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INVESTIGATION OF DISCOMFORT AND DAZZLING GLARE FROM LED LIGHTING SYSTEMS

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Abstract- The brightness of light-emitting diode (LED) light sources has a significant impact on the quality of lighting. Bright areas in the field of view, especially when their brightness is significantly higher than the average brightness of the environment, can create blinding or uncomfortable glare, resulting in temporary blurred vision, visual fatigue, inattention and irritation. The paper analyzes the results of recent studies and recommendations of the International Commission on Illumination (CIE) for assessing discomfort glare. It is noted that the use of a unified glare rating (*UGR*) is ineffective for assessing LED luminaires with uneven brightness distribution and requires clarification. It is shown that the *UGR* value for luminaires with an uneven brightness distribution on the radiating surface can differ by more than 10 units compared to luminaires with uniform brightness of the radiating surface. Based on the results of the study, recommendations were developed to improve methods for calculating the adjusted *UGR* (UGR'). It is shown that the measurement of the average and effective brightness of luminaires, as well as the radiating area coefficient, can be carried out in laboratory conditions using stationary instruments, and in field conditions it is necessary to measure only the brightness of the background environment and the Guth position indexes. To determine UGR', it is necessary to increase *UGR*, determined using the CIE 117:1995 methodology, by $8\log k^2$, where k^2 is a correction factor calculated based on measurements of the effective and average brightness of the luminaire and the solid angles in which the light of the entire luminaire is emitted and the effective luminous area of radiation. The possible degrees of glare that can be created by different luminaire designs were assessed based on the measured luminance of the luminaires and their limit values established by international standards. Based on the results obtained, conclusions and recommendations were made to improve the assessment of the discomfort of luminaires in LED lighting installations with uneven brightness distribution and proposals for informing consumers about the maximum brightness and a correction factor that takes into account the effective brightness and effective radiation area of the luminaires.

Keywords: LED luminaires, unified glare rating, adjusted unified glare rating.

1. INTRODUCTION

Recently, the LED lighting industry has been paying great attention to improving the quality of light, its safety, the comfort of the light environment created by LED light sources, as well as reducing the harmful effects of light on people's health. Problems with the safety of blue light, its effect on circadian rhythms, as well as the impact of glare and flicker of light on human health require a comprehensive study of LED lighting systems, the development of new methods for monitoring parameters and further improvement of LED products.

International standards [1-2] define the principles of visual ergonomics when lighting workplaces. The main goals of visual ergonomics are: improving the perception of visual information, maximizing work safety and ensuring a sufficient level of visual comfort. Lighting characteristics that affect human performance include illumination levels, spatial distribution of brightness, spectral composition of radiation, flicker and glare of light sources.

Good lighting requires equal attention to the quantity and quality of lighting. Modern lighting systems must simultaneously provide good visual perception (natural color, high quality color rendering, absence of visual discomfort), a beneficial non-visual effect, while preventing negative phenomena such as brightness flicker and stroboscopic effect, photobiological hazard of blue light, and jet lag.

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Many publications are devoted to the study of quantitative and qualitative parameters of LED light sources and lighting systems using them [3-12]. This paper examines the issues of quality indicators of LED lighting systems, which include the levels of illumination they create and their uniformity and blinding and uncomfortable glare.

Glare is a property of LED devices or reflective surfaces in their ability to disrupt comfortable vision conditions or impair contrast sensitivity [13]. It occurs in cases where the brightness of luminaires significantly exceeds the brightness of interior surfaces (direct glare) or when the light of such light sources is reflected from surfaces. Glare can manifest itself in one of the following two forms, acting separately or perceived together: uncomfortable glare, which creates discomfort without necessarily impairing the visibility of objects, glare, which interferes with the visibility of objects, but does not necessarily cause a feeling of discomfort.

Glare occurs when a small, high-brightness source is close to the line of sight. It is mainly associated with the physiological reaction of the human eye, and its effect is manifested in the form of loss of visual performance as a result of the presence of a glare source in the field of view.

