Luminous Characteristics of Diffusors

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1. Introduction

Optical parts of luminaires serve for spatial distribution of luminous flux of lamps and according to target application of luminaires are tailored for a concrete function. Optical parts, in general, can be either reflectors or diffusors, in minority applications, also lenses and filters. This paper deals with theory and calculation of diffusors, in particular.

Diffusors are widely used for variety of application in domestics, administrative buildings, industry etc. The shape of diffusor, quality of its surface and construction as a whole strongly depends on the assumed light source and taking into account that diffusors are divided into two main groups – with reflective and transparent optics. From this very rich range of diffusors this paper deals with a chosen type – reflective diffusor for incandescent bulbs. Such luminaires are used in industry for special applications where colour rendering is highly emphasized as nothing compares to incandescent lamps (Ra = 100). Another apllication area covers e.g. desktop luminiares for workplaces which, in fact, have been recently overrided by modern luminaires for low-voltage halogen lamps or flat CFLs.

Calculation of diffusors concentrates on approximate estimation of its efficiency and the shape of LIDC. LIDC in that case must be of cosine type, but taking into account requirements to shading angle, the curve can be angulary limited to a narrow type. Methodology for calculation of such diffusors was well ellaborated in past works (summarized e.g. in [6]) but computeral tools of that time did not allow to perform adequate calculations. Though, many characteristics of studied types of diffusors have been analyzed well. Now, using recent computeral tools it is possible to assembly smart and precise applications both for commercial design of diffusors and for experimental detailed analyses of their optical properties. Aiming to the mentioned tasks, application under the environment of well-known familiar MS Excel and utilizing the VBA (Visual Basic for Applications) development tools has been under preparation. Application is named DCA (DiffCalc class A) and its pair of enhanced options DCEL (DiffCalc class Experimental Lounge). Module 1 contains now the mentioned first type of diffusor – i.e. reflective diffusor for incandescent lamp.

Calculation of diffusors is based on generally valid phundamental formulas for lighting technology, though, slightly modified for the case of actually studied type of diffusor and taking into account conditions and requirements laid down by designer. Calculation of reflective diffusor for incandescent lamp is clearly explained in chapter 3 of this paper. Formulas for different types of diffusors are of similar form.

2. Goals of the Research

Formulas for the design and calculation of different types of diffusors are derived in the past and these are by years well experienced in practice. However, not every properties of such diffusors are analyzed in details until now. Scientific goals are aimed to more detailed study of diffusors as well as improvement of their parameters and can be listed in following points:

- acquirement of graphic interpretation of several parameters linked to studied type of diffusor
- acquirement of dependances between certain parameters that influence to the efficiency of the luminaire (e.g. efficiency vs reflectivity, shape of the forming curve, shading angle etc.)
- mutual relation of the LIDC and the efficiency
- optimization of the diffusor according to required LIDC and maximum efficiency

It is clear that solution of stated tasks requires a compilation of sophisticated computeral application that will make it possible to obtain such complicated graphs. As it follows from the methodology (see chapter 3), calculation is represented by a series of procedures that must be performed in a specific order, including also cycles and if-then decision processes. For tabular calculations and graphic interpretation, an ideal tool seems to be with no doubt MS Excel extended with program developing language Visual Basic (VBA) to realize namely for-next and if-then cycles and branching.

This paper aims to bring to the public particular results from the recently developing application DCA, i.e. particular results from the goals-in-points above.

3. Methodology

Rotary symmetric reflective diffusor for incendascent lamp is defined by a set of parameters that will significantly influence to resulting properties. Some of inputs are of limiting nature - e.g. technology angle where the cap holding the lamp is placed and this angular range cannot contribute to overall efficiency but the luminous flux will be lost here. Some of inputs are evaluated on the desire of designer who choose e.g. a proper shading angle depending on application of the luminaire. The rest of input parameters help to define the forming curve of the reflecting diffusor but is clear that efficiency nor LIDC will much depend on the exact shape rather on depth of diffusor's body. For convenience, conesections are commonly used for the role of diffusor's forming curve, i.e. ellipse (or circle as a special case of ellipse) for its relative „compactness“ to the lamp, parabola for its neutrality according to the lamp measures and good collimating properties (valuable only for reflectors with less diffuse surface), hyperbolas are in this case not so much applicable.

