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STUDY OF ENERGY EFFICIENCY INDICATORS OF LED LIGHT SOURCES

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Abstract- Studies have been carried out on the energy efficiency (EE) and radiation quality of light-emitting diode (LED) lamps and luminaires for general lighting. LED lamps with G13 base and outdoor luminaires have been shown to achieve the A++ EE level. LED lamps with E27 base and indoor luminaires with diffusers have a luminous efficiency 30% lower and comply with classes A+, A and B. The correlated color temperature (CCT) of indoor LED light sources is 3000-5500K and the overall color quality is 75-93. Chromaticity deviation from nominal values reaches up to 7+. The article draws conclusions regarding the EE and the quality of the radiation of LED lamps and luminaires.

Keywords: LED Lamps and Luminaires, Correlated Color Temperature, Energy Efficiency, Color Rendering, Radiation Quality.

1. INTRODUCTION

For the increase in demand for electrical energy, the solution to save energy consumption in lighting installations is a strategic task of each state [1]. According to the International Energy Agency, 19% of the world's electricity production is used for lighting [2]. Saving electrical energy for lighting is defined as the most effective way to reduce the consumption and waste of carbon dioxide into the atmosphere [3]. Today, it is much more profitable to reduce energy consumption for lighting due to modern technologies, such as the use of energy-efficient LED lamps and luminaires, rather than creating new additional capacities to meet the growing needs of light energy.

The main indicator of the EE of light sources is the luminous efficiency. An equally important problem today is the quality of radiation generated by modern light sources [4, 5]. High-quality light increases productivity and mood, effectively affects the duration of sleep [6, 7]. Lighting installations should provide good visual perception, a favorable non-visual effect, and it is necessary to avoid adverse factors affecting human health, such as pulsation of the light flux, photobiological hazard, and biorhythm disturbance. To create energy-efficient lighting installations, it is unacceptable to increase the luminous efficiency by reducing the radiation quality parameters.

An analysis of the literature shows that intensive scientific research is being carried out to improve energy efficiency and improve the quality of the radiation of light sources [8-13]. It is proposed to maintain a balance between the quality of radiation and the energy consumed by light sources [8]. Despite the fact that the issues of energy efficiency are paramount tasks, the quality of light is considered an equally important task [9]. Of particular interest is the solution of the quality of radiation of light sources in three directions: visual, biological and emotional [10]. The first direction reflects the functioning of the visual apparatus, the second - the results of daily activities, the third-normal conditions for functioning in the environment. In [14, 15], the issues of the influence of the quality of radiation, the photobiological safety of lamps and luminaires are considered.

The parameters characterizing the quality of radiation include: color, color rendering, brightness modulation, thermal and photochemical hazard, impact on human circadian rhythms, glare, which creates discomfort and blinding effect [16]. Today, LED light sources form the basis of artificial lighting. In addition to high luminous efficacy and stability of parameters during combustion, they are resistance to attack by corrosive media and do not create waste of hazardous toxic substances. Thanks to the appropriate geometrical parameters of LED light sources, it is possible to use efficient optics for various design solutions.

Despite great advances in EE and reliability, lighting systems using LEDs do not always meet today's requirements for light quality. In connection with the increase in these requirements, the consumer needs information not only about CCT and color rendering index (R_a), but also about the deviation of colorimetric parameters from the normalized values, angular color unevenness, color rendering quality assessment in the new system, which includes the fidelity index (R_f) and the gamut index (R_g) according to [17]. The EE and the quality of the radiation of LED lamps and luminaires have been studied in many works. The most extensive study of LEDs has been conducted by the United States Department of Energy "LED Lighting Facts" program and published in periodic research reports. Part of this information with analytical conclusions was published in [18, 19]. The results of the study of EE and the quality of radiation of LED lamps and luminaires were also published in other works [20, 21].