In contrast, uncomfortable glare causes irritation and distraction due to the presence of a source of glare in some part of the visual field [3]. Uncomfortable glare is mainly associated with a person's psychological reaction, which depends on the level of adaptation of the observer, as well as on the size, number, brightness and location of light sources in the field of view.

Brightness levels of modern LEDs can be very high (exceeding 10^7 cd/m^2). Even low-power LEDs produce glare that can cause discomfort or temporarily reduce visual acuity. Although glare is temporary and does not cause eye damage, it is a source of indirect danger - it can cause accidents due to glare.

The quality of lighting using LED luminaires is affected by the intensity of light rays and, in connection with this, there is a need to study the uncomfortable, blinding glare of LED installations in accordance with the requirements of the standards.

Lighting using LED light sources is relatively new compared to other sources, so it is important to consider all possible impacts on human health and the environment.

Excessive light levels and brightness contrasts can lead to glare. Bright areas in the field of view, especially when their brightness is significantly higher than the average brightness of the surrounding environment, can create a glare or discomfort that can lead to temporary visual impairment and visual fatigue, irritation and distraction.

Today, to assess the uncomfortable glare of light sources, the generalized discomfort indicator proposed in [13] *UGR* is mainly used. It is based on a mathematical formula that takes into account the solid angle subtended by the luminous area of the luminaire, the position of the luminaire, the brightness of the background and the average brightness of the luminous area of the luminaire. Several factors influence the *UGR* of a lighting system, including luminaire placement, number of luminaires, intensity of light sources, size and shape of light sources, reflectivity of room surfaces, and viewing position. The result of the *UGR* calculation is a number with values ranging from 10 to 30, with lower values indicating less discomfort caused by glare. A *UGR* of 19 or lower is considered acceptable for most indoor environments (offices, classrooms, etc.), with higher values indicating increased levels of discomfort caused by glare.

Recommended *UGR* limit values - form the series: 10, 13, 16, 19, 22, 25, 28. The steps indicate the level of gloss change and are characterized as: < 10 - invisible; < 13 - inconspicuous; < 16 - noticeable; < 19 - acceptable; < 22 - limitedly acceptable; > 25 - tangible; > 28 - significant discomfort.

UGR can be determined from Equation (1) [14]:

$$UGR = 8\log\left(\frac{0.25}{L_b}\sum_{i=1}^{N}\frac{L_i^2\cdot\omega_i}{p_i^2}\right) \quad (1)$$

where, L_b is spatial distribution of radiation, which depends on the vertical illumination E, directed towards the observation, L_i is brightness of the i-th light source directed towards the observation, ω_i is solid angle of the emitting part of the i-th light source towards the observation view, N is the number of luminaires in the lighting installation, and p_i is a parameter characterizing the location of each light source and observer.

The p_i can be determined from the dependence of the relative coordinates of the position of the center of the luminaire $\frac{x_T}{y_R}$, $\frac{H}{y_R}$ in the coordinate system relative to the observer (Figure 1) [9]. UGR can be calculated from luminaire intensities using Equation (2):

$$UGR = 8\log\sum_{i=1}^{N}\left(\frac{\pi}{4E}\cdot\frac{I_{c\gamma i}^2}{A_i\cdot D_i^2\cdot p_i^2}\right) \quad (2)$$

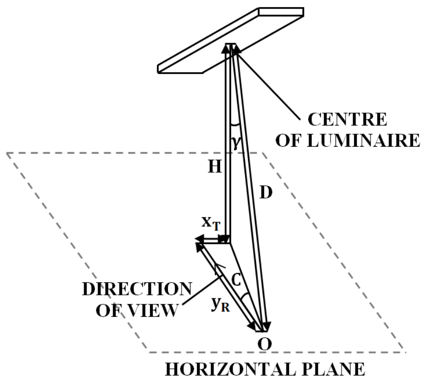


Figure 1. Position of luminaire center relative to observer O [9]

where, $I_{c\gamma i}$ is the intensity of the light rays of the light source along the propagation perimeter, $C = \mathrm{arctg}(x_T / y_R)$ is azimuthal angle, $\gamma = \arccos(H / D)$ is meridional angle, and A is the area of projection of the emitted surface of the luminaire onto area perpendicular to line of sight.

