for luminance from mesopic to scotopic vision

type	vision					
	photopic	mesopic				
	Φ (lm)	$\Phi''_{L=3.0}$ (lm)	$\Phi''_{L=2.0}$ (lm)	$\Phi''_{L=1.0}$ (lm)	$\Phi''_{L=0.5}$ (lm)	$\Phi''_{L=0.3}$ (lm)
A	5 053	5 171	5 272	5 465	5 687	5 873
B	6 011	6 156	6 280	6 517	6 789	7 018
C	8 400	8 669	8 902	9 343	9 850	10 276
D	6 417	6 600	6 757	7 057	7 401	7 690
E	1 080	1 095	1 107	1 131	1 158	1 181
F	6 716	6 838	6 944	7 144	7 374	7 567
G	3 206	3 332	3 441	3 647	3 884	4 083
H	12 300	12 612	12 881	13 392	13 980	14 472
I	8 075	7 943	7 829	7 612	7 363	7 154

Table 3 Luminous flux of selected luminaries for luminance from mesopic to scotopic vision

type	vision				
	mesopic				scotopic
	$\Phi''_{L=0.1}$ (lm)	$\Phi''_{L=0.05}$ (lm)	$\Phi''_{L=0.03}$ (lm)	$\Phi''_{L=0.01}$ (lm)	Φ' (lm)
A	6 357	6 741	7 078	8 019	8 846
B	7 612	8 084	8 497	9 652	10 669
C	11 384	12 263	13 032	15 186	17 076
D	8 441	9 038	9 559	11 020	12 303
E	1 241	1 288	1 330	1 446	1 548
F	8 069	8 468	8 816	9 793	10 652
G	4 600	5 011	5 371	6 377	7 260
H	15 755	16 773	17 664	20 158	22 347
I	6 611	6 179	5 802	4 745	3 825

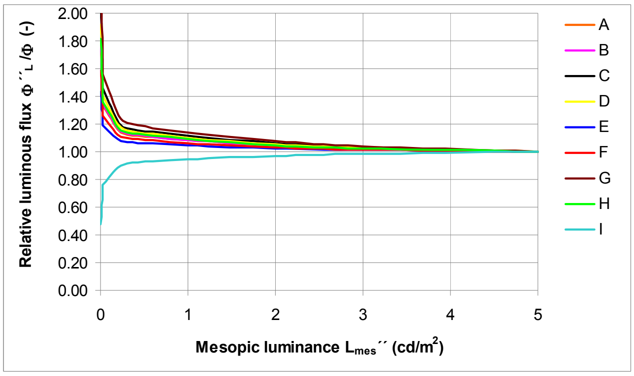

Fig. 3 The dependence of the relative luminous flux of selected luminaires to the mesopic luminance

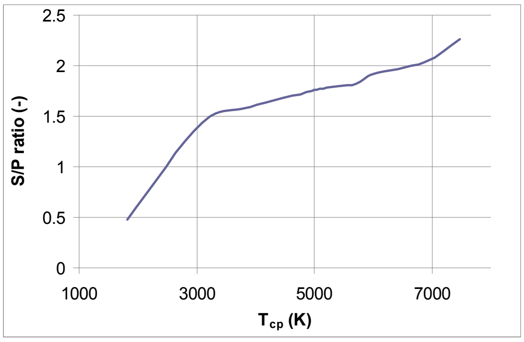

Fig. 4 The dependence of S/P ratio of selected luminaires on correlated colour temperature T_{cp}

From final values of luminous flux for photopic and scotopic vision were calculated S/P ratios. In figure 4 is shown, for selected luminaires, the dependence of S/P ratio on the correlated colour temperature.

Conclusions

Using the new system of mesopic photometry based on visual performance MES2-system were determined luminous fluxes of selected luminaires in terms of mesopic vision. Results of analyzes confirmed the assumption that the luminous flux in mesopic region related to the spectral composition of light, that can be simply expressed by correlated colour temperature. The adaptation luminance decrease, in case of light sources with a low correlate colour temperature, can lead to a decrease of luminous flux (low portion of the radiation in the blue region), while in case of light sources with a high correlated colour temperature (large proportion of the radiation in the blue region), can lead to a increase of luminous flux.

Results of existing studies show that consideration of mesopic photometry in practice may probably influence the quality of visual perception, visual performance, driver reaction time and energy performance requirements of outdoor lighting systems. After analysis of the changes of luminous flux of different types light sources in conditions of mesopic vision will further investigations and research aims on the issues more detailed analysis of adaptation field of human eye, because it is a critical problem for practical application of the mesopic photometry in the lighting design, particularly in the street lighting.

REFERENCES

[1] CIE 191-2010 Recomended system for mesopic photometry based on visual performance (2010), p.73

[2] Goodman T., Photometric Measurement using the CIE System for Mesopic Photometry, *CIE Introductory Tutorial on Mesopic Photometry* (2012)

[3] Habel J., Zrak a vidění (1. část). *Magazine Světlo*, (2008), No. 5, 53-55

[4] Habel J., et al. Světelná technika a osvětlování, *FCC Public*, Praha (1995), 437p

[5] Habel J., Žák P., Význam mezopického vidění pro praxi. *Magazine Světlo* (2007), No.6, 52-54

[6] Halonen L., Puolaka M.; CIE System for Mesopic Photometry, *CIE Introductory Tutorial & workshop on Mesopic Photometry*; (2012)

[7] ISO 23539:2005(E)/CIE S010/E:2004 Photometry – The CIE System of Physical Photometry (2004)

***Authors**: prof. Ing. Jiří Habel, DrCs., email: habel@fel.cvut.cz, Ing. Petr Žák, Ph.D., email: zakpetr@fel.cvut.cz, Ing. Jan Zálešák, email: zalesja1@fel.cvut.cz, Czech Technical University in Prague, Faculty of Electrical Engineering, Technická 2, 160 00, Prague*