It is shown that the EE indicator of lighting devices has reached values exceeding 100 lm/W, and for outdoor lighting luminaires-140 lm/W. CCT for indoor lighting luminaires is mainly in the range of 3000-4000 K, and for outdoor lighting it exceeds 5000 K. The R_a of indoor lighting luminaires mainly corresponds to 80-85, and for outdoor-70-80. The EE index of lighting devices with E27 base is between 70-100 lm/W, CCT between 3000-4500 K, R_a=78-92. It is shown that the difference in chromaticity differs four times from the normalized parameters; comparative measurements of color were performed using the indices R_a, R_f, and R_g [21]. Given that the EE and radiation parameters of LED light sources are constantly increasing, the study of their performance is an urgent task.

2. PRESENTATION OF RESEARCH RESULTS

2.1. Determination of EE Classes and Luminous Efficiency of LED Lamps and Luminaires

In this paper, LED lamps and luminaires are investigated, the luminous efficiency and EE classes of these lamps with an E27 base to replace incandescent lamps, LED lamps with a G13 base to replace luminescent light sources are determined. Lighting and electrical values of lighting devices are measured in accordance with [22], the definition of EE classes is in accordance with [23]. The values obtained are shown in Table 1.

Table 1. Significance of EE indicators

Name of lighting devices	Power range, W	Average value of luminous efficiency, lm/W	Minimum and maximum values of luminous efficiency, lm/W	Energy efficiency classes
LED lamps with E27 base	5-12	88	67-110	A+ A B
LED lamps with G13 base	8-68	135	99-145	A++ A+
Luminaires with diffusers for indoor lighting	30-80	86	71-112	A+ A B
Luminaires for outdoor lighting	20-1200	136	106-155	A++ A+ A

As can be seen from the table, LED lamps and luminaires for outdoor lighting have achieved the highest EE class A++. LED lamps with E27 base for replacing incandescent and compact luminescent lamps, as well as luminaires for indoor lighting of buildings, have a luminous efficiency 30% lower and comply with EE classes B-A+. This decrease is caused by the need to reduce the brightness of luminaires and lamps to ensure comfortable lighting. Comparative studies of the brightness of the radiation of LED lamps and luminaires show that without light diffusers their maximum brightness can reach values of 10 Mcd/m^2. Using diffusers, the brightness can be reduced to 3-5 kcd/m^2; however, the luminous efficiency decreases from 120-150 lm/W to 80-110 lm/W.

2.2. Determination of Colorimetric Parameters

Angular color irregularities, deviation of color parameters (the number of steps of Mac-Adam ellipses) from normalized values, and color rendering quality indicators in a two-dimensional system according to the method in [17] were studied. For a given CCT, the quality of the radiation is affected by the offset of the points on the x,y diagram from the nominal values within 3 step Mac-Adam ellipses. The sizes of the ellipses are determined by the number of standard deviations of color matching (SDCM). The human eye can distinguish the difference in color already at three SDCM, and at five, these differences are very noticeable.

When moving from the xy coordinate plane to u′v′, the Mac-Adam ellipses become circles (Figure 1) [30]. The step of the ellipse corresponds to the standard deviation of the u′ and v′ coordinates by 0.0011 (u′v′ on the chromaticity diagram). Standardized CCT nominal values and chromaticity coordinate tolerances for LED lamps and luminaires are defined in [24-26]. According to the accuracy of obtaining CCT, four categories are established-3, 5, 7 and 7+ step Mac-Adam ellipses.

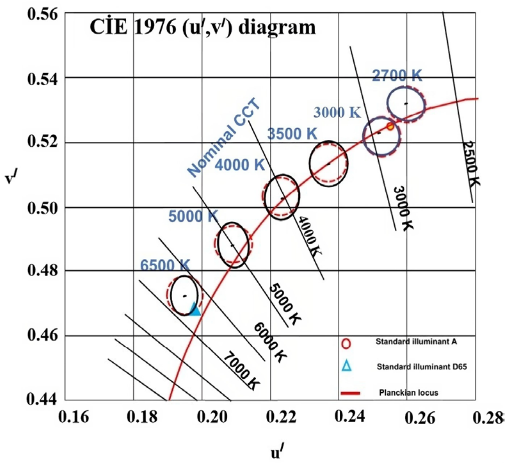

Figure 1. Five-step Mac-Adam ellipses (solid line) and circles (radius 0.0055, dotted line) in the CIE 1976 ($u'v'$) chromaticity diagram [30]