UGR can also be determined using complex tables according to [15]. However, this method is not applicable for light sources with small sizes and uneven brightness distribution. For lamps with many point light sources, it is impossible to use the average brightness value from these sources over the entire area of the lamp, because this approach significantly underestimates the indicator and does not reflect the physiological sensation of brightness [5, 16, 17].

As numerous studies have shown, this technique is ineffective for assessing lamps with uneven brightness and requires clarification [3, 16-18]. CIE in [18] introduced temporary changes to the methodology for determining *UGR*, which will remain in effect until practical results are obtained from applying the fundamental approach based on physiological and psychological mechanisms.

The feeling of discomfort increases with increasing brightness of the source, decreasing solid angles, which is created by the number of light sources in the field of view, and decreases with increasing background brightness and increasing the angle between the line of sight and the direction from the light source to the eye. There is also evidence in the literature of a connection between pupil constriction and uncomfortable glare [19].

Methods for assessing discomfort glare using *UGR* have been developed for discharge lamp luminaires, which have a significantly different brightness distribution than LED luminaires.

In 2021, the EN 12464-1 standard [20] was revised, and one of the important changes was the addition of Annex A "Recommended practice for implementing the UGR tabular method for "non-standard" situations." The appendix explains that the *UGR* methodology is used to select appropriate luminaires for a given space, but it is not an accurate prediction of the effects of glare. For non-standard situations, such as irregularly shaped rooms, the dimensions of the room can be approximately determined by fitting it into a rectangle. If multiple types of luminaires are used, the *UGR* should be determined for each type, and the highest *UGR* value should be compared with the established worst-case scenario limit value [21].

Unevenness is a significant factor in quantifying glare discomfort. According to the methodology [14], *UGR* is calculated using Equation (1), which assumes a uniform distribution of brightness in the luminaire. However, this assumption is not valid for many LED luminaires, which have an uneven brightness distribution. This may result in *UGR* values that do not accurately reflect glare discomfort levels.

CIE in [18] proposed to introduce a correction factor into Equation (1) to evaluate LED lamps. The adjusted UGR' should be defined as

$$UGR' = 8\log\left(\frac{0.25}{L_b}\sum k^2 \frac{L_S^2 \cdot \omega_i}{p_i^2}\right) \tag{3}$$

where, $k^2 = \frac{L_{eff}^2}{L_S^2} \cdot \frac{\omega_{eff}}{\omega}$ is correction factor, L_{eff} is effective brightness, ω_{eff} is effective solid angle of the total light area with L_{eff}, L_S is average brightness of the luminaire, ω is the solid angle at which the light of the entire luminaire is emitted, and p_i is Guth position index for the *i*-th luminaire.

One way to determine the effective brightness L_{eff} is based on the nature of brightnesses. For L_{eff} calculations, the brightness is taken within the effective area A_{eff}, determined by the angle ω_{eff}. The ratio A_{eff} / A is called the effective area coefficient, which is proportional to ω_{eff} / ω.

In luminaires with non-uniform brightness, the effective area is less than the total area of luminaire A and the effective brightness will be significantly higher.

The purpose of this work is to study the luminance distribution in typical LED luminaires for general lighting and evaluate their potential differences in assessing the level of *UGR*, as well as to study the glare of LED luminaires based on the boundary brightness curves and an assessment of the lighting quality classes that these luminaires can provide.

2. RESEARCH RESULTS

The research was carried out at the accredited electric lamp testing center of the state enterprise Poltava Standard and Metrology (Poltavastandartmetrologiya).

To assess discomfort and glare, industrial samples of LED luminaires for general indoor lighting were studied. The luminaires had diffusers with diffuse and mixed light transmission (partially diffuse and directional). Some structures had transparent protective plastic instead of light diffusers. The LEDs in the luminaire were mounted both evenly over the area and along the perimeter of the luminaire body.