Forming curve based on a conesection is defined by excentricity ε (equal to 1 for parabola, less than 1 for ellipse and more than 1 for hyperbola), inclination angle μ and parameter **p** (overall size of the diffusor). Every point of the forming curve can be fully described by a pair of polar coordinates (r,φ) where **r** is the length of vector with its origin placed to the origin **O** (0,0) and under the angle φ aiming to this point. Then the equation that describes the forming curve can be written in the following form:

$$r_D = \frac{p}{1 + \varepsilon \cos(\varphi - \mu)} \tag{1}$$

Inputs can be either p, ε, μ or some more meaningful dimensions D, H, δ. When e.g. D is stated as known, because it aims to the rim point of diffusor through which the curve must necessarily run, the overall size of diffusor through the p parameter can be calculated combining Eq. 1 with the relation between D and the shading angle δ; this equation follows from a simple geometry depicted on Fig. 1.

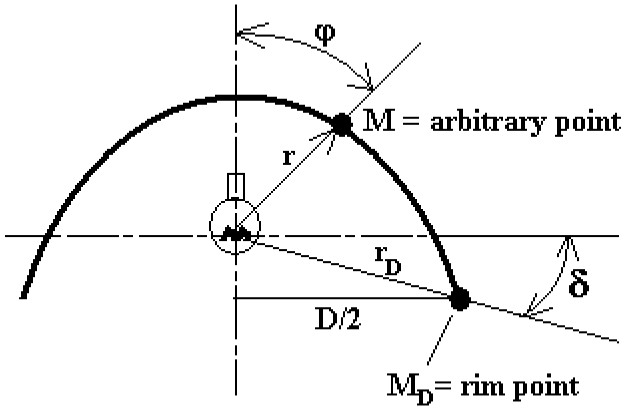


Fig.1 Geometry of a diffusor for incandescent lamp

$$r_D = \frac{D}{2\cos\delta} \tag{2}$$

Here in Eq. 1 must be substituted $\varphi = 90° + \delta$ what is, of course, valid for the investigated rim point of the diffusor.

Efficiency of luminaire can be expressed under the assumption that reflectivity of the diffusor is constant across its surface and flux losses throughout the bulb of the lamp can be neglected. So the overall luminous flux of the lamp is divided into three regions – the one enlabeled Φ_0 is passing directly out of the luminaire throughout the bottom output aperture without any affection to its spatial distribution (in terms of LIDC), another part enlabeled Φ_D reaches first the diffusor's surface and a small part of luminous flux is irreversibly lost on the technology angle. Both Φ_0 and Φ_D can be expressed as portions of original luminous flux of the lamp Φ_Z

$$\Phi_0 = m_1 \Phi_Z \tag{3}$$

$$\Phi_D = m_2 \Phi_Z \tag{4}$$

For further analyzes we can take m_1 and m_2 as abstract portions ($m_1 + m_2 \leq 1$) of the Φ_Z but for practical calculations is convenient to determine both fluxes Φ_0 and Φ_D directly from LIDC of the lamp. Of course, this must be recalculated for a given luminius flux of the lamp Φ_Z because LIDC is (almost) always given relatively to a 1 000 lm source. Then this LIDC is divided into certain number of zones (bordered by angles α_1 and α_2) and each zone gives a zonal luminous flux

$$\Delta\Phi = 2\pi I_\alpha (\cos\alpha_1 - \cos\alpha_2) = 4\pi I_\alpha \sin\alpha_{av} \sin\frac{\Delta\alpha}{2} \tag{5}$$

where $\alpha_{av} = \frac{\alpha_1 + \alpha_2}{2}$ and $\Delta\alpha = \alpha_2 - \alpha_1$.

For the usual 10° step following equation will be valid:

$$\Delta\Phi = 1{,}095 I_\alpha \sin\alpha_{av} \tag{6}$$

Corresponding components of luminous flux can be obtained over summarizations of the Eq. 6 through rim angles of the diffusor starting from technology (neck) angle to 90° + δ for Φ_D and continuing up to 180° for Φ_0. It is important to note that angles α from the lamp's LIDC are read from the bottom (nadir) when angles φ are read from the top (zenith).

