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Measurement of photobiological indicators of radiation of light sources

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Abstract

The analysis of scientific publications and research on the photobiological safety of artificial light sources is carried out. It is established that optical radiation can affect the general and hormonal state of the body. The main criterion for taking into account the limits of photobiological radiation hazard is the integral energy of brightness on the surface of the human eye or skin, and to determine it, it is necessary to create specific photometric devices. To study the photobiological indicators of radiation from lamps and lamp systems, it is necessary to create specific equipment and develop special measurement techniques. The article discusses the standard and alternative methods for determining the photobiological indicators of optical radiation. These methods make it possible to determine the main factors of the photobiological effect of radiation from light sources, such as the spectral composition of the light, the duration of action and the luminance of the light source in the corresponding spectral range. The necessity of developing a national standard of photobiological hazard of radiation sources and its harmonization with the international standard IEC 62471, which requires a number of studies, has been established.

Keywords: photobiological safety; radiation; spectral density; acceptance angle; standard method; alternative method.

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Formulation of the problem

In scientific circles, the issue of radiation safety of solid-state light sources is rising ever more. As is known, the photometric data of light sources are based on the spectral sensitivity of the human eye. Scientists have proved the blue component of radiation, which is particularly pronounced in LEDs [1, 2]. Melanospastic processes in the body have also been established, which are influenced by the spectral composition of radiation and the level of illumination, which in turn affects the human hormonal state. Some studies [3] also show the effect of the optical radiation of solid-state light sources on the function and condition of the human brain and even their bactericidal action. In connection with this, there is a problem of determining indicators of radiation of artificial light sources of their photobiological effects on the body and taking into account these parameters when designing LED lighting installations.

Analysis of research and publications

The main normative document that classifies light sources for their photobiological safety is the standard IEC 62471 “Photobiological safety of lamps and lamp systems” [4]. Based on this standard, SSTU IEC 62471:2009 has been developed in Ukraine. The main requirement of these standards is to reduce the human limiting radiation from lamps and lamp systems within the established limits and, thus, the standard divides all sources of optical radiation into four risk groups with the established exposure limit value:

- Zero risk group. The effect of radiation from such light sources may occur in 10000 seconds or more.
- The first group of risk. Maximum radiation exposure time from 100 to 10000 seconds.
- The second group of risk. The maximum radiation exposure is possible within the range of 0.25 to 100 seconds.
- The third group of risk. The time of radiation exposure does not exceed 0.25 seconds.

Thus, the limits of photobiological safety of radiation of light sources are defined by the standard as the integral energy luminance on the surface of the human eye or skin. Therefore, the determination of the parameters of photobiological indicators of the radiation of lamps and lamp systems requires specific equipment and techniques. Such techniques are being developed by scientists from different countries, but new discoveries require their constant improvement and even revision of existing norms and standards.

Due to the extensive use of solid-state light sources in people’s everyday life, the question is in how safe their radiation is and what photobiological effect they can give to the body. In order to study the photobiological radiation indicators of LED light sources, a number of studies have been developed in different countries. In particular, a comprehensive assessment of the photobiotic safety of solid-state light sources, conducted by German scientists, shows that the use of LEDs in workplace lighting systems does not pose any danger [5]. Scientists note that when selecting lamps, it is necessary to pay attention to their luminance, and high-power LEDs should always be used to avoid direct exposure to their radiation from a short distance.

In particular, as noted in one of the studies, optical radiation in the range of 380—1400 nm easily passes through the eye environment and is absorbed by the retina. In this case, the danger to the retina may be caused by energy illumination on it or energy exposure [6]. To determine the energy of the retina of the eye, the expression is proposed:

$$E_r = \pi \cdot L_s \cdot \tau \cdot d_e^2 / (4 \cdot f^2), \qquad (1)$$

where E_r — energy of the retina; L_s — energy luminance of the light source; τ – coefficient of transmission of the environment of the eye; d_e — pupil diameter; f — effective focal length of the eye.

Therefore, the energy of the retina of the eye is directly related to the integral energy luminance of the light source in sight [7].

Most medical and biological data suggest that medium blue light does phototoxic effects, which lead to a gradual irreversible loss of visual functions. The lens is a natural protector of the eye from photo-rejection of the retina by medium blue radiation. It should be noted that the lens with age loses its transparency and, accordingly, less light passes to the retina. This complicates the process of determining and generalizing the photobiological effect of radiation, since one must take into account the age and physiological characteristics of the human's vision. This is evident from the spectral and age dependences of the transmission coefficient of the lens (Fig. 1) [8].

Another parameter that arises when taking into account the photobiological effect of radiation on the body is the synthesis of melatonin. As it is known, melatonin is produced by an epiphysis that is sensitive to the radiation spectrum. Reducing or increasing the level of melatonin is controlled by the amount of light that gets to the eye. In turn, melatonin regulates the general condition of the body, the hormonal level, body temperature and affects circadian rhythms. The active generation of melatonin in the body begins at night, and with a bright daylight, its production is suppressed. The wavelength of 450—480 nm most inhibits the generation of melatonin and, therefore, the blue color of the radiation is most sensitive to melatonin. This creates a photobiological danger of radiation at night, especially in the short-wave range. The dependence of the relative spectral sensitivity of melatonin on the wavelength of optical radiation is shown in Fig. 2.