In luminaires with LEDs mounted over the luminaire area, brightness heterogeneity is in many cases observed visually. Luminaires without diffusers have a high spot brightness compared to the low brightness of other parts of the luminaire. In luminaires with diffuse diffusers, as a rule, light spots of increased brightness are not visible.

The average brightness of the L_S luminaire was determined by measuring the luminous intensity relative to the observation and dimensions of the light source. Luminous intensity was measured using a GO 2000 goniophotometer. Luminous intensity curves and luminous flux were measured at the same time. The errors in measuring these photometric quantities did not exceed ±3%.

Brightness was calculated using Equation (4):

$$L = \frac{I}{A} \tag{4}$$

where, L is overall brightness, cd/m^2, I is luminous intensity, cd, and A is area of the luminaire emitting light, m^2.

The average brightness and brightness L_{eff} were measured using a set of test equipment OST 300 [22], the Spectro radiometric system which contains a monochromator, a photometric detector, a system for measuring the size of light sources, which simulates the human eye in a field of view of 100, 11 and 1.7 mrad, apertures to limit the field of view and reference light sources (Figure 2).

The system is used to measure spectral power distribution, brightness, irradiance, illumination, apparent light source size, color temperature, color rendering index and other parameters.

The device is equipped with a lens with a large aperture, which allows you to measure the object under study from short and long distances and with a resolution of more than one million pixels. Brightness in different fields of view (1.7 mrad, 11 mrad and 100 mrad) can be measured simultaneously. The accuracy of illumination and brightness measurement is ±5%.

It is possible to measure the area of radiation with a certain brightness in a certain direction. In our studies, we measured an area with a brightness greater than 500 cd/m^2, which is considered a source of glare [5, 14].

Figure 3 shows examples of uneven distribution of source brightness and areas selected for measurement in different fields of view.

The degree of influence of brightness L_{eff} and area coefficient A_{eff} / A on the value of UGR' was studied using a luminaire in which the light diffusers were changed. Plastic with diffuse and directional-diffuse transmission, as well as transparent protective glass, were used as light-scattering materials.

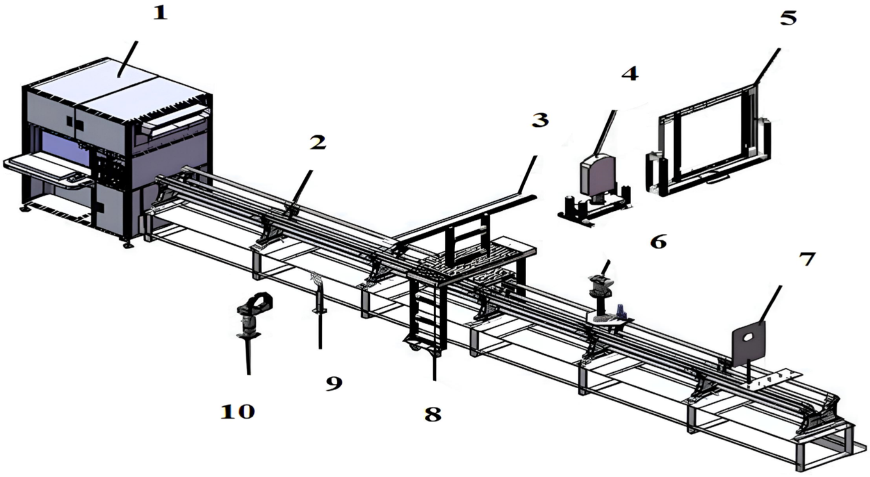
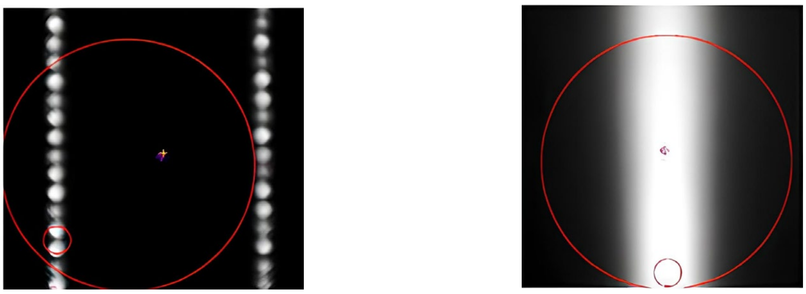