After incidence of Φ_D to diffusor's surface this is scattered – part of it is aimed out of luminaire throu the bottom aperture and the other part is passed again to diffusor where this way a multireflection happens. Luminous flux incident to the diffusor after multireflections can be expressed in a form of unlimited geometric series

$$\Phi_D^\infty = \Phi_D + \rho_D \Phi_D (1-u) + \rho_D^2 \Phi_D (1-u)^2 + \ldots \tag{7}$$

where **u** is utilization factor given by formula

$$u = \frac{A_0}{A_D} \tag{8}$$

where A_0 – area of the bottom output aperture of the luminaire

A_D – area of the diffusor's surface.

Area of bottom aperture can be obtained from a known equation $A_0 = \frac{\pi D^2}{4}$

but calculation of area of rotary symmetric body formed by ellipse (ellipsoide) is more complicated. We can use Simpson's formula for this task, when diffusor is again divided into zonal regions, then particular areas of those zones can be calculated as follows:

$$\Delta A_D = \frac{\pi\Delta\varphi}{3}\left(\frac{r_{i-1}^2 \sin\varphi_{i-1}}{\cos\frac{\varphi_{i-1}-\alpha_{i-1}}{2}} + 4\frac{r_{str}^2 \sin\varphi_{str}}{\cos\frac{\varphi_{str}-\alpha_{str}}{2}} + \frac{r_i^2 \sin\varphi_i}{\cos\frac{\varphi_i-\alpha_i}{2}} \right) \tag{9}$$

Here the angle α (with general index) stands for a ray angle after reflection that depends on the ray angle before reflection φ as this is usual for calculation of reflectors. We can again take a step Δφ = 10°, i.e. approximately 0,1745 rad. Angle of the ray after reflection can be calculated from the resulting formula of the solution of the differential equation of reflection valid for conesections

$$\alpha = \varphi - 2arctg\,\frac{\varepsilon\sin(\varphi-\mu)}{1+\varepsilon\cos(\varphi-\mu)} \tag{10}$$

Area of the diffusor can be then obtained over summarization of Eq. 10 similarly as it was for Eq. 6, now in the range of angles from neck angle to 90° + δ.

Luminous flux which is finally passing out of the luminaire after multireflections can be calculated as follows:

$$\rho_D u \Phi_D^{\infty} = \rho_D u \kappa \Phi_D = \rho_D u \kappa m_2 \Phi_Z \tag{11}$$

where κ stands for coefficient of multireflections and can be defined as

$$\kappa = \frac{\Phi_D^{\infty}}{\Phi_D} = \frac{1}{1-\rho_D(1-u)} \tag{12}$$

Total luminous flux passing out of luminaire is then

$$\Phi_S = m_1 \Phi_Z + \rho_D u \kappa m_2 \Phi_Z \tag{13}$$

and relating to the luminous flux of the source we obtain the resulting formula for efficiency of the luminaire

$$\boxed{\eta = m_1 + \rho_D u \kappa m_2} \tag{14}$$

Luminous intensity distribution curve (LIDC) for a reflective diffusor for incandescent source can be derived under assumption that luminance of diffusor's surface is in all directions equal so this surface can be substituted by an area of luminaire's bottom aperture with uniform luminance. For that specified case it is obvious to define the total average luminance of diffusor

$$L_{av} = \frac{\kappa \rho_D \Phi_D}{\pi A_D} \tag{15}$$

and the final epression for luminous intensity will consist of two parts – first component stands for direct contribution from the light source via aperture and second component takes the contribution reflected from diffusor (after multireflections represented by κ)

$$I_{S\alpha} = I_{Z\alpha} k_{\alpha} + L_{av} A_0 \cos\alpha \tag{16}$$

where k_{α} is a Heaviside type function equal to 1 in the range from $\alpha = 0$ (note that this angle is read from nadir) to $\alpha = 90 - \delta$ and it is equal to 0 for the rest of angles. Meaning of this function is that the light source contributes directly to investigated direction α only if it is not shaded by diffusor's body.

4. Results and Discussion

Methodology presented in chapter 3 has been implemented in the environment of MS Excel utilizing VBA programming technologies. Research was on the very first stage concentrated on analyzes of inputs and outputs and what is crucially important to reach the maximum efficiency hand-in-hand with acquisition of desired LIDC. It is clear that the more deep will diffusor be the more narrow is the LIDC but less is the efficiency. And vice versa, shallow diffusor will minimally influence to modification of source's original LIDC though the efficiency will be highest.