The R_a, which reflects the quality of reproduction of color shades of illuminated objects, also belongs to the main parameters of radiation quality. R_a gives the average color rendering characteristic, which is determined on the basis of the difference in colors obtained from 8 standard color samples when moving from the color source under test to the reference. The measurement technique for R_a is defined by the standard [27]. It should be noted that today the evaluation of color rendering using R_a does not fully satisfy practical needs. The International Commission on Illumination (CIE) notes that it is not sufficient to use R_a alone to evaluate the color rendering of lamps and luminaires with high color requirements.

A method for evaluating color rendering using 99 control samples has been developed [17]. This method involves evaluation by two indices: R_f-fidelity; R_g-gamut. The R_f index shows how close the color is too natural and varies from 100 to 0. The R_g index indicates the degree of color saturation and varies from 60 to 140 units.

For the average value R_g=100; at R_g>100 saturation tends to increase, and at R_g<100 to decrease. The average value of R_f and R_g is depicted as a single point on the coordinate graph (Figure 2) [17]. The points plotted in Figure 2 show the results of measuring the quality R_a of LED lamps and luminaires.

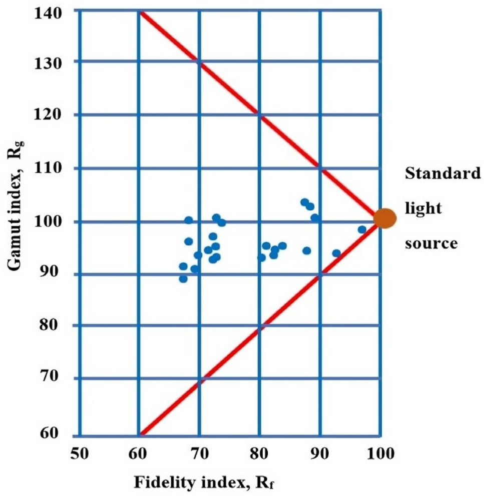

Figure 2. Graphical representation of R_f and R_g [17]

Based on the studies of the quality of color rendering using R_a, R_f and R_g, it was determined that at levels R_a<90, the difference between R_a and R_f is insignificant and the use of R_a when assessing the color rendering of LED lamps and luminaires in this range does not introduce large errors. At R_a>90, R_a is overestimated in relation to R_f by 3-5 units, therefore, to measure the color rendering quality of light sources with increased color requirements, it is necessary to use not only R_a, but also additional R_f, R_g. A study of LED lamps and indoor lighting luminaires shows that they mainly have a CCT in the range of 3000-5500 K, and R_a in the range of 75-93.

Luminaires for outdoor lighting have a higher CCT-in the range of 4000-6500 K, and R_a=70-85. The deviation of color from the nominal values for indoor lighting luminaires and lamps is in the range from 1 to 7 SDCM units, and for outdoor lighting luminaires-7+ SDCM units. The quality of color rendering in terms of R_a values is conditionally divided into six classes, the characteristics of which are given in Table 2 [16].

Table 2. Classification of the color rendering of light sources [16]

Color rendering characteristic	Color rendering classes	R_a, rel. units
Excellent	1A	90-100
Excellent	1B	80-89
Good	2A	70-79
Good	2B	60-69
Mediocre	3	40-59
Bad	4	<39

The color rendering quality of LED light sources inside the objects under study corresponds mainly to class 1B. Lamps and luminaires entering the lighting market with a color rendering quality corresponding to class 1A do not exceed 10-15%.

The radiation level classes of lighting devices for outdoor lighting correspond to classes 1B and 2A. It is known that LED light sources have angular color unevenness [28, 29]. A significant difference (more than 1000 K) occurs in high-power LEDs with high CCT. A large spread of color parameters [29] makes it difficult to use lighting devices where it is necessary to ensure the requirements for color uniformity.