Figure 2. OST 300 circuit
1: mobile operating platform, 2: optical rails with auxiliary equipment, 3, 4, 5, 9, 10: replaceable holders for lamps and luminaires, 6: movable carriage for laser measurement, 7: movable diaphragm of the field of view, 8: movable platform for studying lamps and luminaires



a) b)
Figure 3. Example of uneven distribution of brightness of light sources and areas allocated for measurement in different fields of view

The use of light diffusers changes the distribution of brightness-with diffuse transmission, almost uniform brightness is ensured over the entire area, and with directional diffuse transmission, the area of the light spot expands and the effective brightness decreases. At the same time, the background brightness increases. To calculate UGR' we considered case for one luminaire. In this case, expression (3) can be written as [9]

$$UGR' = UGR + 8\log\left(\frac{L_{eff}^2}{L_S^2}\cdot\frac{\omega_{eff}}{\omega}\right) = UGR + 8\log k^2 \qquad (5)$$

Since the coefficient k does not depend on the background brightness L_B, the Guth position index and on ω, but depends on the ratio L_{eff} / L and, ω_{eff} / ω it can be determined not in the field (the room where the lighting system is installed), but in laboratories and provide information on the k-factor value for each luminaire design.

When determining UGR' in real conditions, UGR will need to be increased by $8\log k^2$. This will significantly simplify the assessment of UGR', since it will be possible to use stationary instruments to determine L_{eff} / L, L_S and ω_{eff} / ω.

For lighting systems with multiple luminaires, the UGR will differ from this parameter for a single luminaire, since for each luminaire there will be different values of the Guth position index p, which depend on the direction of the field of view. UGR' is influenced by the number of light sources in the observation field of view. To determine the dependence of UGR' on effective brightness and effective area coefficient, such a simplification is justified [9].

The expression $8\log k^2$ is the difference (ΔUGR) between the values obtained when determining UGR and UGR' using the CIE 117:1995 and CIE 232:2019 methods. The dependence of ΔUGR on k^2 is shown in Figure 4.

A twofold decrease in the radiation area of a lamp with a brightness greater than 500 cd/m^2 (at the same luminous power) increases the $\Delta UGR'$ value by 8 units [24].

Determining UGR' for a single luminaire is a worst-case scenario, but it does present the possibility of publishing the ΔUGR value in the specification for an individual luminaire. This information can be used to calculate the predicted glare response in a room illuminated by such luminaires.

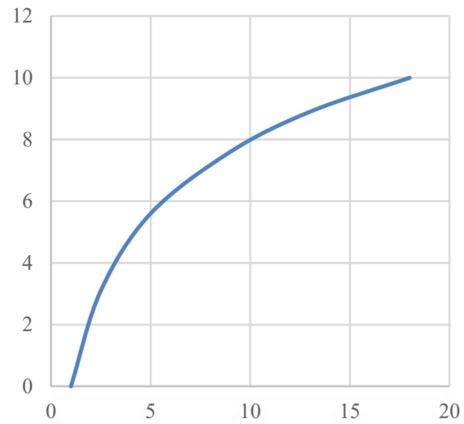


Figure 4. Dependence of ΔUGR on k^2

Table 1 shows the results of measurement and calculation of UGR for a luminaire without a diffuser, with a prismatic and diffuse diffuser. When calculating, the background brightness in the room L_b was taken equal to 170 cd/m^2. The effective brightness and effective radiation area of the lamp were measured at an angle of 60° to radiation receiver at a distance of 2 m.