Having a look at inputs and outputs one may wonder why so much input parameters are needed. There must necessarily exist ways for optimization of the calculation process minimizing some of inputs to „boundary" parameters. What exactly impacts to resulting efficiency and LIDC of luminaire and how?

a) LIDC of the lamp: through spatial distribution of its luminous flux; the more it is directed downwards the less it influences to LIDC and efficiency decrease. This input is given by the lamp used and as the diffusor is designed for a concrete given lamp, this input parameter cannot be changed.

b) Technology „neck" angle: is given by geometry of the lamp used as well as socket-cap connections in the luminaire. This parameter cannot be modified as well but in most of cases this can be neglected because shading of flux of the filament by cap of the bulb is implicitly involved in lamp's LIDC.

c) Shading angle δ: can be chosen by designer on the basis of its desire to supress the outgoing flux into some angular range. Shading angle can be derived from desired LIDC of the luminaire. Shading angle directly defines the m_1/m_2 portion from Eq. 3, Eq. 4 or Eq. 14, respectively.

d) Forming curve: is defined by a set of parameters – the relative size p, excentricity ε and inclination angle μ. Shape of forming curve itself is not expected to significantly affect to resulting LIDC but depth of diffusor hand-in-hand its closeness to the bulb undoubtly will affect. Having a closer look at parameters of the forming curve, there is no reason to choose inclination angle μ other than 0. Excentricity ε defines the shape of diffusor, ellipse with small excentricity close to 1 (e.g. down to 0,8) and/or parabola may match requirements at the best. Relative size parameter p defines the overall size of diffusor and has no affect to its shape. Taking into account basic photometric conventions altogther with requirements to minimize the size of diffusor's body (material savings, space savings) with adequate inner space for heat rejection, this parameter is not expected to exceed 5.

e) Reflectivity ρ: should be as close to 1 as possible taking into account technology and financial limitations.

What concerns the outputs, efficiency of the luminaire should be as high as possible and LIDC should be of cosine type limited angularly by shading.

From Eq. 14 indirectly follows that for m_1/m_2 portions is responsible the shading angle which depends on desired LIDC of the designed luminaire. Thus, the main way how to increase the efficiency lies in maximization of the expression ρ.u.κ when reflectivity is desired to be high. Combinig this expression with Eq. 12 gives another expression with more clear relations:

$$\frac{\rho u}{1-\rho(1-u)} \tag{17}$$

where only **u** acts as a quantity which can be a matter of consideration taking into account its definition according to Eq. 8. It can be shown via analytical tools of mathematics that also **u** is desired to be as high as possible. But closer look at Ex. 17 shows that variables **u** and **κ** are always in conjunction, moreover, one of them (no matter which one) is always less than 1 and the other must be then more than 1 so they elliminate each other. These must be therefore taken altogether. Graphs ackquired from the DCA application show their dependance (u vs ρ.u.κ) and is depicted on Fig. 2 for different regions of the utility factor **u**.

Three modes can be recognized as:

$u < 1$	$A_0 < A_D$
$u = 1$	$A_0 = A_D$
$u > 1$	$A_0 > A_D$

But for $\delta > 0$ there will always be $A_0 < A_D$ and the limitation is following:

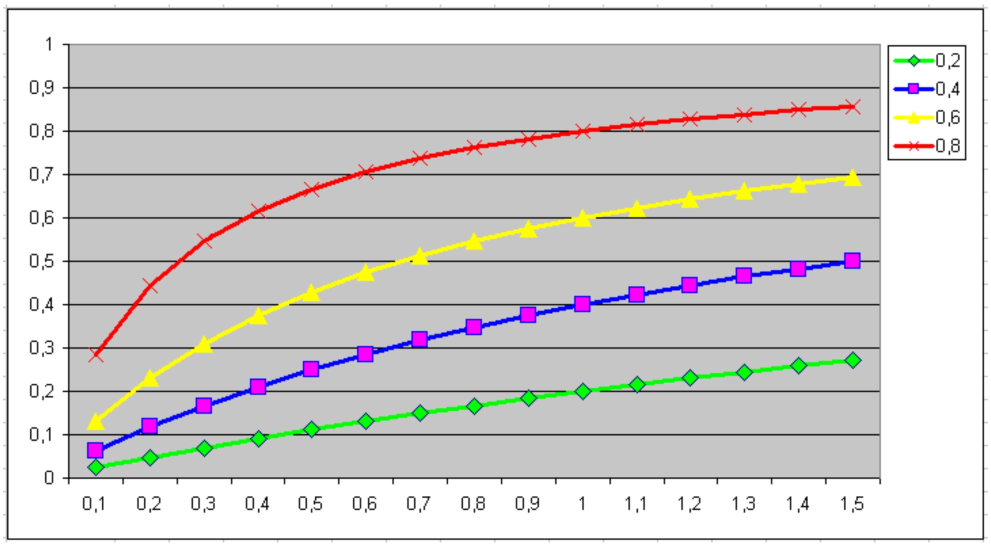
$u.\kappa < 1$

Difference between the expression **u.κ** and **ρ.u.κ** is only in a liner shift of curves downwards. Graphs show very important consequences that point to the nature of diffusors and the result is that due to multireflections the efficiency is mainly limited by reflectivity and diffusors depth because area of the diffusor grows with it in comparison to output area.

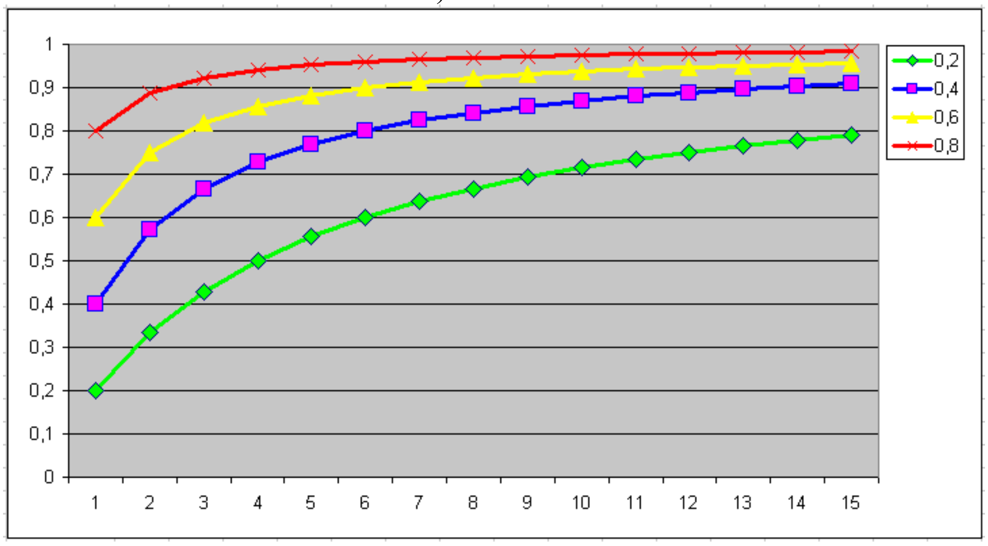
Lookout of the DCA application is briefly illustrated on Fig. 3.

5. Conclusions

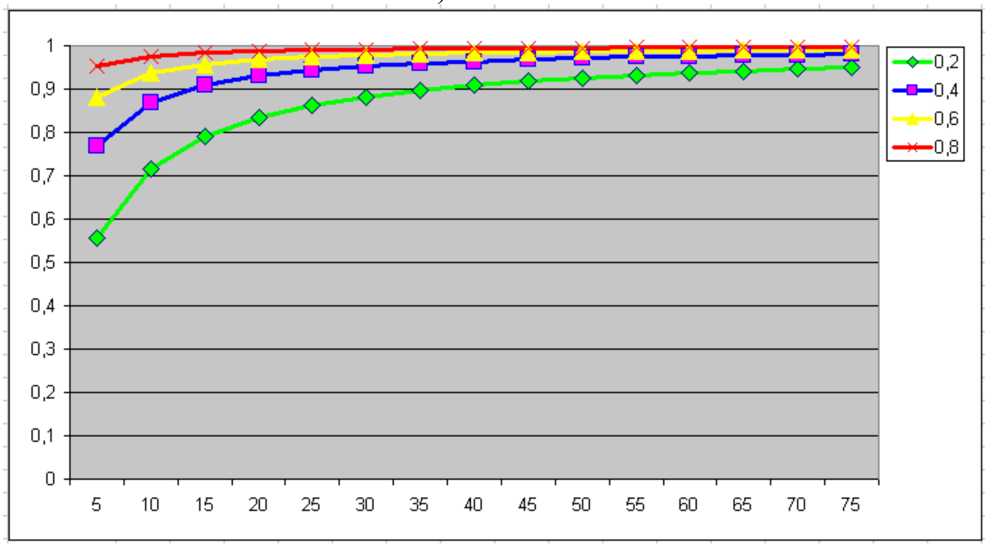
The DCA application is yet under development and its special edition called Experimental Lounge just under preparation. This application already provided first results that help to understand characteristics of diffusors of studied type. Next work on the application will be concentrated on its development toward acquisition of rich cluster of graphs and, in the very first order, to optimization processes on the design of diffusors. The DCA application is intended to serve as a tool for designer while Experimental Lounge is expected to provide more disposal for researcher to analyze relations between inputs and outputs. For example this application should be equipped with instant LIDC illustration (of the luminaire) as operator will manipulate with inputs.