CIE in [30] recommends using not Mac-Adam ellipses on the CIE (x, y) chromaticity diagram, but circles on the equal contrast CIE (u',v') diagram for color tolerances. In the (u',v') diagram, the n-step Mac-Adam ellipse is defined as a circle with a radius of 0.0011×n. For the center point with coordinates (u'_c, v'_c), the n-step circle is expressed by Equation (1) and corresponds to the n-step Mac-Adam ellipse [30]:

$$(u'-u'_c)^2+(v'-v'_c)^2=(0.0011\times n)^2 \quad (1)$$

A noticeable difference in the color of light occurs with a probability of 50%, when the coordinates (u',v') change by 0.0013. The chromaticity difference $(\Delta_{u'v'})$ is usually expressed by the distance on the CIE diagram (u',v') between points with coordinates (u'_1, v'_1), (u'_2, v'_2), [30]:

$$\Delta_{u'v'}=\sqrt{(u'_2-u'_1)^2+(v'_2-v'_1)^2} \quad (2)$$

An assessment of the level of the angle of unevenness of the radiation quality of lighting devices for indoor and outdoor lighting was carried out. To study the colorimetric parameters depending on the viewing angle, a GO2000 goniophotometer and an MK350S spectroradiometer were used. The radiation spectrum was measured every 10° in the range of angles from-90° to + 90°. Based on the measured spectra, using the software of the MK350S spectroradiometer, the following colorimetric parameters were determined for each viewing angle: chromaticity coordinates, CCT and R_a.

The angular unevenness of chromaticity $(\Delta_{u'v'})$ and its averaged values are determined according to the recommendations [30]. The level of change in the angle of unevenness of color values was studied on lighting devices with different reflectors. The name of the reflectors of lighting devices, the obtained values of experimental data and calculations are shown in Table 3. All studied LED lighting devices with translucent-scattering have acceptable color values. Their angle unevenness $(\Delta_{u'v'})$ does not exceed 0.0031 and is less than three-step Mac-Adam ellipses (one step corresponds to 0.0013), which meets the requirements for high-quality lighting.

Lighting devices with transparent optics, beam splitter scattering and diverging lens have a more angle of unevenness than three-step ellipses. The angle unevenness of chromaticity $\Delta_{u'v'}$ of these luminaires is in the range of 0.0048-0.0096. The greatest unevenness has luminaires with a prismatic diffuser.

Table 3. Obtained EE indicators data for LED lighting products

Lighting devices types	CCT, K		$\Delta_{u'v'}$, rel. un.	R_a, rel. un.	
	0°	80°		0°	80°
Translucent-scattering light source	3083	3089	0.0014	83.5	83.5
Indoor LED luminaire with transparent optics	6472	5857	0.0070	83.6	83.3
Lighting device with translucent-scattering optics	5413	5453	0.0019	82.9	83.0
Indoor LED luminaire with prismatic diffuser	6310	6976	0.0096	71.6	75.9
Outdoor LED luminaire with lens optics	4097	3810	0.0069	75.0	75.3
Outdoor LED luminaire with transparent protective glass	4764	4100	0.0048	70.4	69.1

3. CONCLUSION AND RECOMMENDATIONS

An analysis of the obtained values of the luminous efficiency of LED lighting devices shows that in the near future they can correspond to an increased EE class A++. To reduce discomfort, the use of reflectors leads to a decrease in light output by 30%. At the same time, to prevent the loss of light energy, it is necessary to create reflectors with increased efficiency. The lower and upper limits of the color rendering quality index of the indicated lighting devices for indoor lighting are respectively 7-10% higher than for outdoor lighting. For indoor lighting, where standards require a higher level of color rendering quality, LED luminaires must have a color rendering class of 1A (R_a>90) and color tolerances within three-step Mac-Adam ellipses. The obtained values of the indicator R_a of the studied lighting devices differ little from the data given by other researchers. However, a large discrepancy is observed in the results of deviations of the color coordinates of LED lamps and luminaires from the nominal values of the steps of the Mac-Adam ellipse.