Table 1. Parameters of the studied luminaires

Characteristics of the luminaire	L_S, cd/m^2	L_{eff}, cd/m^2	$\frac{A_{eff}}{A}$, rel. units	k^2, rel. units	UGR	$UGR = UGR' + 8\log k^2$
without diffuser	3430	8.9×10^5	4.5×10^{-3}	13	21	30
with diffuse diffuser	1825	1825	1	0	17	17
with prismatic diffuser	2070	2.25×10^4	2.1×10^{-2}	2.5	18	21

As can be seen from the results obtained, for a luminaire without a light diffuser the UGR' value exceeds the UGR by 9 units, and when using a prismatic (directional diffuser) light diffuser by 3 units. Studies of commercial samples of LED luminaires of different designs (with different degrees of light scattering) have shown that UGR' is in the range of values from 14 to 30. The increase in UGR' can reach 10 or more units, which is very significant when assessing the level of uncomfortable gloss.

It should also be noted that from the point of view of reducing the level of perception of uncomfortable glare, LED luminaires with lower color temperatures should be used. The level of glare of luminaires for indoor lighting was determined on the basis of boundary brightness curves in the range of critical angles from 45° to 85° relative to the vertical (Figure 5).

The limitation is sufficient if the average brightness of the luminaire does not exceed the values of the brightness curves for the corresponding critical angles γ, as shown in Figure 5 [13].

For different visual work in different rooms, the degree of glare is determined by the requirements for the quality of lighting. Five quality classes have been defined: 1- most elevated; 2- elevated; 3- less elevated; 4- satisfactory and 5- unsatisfactory.

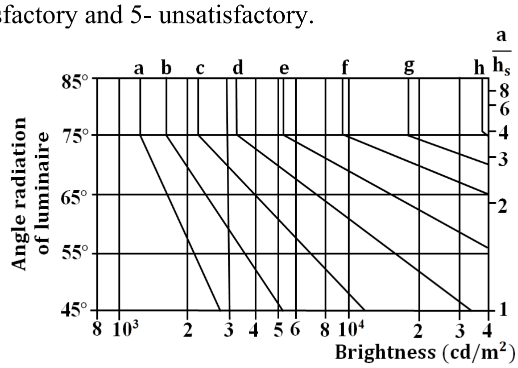


Figure 5. Limit brightness curves (for luminaires without emitting side surfaces) [13]

The degrees of glare cover the main characteristic points (0- no glare; 2- slight glare; 4- significant glare; 6- intolerable glare). Table 2 shows the correspondence between the maximum brightness curves and the degree of glare for different illumination levels and their quality classes [13]. Limit luminance curves can be applied under the following conditions:

- only general lighting is considered;
- line of sight is directed mainly horizontally or downward;
- ceiling reflection coefficient is not less than 0.5, and walls - not less than 0.2.

Since LED luminaires can have significant brightness variability (and the degree of glare is determined by the maximum brightness in the field of view of observation), it is therefore necessary to determine the overall brightness.

Table 2. Correspondence of the maximum brightness and glare curves for different illumination levels and their quality classes [12]

Degree blindness	Quality class	Illumination value, lx							
		a	b	c	d	e	f	g	h
1.15	1	2×10^3	10^3	5×10^2	$<3\times10^2$				
1.5	2		2×10^3	10^3	5×10^2	$<3\times10^2$			
1.85	3			2×10^3	10^3	5×10^2	$<3\times10^2$		
2.2	4				2×10^3	10^3	5×10^2	$<3\times10^2$	
2.55	5					2×10^3	10^3	5×10^2	$<3\times10^2$

To assess the potential for glare caused by LED lighting installations, commercial samples of LED indoor lighting fixtures, which are widely used, were examined. The degree of glare and lighting quality classes that can be achieved using these luminaires were assessed by measuring their maximum brightness using a set of test equipment OST 300.

Using the maximum brightness curves (Figure 5), the correspondence values of the maximum brightness curves, the degrees of glare for different levels of illumination and quality classes (Table 2), you can determine the degree of glare and the class of lighting quality that a given luminaire can provide. The results of measurements and calculations are given in Table 3.

Table 3. Obtained estimates of the degree of glare, quality of lighting of LED luminaires

Maximum brightness cd/m^2	Glare level	Lighting quality classes
2.314×10^3	Absent	1; 2
4.19×10^3	Absent	2; 3
13.23×10^3	Minor	3; 4
33.38×10^3	Minor	4; 5
59.25×10^3	Significant	5

As can be seen from the obtained results of LED luminaires for general lighting supplied to the Ukrainian market, they mostly provide a high class of lighting quality.