a) for u < 1



b) for u > 1



c) for u >> 1

Fig.2 Graphical interpretation of dependance (ρ.u.κ) vs u

A: Reflective Diffusor for Incandescent Lamps

Input Sheet

Lamp parameters

Input power: P_Z = 200 W **Efficacy:** η_Z = 11 lm/W

Luminous flux: Φ_Z = 2 200 lm

Luminous intensity distribution curve (LIDC):

φ (°)	5	15	25	35	45	55	65	75	85	95	105	115	125	135	145	155	165	175
$I_{\varphi 1000}$ (cd)	91	89	89	88	83	79	76	76	70	63	69	78	85	89	93	94	73	28
I_{φ} (cd)	200,2	195,8	195,8	193,6	182,6	173,8	167,2	167,2	154,0	138,6	151,8	171,6	187,0	195,8	204,6	206,8	160,6	61,6

Diffusor parameters

Reflectivity coefficient: ρ = 0,8

Conesection shape of the diffusor: ellipse

Parameter: p = 127,55 p.u.

Excentricity: ε = 0,8

Rotation: μ = 0 °

a) Input Sheet

A: Reflective Diffusor for Incandescent Lamps

Luminous Flux

General parameters

Total luminous flux calculated from LIDC: 2 171,8 lm

Flux to socket:	165,2 lm	7,6 %
Flux to diffusor:	1 241,4 lm	57,2 %
Flux to aperture:	765,2 lm	35,2 %

Luminous flux measured: 2 200 lm

Error: 1,3 %

Total luminous flux outgoing: 1 724,9 lm

Efficiency:
79,42%

Auxiliary parameters

Utility factor: u = 0,852

Multireflection factor: κ = 1,135

Luminous flux outpassing after multireflections: Φ^{∞} = 959,7 lm

b) Calculation of Luminous Flux & Efficiency

Fig.3 Screenshots from the DCA application

Another tasks will be aimed on enhancement of this application to other types of diffusors, i.e. in connection with other types of light sources – low voltage halogens, FLs, CFLs, discharge lamps etc.

References

[1] GASPAROVSKY, D.: Mathematical modelling of forming curves of reflectors by means of computers. In Proc.: Svetlo ’96, Brno 1996, pp. 47 – 51 (in Slovak)

[2] GASPAROVSKY, D.: Mathematische Modelierung der Reflektoren von Leuchten.. In Proc.: Lux Junior ’97, Ilmenau 1997, pp. 100 – 109 (in German)

[3] GASPAROVSKY, D.: Computer aided modelling and calculation of reflectors of luminaires.. In Proc.: Svetlo 2001, Bratislava 2001, pp. 214 – 221 (in English)

[4] GASPAROVSKY, D.: Novel Approach to Derivation of Differential Equation of Reflection at Conformal Angle Definition. In: Journal of Electrical Engineering Vol. 54, No. 3-4, ISSN 1335-3632, Bratislava 2003, pp. 104 – 106 (in English)

[5] VESELOVSKY, J.- KROPAC, M.: Design methods of Luminaires’ Reflector. In: Osvetlovacia technika 2002, No. 2, Nove Zamky 2002, pp. 34 – 37 (in Slovak)

[6] HORNAK, P.- TREMBAC, V.V.- AIZENBERG, J.B.: Luminaires and Light Sources. Alfa Bratislava 1983 (in Slovak)