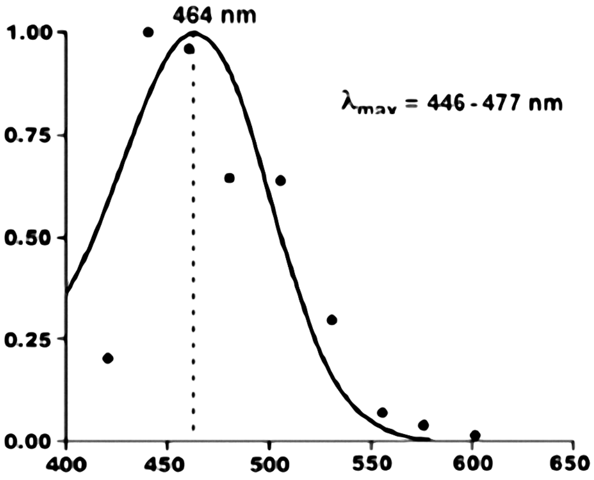

Fig. 2. Spectral sensitivity of melatonin

Recent studies from the University of North Carolina have shown that light with a wavelength of 405 nm imposes certain groups of bacteria on surfaces with a radiation duration from 1 to 96 hours [7]. As previously known, the bactericidal action is manifested by ultraviolet radiation. However, radiation with a wavelength of 405 nm is visible and most expressed in solid-state light sources. So in the Mauri Medical

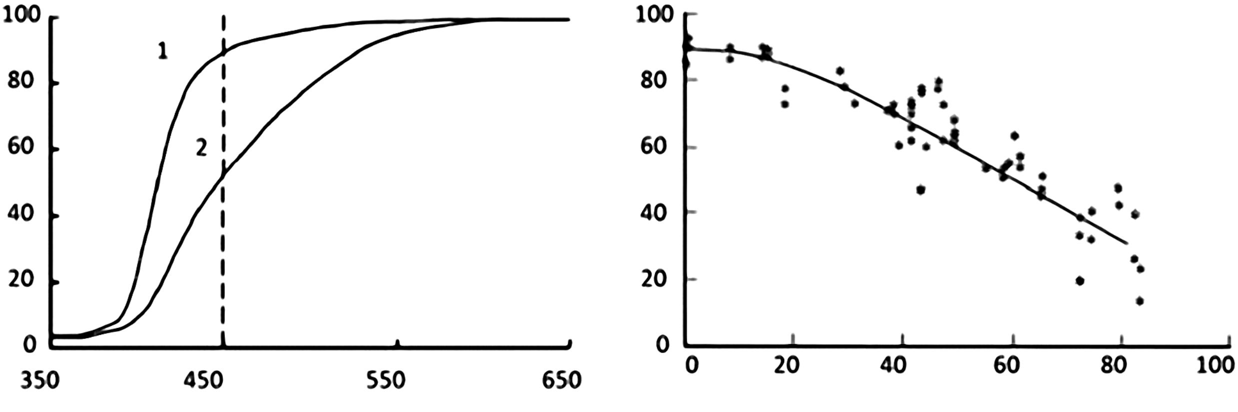

Fig. 1. Average statistical spectral and age dependences of the transmission coefficient T of the eye-lens of people

Center, it was found that a year later in an operating room that was illuminated by light-emitting diode light sources, the number of bacteria was reduced by 85 percent, and the number of chronic infectious diseases – by 73 percent. In this way, blue radiation can provide continuous disinfection of the room. However, the question of to what extent such radiation exposure is safe for the human body remains open. Therefore, another important parameter of the photobiological effect of radiation is the exposure time and radiation dose that a person can receive from radiation with a wavelength of 405 nm.

Thus, the decisive factors of the photobiological effect of radiation of light sources are three independent factors that together define the “dose of blue light”: the spectral composition of light, the duration of action and the luminance of the light source in the corresponding spectral range.

Determination of spectral density of radiation of light sources

The main characteristic of the photobiological effect of radiation of light sources is the spectral density, which makes it possible to estimate such possible radiation hazards as the thermal effect of radiation on the retina and its photochemical damage.

For the origin of damage to the retina of the eye, the size of the irradiated surface of the retina is of decisive importance by the light source. The minimum image on the retina is limited to an angle of 1.7–8.5 mrad. Fixation of the eye is carried out very quickly within 150–400 ms and can spontaneously interrupt, moving the field of view within the angle of 1–5 degrees two or three times per second. Such eye movements lead to the fact that the radiation of the light source extends over a large area of the retina in a short time. With radiation duration of more than 10 seconds, the image of the point source of light covers the retinal area corresponding to an angle of approximately 11 mrad. The ability to look at one point for more than 100 seconds disappears, which leads to the distribution of light on the retina, and the diameter of the irradiated surface of the retina increases. When exposed to radiation for 10000 seconds, a direct image of the point source of light appears on the retina, and the angle reaches 100 mrad. At the same time, eye movement increases the exposure time, reducing the risk of damage to the retina.