To inform consumers, it is advisable to indicate the maximum brightness in the documentation for luminaires (including catalogues). This will simplify the selection of luminaires for specific applications.

3. CONCLUSIONS

1. The adjusted generalized discomfort index UGR' for LED luminaires with uneven brightness may differ significantly from the standard UGR calculated by the traditional method. For high effective brightness and small effective radiant area, the difference between UGR' and UGR can be 10 or more units;
2. Since the correction factor k^2 does not depend on the background brightness and the Guth position index, measurements of overall and effective brightness and radiating area coefficient can be carried out in laboratory conditions;
3. To determine the UGR' of an LED lighting installation in "field" conditions, it will be enough to measure the background brightness and the Guth position index and calculate the UGR using the traditional method, increasing this indicator by 8logk^2;
4. To simplify the design of LED lighting installations and assess their uncomfortable glare, it is advisable to provide information on the correction factor k^2 (or the value 8logk^2) in the documentation for the luminaire;
5. To simplify the design of LED lighting installations, it is advisable to indicate their maximum brightness in the documentation for luminaires and catalogs.

NOMENCLATURES

1. Acronyms

LED: Light-emitting diode
CIE: International Commission on Illumination
UGR: Unified glare rating
UGR' : Adjusted unified glare rating

2. Symbols / Parameters

L: Overall brightness
L_b: Background brightness
L_i: Brightness of the i-th luminaire
L_S: Average brightness of the luminaire
E: Vertical illumination
N: Number of luminaires in the lighting installation
ω: Solid angle
ω_i: Solid angle of the emitting part of the i-th luminaire
ω_{eff}: Effective solid angle
p_i: Guth index for each individual luminaire
C: Azimuthal angle
γ : Meridional angle
A: Area
A_{eff}: Effective area
k^2: Correction factor
I: Luminous intensity

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Doctorate: Lighting Technology and Light Sources, Faculty of Power Supply and Lighting of Cities, Kharkov Institute of Municipal Engineers, Kharkov, Ukraine, 1990
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Research Interests: Lighting Technology and Light Sources, Electric Machines, Electrical Apparatuses
Scientific Publications: 55 Papers, 1 Book, 19 Scientific-Methodical Sentences, 8 Patents, 6 Certificates of Authorship

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Research Interests: Lighting Technology and Light Sources, Energy Saving Technologies, Electrical Engineering, Electromechanics and Electrical Technologies
Scientific Publications: 150 Papers

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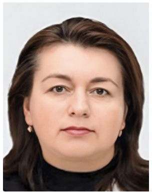
Research Interests: Lighting Technology and Light Sources, Energy Saving Technologies, Electric Machines, Electrical Apparatuses
Scientific Publications: 28 Papers, 2 Patents



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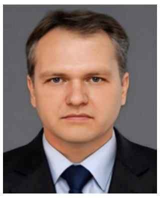
Research Interests: Lighting Technology and Light Sources, Power Engineering, Electrical Engineering and Electromechanics
Scientific Publications: 91 Papers, 16 Scientific-Methodical Sentences, 4 Patents



Name: **Oleksandr**
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The Last Scientific Position: Head of Department of Automation, Electronics and Telecommunications, Yuriy Kondratyuk Poltava Polytechnic, Poltava, Ukraine, Since 2018
Research Interests: Energy, Electronic Communications, Electrical Engineering and Electro Mechanic
Scientific Publications: 121 Papers, 28 Scientific-Methodical Sentences, 3 Monographs, 2 Patents

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The Last Scientific Position: Prof., Department of Automation, Electronics and Telecommunications, Yuriy Kondratyuk Poltava Polytechnic, Poltava, Ukraine, Since 2019
Research Interests: Lighting Technology and Light Sources, Energy Saving Technologies, Electrical Engineering and Electrotechnology
Scientific Publications: 250 Papers