Based on the work performed, the following conclusions can be drawn:

1. LED replacement lamps for luminescent lamps and luminaires for outdoor lighting have achieved EE class A++. LED lamps with E27 base and indoor lighting luminaires with diffusers have a luminous efficiency 30% lower and correspond to classes A+, A and B;
2. For work indoors, LED lighting devices have CCT mainly 3000-5500 K, and R_a in the range of 75-93. Lamps for outdoor lighting have a higher CCT in the range of 4000-6500 K, R_a=70-85;
3. Color rendering LED light sources for indoor lighting corresponds to color rendering classes 1A, 1B and 2A, and for outdoor lighting corresponds to color rendering classes 1B and 2A;
4. Deviation of chromaticity from nominal values for indoor lighting luminaires is in the range from 1 to 7 SDCM units, and for outdoor lighting luminaires-up to 7+ SDCM units;
5. The angular unevenness of the color of LED light sources with translucent-scattering is less than the three-step Mac-Adam ellipses ($\Delta_{u'v'} < 0.0031$). Lighting devices that have angular non-uniformity $\Delta_{u'v'}$ in the range of 0.0048-0.0096 correspond to deviations of up to 7+ three-step ellipses of Mac-Adam.

Compared to other light sources, LED lighting devices have more functionality. This is the independence of on-off cycles for a lifetime, when adjusting the luminous flux, there is no significant change in luminous efficiency and color, instantaneous entry to the nominal light mode, environmental friendliness, therefore, in indicators to increase EE, their developers and manufacturers need to ensure high uniformity and quality of light.

NOMENCLATURES

1. Acronyms

EE: Energy efficiency
CIE: International Commission on Illumination
SDCM: Standard deviation of color matching

2. Symbols / Parameters

(x, y), (u', v') : Chromaticity diagrams
$u'_c, v'_c, u'_1, v'_1, u'_2, v'_2$: Coordinate points
$\Delta_{u'v'}$: Chromaticity differences

REFERENCES

[1] T. Haidi, B. Cheddadi, "State of Wind Energy in the World: Evolution, Impacts and Perspectives", International Journal on Technical and Physical Problems of Engineering (IJTPE), Issue 51, Vol. 14, No. 2, pp. 347-352, June 2022.
[2] https://shop220.ru/pdf/?id=742.
[3] E. Tetri, L. Halonen, "Trends in the Development of Energy-Efficient Lighting", Light and Engineering, No. 3, pp. 51-52, 2010.
[4] W. Bommel, "Lighting Quality and Energy Efficiency: Critical Review", Light and Engineering, No. 1, pp. 6-12, 2011.
[5] W. Bommel, "Knowledge Required for Modern Lighting Technicians", Light and Engineering, No. 2, pp. 16-32, 2020.
[6] S.M. Berman, R.D. Klier, "Recently Discovered Human Photoreceptor and Previous Studies in the Field of Vision", Light and Engineering, No. 3, pp. 49-53, 2008.
[7] CIE158:2009, "Ocular Lighting Effects on Human Physiology and Behavior", p. 64, Vienna, Austria, 2009.
[8] A. Ludwig, "The Problem of Balance - the View of the Lighting Industry on Energy Efficiency and Quality of Lighting", Light and Engineering, No. 3, pp. 3-7, 2010.
[9] A.V. Jennifer, R.N. Guy, C.J. Carol, D.A. Chantal, S. Mancini, "High-Quality Lighting: Energy-Efficiency That Enhances Employee Well-Being", Lighting Quality and Efficiency (CIE2010), pp. 197-204, Vienna, Austria, 2010.
[10] B. Martau, P.S. Scarazzato, M.P. Hidalgo, I. Torres, C. Luz, "Lighting and Health: Case Study in Retail Stores", The CIE2010, Lighting Quality and Efficiency, Vienna, Austria, pp. 234-246, 2010.
[11] O.C. Ozerdem, S. Biricik, "Overview of Energy System and Major Power Quality Problems in North Cyprus", International Journal on Technical and Physical

Problems of Engineering (IJTPE), Issue 8, Vol. 3, No. 3, pp. 71-75, September 2011.
[12] M. Ari, M.C. Taplamacioglu, "In the Light of Global Developments, Turkey's Electricity Market, Role and Capacity of Electricity Generation Companies", International Journal on Technical and Physical Problems of Engineering (IJTPE), Issue 12, Vol. 4, No. 3, pp. 152-156, September 2012.
[13] O.B. Sezgin, H. Gozde, M.C. Taplamacioglu, M. Ari, "Energy Efficiency Works at the Airports", International Journal on Technical and Physical Problems of Engineering (IJTPE), Issue 30, Vol. 9, No. 1, pp. 23-29, March 2017.
[14] O.S. Pitiakov, S.A. Baghirov, P.I. Neyezhmakov, S.V. Shpak, S.H. Kyslytsia, H.M. Kozhushko, "Photobiological Safety of Image Projectors with Halogen Incandescent Lamps", International Journal on Technical and Physical Problems of Engineering (IJTPE), Issue 53, Vol. 14, No. 4, pp. 123-127, December 2022.
[15] P. Neyezhmakov, O. Pitiakov, S. Shpak, S. Baghirov, T. Sakhno, G. Kozhushko, "Luminance Flicker of LED Lamps and Lighting Fittings for General Lighting", Ukrainian Metrological Journal, No. 3, pp. 33-42, Kharkov, Ukraine, September 2022.
[16] Y.B. Eisenberg, "Reference Book on Light and Engineering", Sign, p. 952, Moscow, Russia, 2006.
[17] IES-TM-30-18, "Method for Evaluating Light Source Color Rendition", Illuminating Engineering of North America, p. 34, New York, USA, 2018.
[18] Outdoor Lighting, "Report LED Lighting Facts 2014", Modern Lighting Engineering, No. 4, pp. 4-10, 2015.
[19] "Indoor Lighting. Report LED Lighting Facts 2014", Modern Lighting Engineering, No. 2, pp. 3-9, 2015.
[20] "Indoor General Lighting", Modern Lighting Engineering, No. 6, pp. 8-13, 2014.
[21] S.V. Shpak, L.N. Guba, Y.A. Basova, S.A. Baghirov, H.M. Kozhushko, "Research of the Quality of Color Rendering of LED Lamps and Luminaries", Scientific Bulletin, No. 1, Vol. 91, pp. 105-116, Poltava, Ukraine, November 2019.
[22] EN 13032-4, "Light and Lighting-Measurement and Presentation of Photometric Data of Lamps and Luminaires", Part 4: LED Lamps, Modules and Luminaires, 2015.
[23] The Cabinet Ministers of Ukraine, "Technical Regulation of Energy Labeling of Electric Lamps and Luminaires", Approved by Resolution of the Cabinet Ministers of Ukraine, No. 340, Kiev, Ukraine, 2015.
[24] IEC 62612:2013, "Self-Ballasted LED Lamps for General Lighting Services with Supply Voltages > 50 V-Performance Requirements", p. 87, 2013.
[25] IEC 62717:2014, "LED Modules for General Lighting - Performance Requirements", p. 96, 2014.
[26] IEC 62722-2-1:2014, "Luminaire Performance - Part 2-1: Particular Requirements for LED Luminaires", p. 38, 2014.
[27] CIE 013.3-1995, "Method of Measuring and Specifying Colour Rendering Properties of Light Sources", Vienna, Austria, p. 20, 1995.
[28] S. Glinter, "The Application of LEDs for General Lighting", Semiconductor Lighting Engineering, No. 2, pp. 50-52, 2010.
[29] S. Nikiforov, "Study of High-Power LEDs from Seoul Semiconductor for Lighting Applications", Semiconductor Lighting Engineering, No. 5, pp. 22-26, 2013.
[30] CIE TN 001, "Technical Note: Chromaticity Difference Specification for Light Sources", Vienna, Austria, p. 9, 2014.

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