The size of acceptance angle is associated with eye senses that distribute power radiation sources on the retina. It does not depend on the size of the light source. To assess the thermal and photochemical retinal hazard, scientists suggested comparison shown in Table [7]. With this, for the light sources with radiation angle greater than the angle of 100 mrad, measurement results do not depend on the acceptance angle of eyes.

Table

The acceptance angle for determination of radiation density at photochemical and thermal danger for retina of the eye

Dangerous	Exposure duration	Acceptance angle, mrad
Photochemical danger	0.25 s ⩽ t < 10 s	1.7
	10 s ⩽ t < 100 s	11
	100 s ⩽ t < 10000 s	100
Thermal danger	0.25 s ⩽ t < 10 s	1.7
	10 s ⩽ t < 100 s	11
Thermal danger	t > 10 s	11

To determine the spectral density of radiation, the following two methods can be used:

- the acceptance angle is determined by the field board installed in front of the detector (standard method);
- the acceptance angle is determined using the field board installed in front of the source of radiation (alternative method).

With a standard measurement method, the optical system displays the light source on the detector or the circular panel. The acceptance angle is set through the field diaphragm, and the measuring aperture operates on the pupil of the eye. In this case, the minimum diameter of irradiation of the diaphragm must be equal to the determined and averaged pupil diameter – 7 mm. For light sources having a spatially uniform radiation density, the diameter of the measuring diaphragm may exceed 7 mm.

Fig. 3 shows a fundamental scheme for measuring the density of radiation by the standard method. In this case, the acceptance angle will be determined by the formula:

$$y = \frac{d_1}{b}, \qquad (2)$$

where d_1 is the diameter of the diaphragm field; b – the distance from the aperture to the receiver.

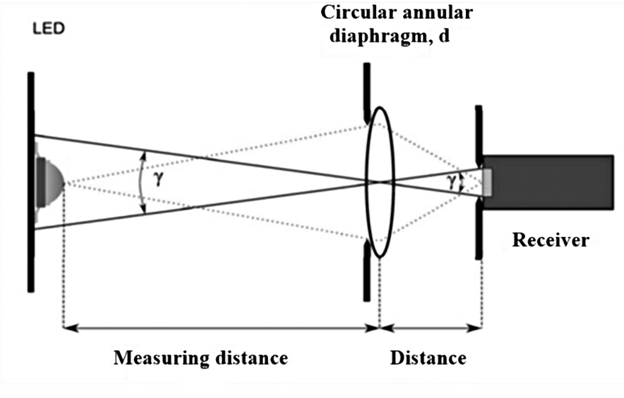

Fig. 3. Optical circuit for measuring the density of radiation by the standard method

An alternative method of measuring the density of radiation is to determine the radiation density at a predetermined acceptance angle. Such a method should only be used if the acceptance angle is formed at small distances of the receiver of radiation to the source. In this case, the diaphragm with a diameter d_2 is located directly in front of the source of radiation (as shown in Fig. 4).

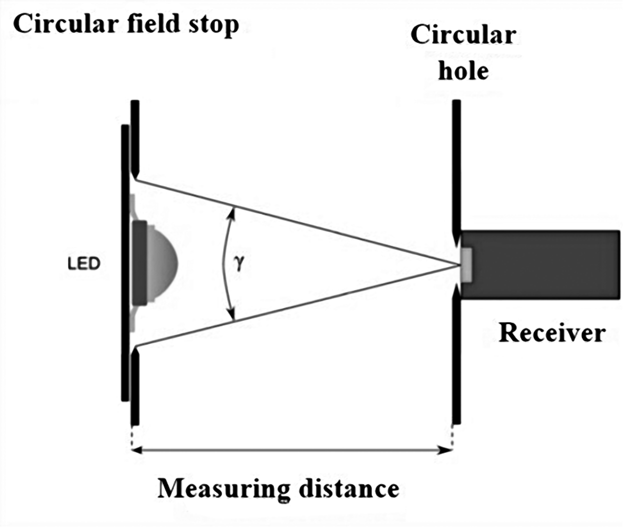

Fig. 4. Optical circuit for measuring the density of radiation by an alternative method

Small acceptance angles with an alternative method are determined by the formula:

$$\gamma = \frac{d_2}{r}, \tag{3}$$

where r – measuring distance.

The relationship between the illuminance E being measured and the luminance L of the source in the field of view of the observation will be determined by the expression:

$$E = L \cdot \Omega, \tag{4}$$

where Ω is the solid angle formed by the acceptance angle γ. For small spot light sources, this solid angle is determined by the formula:

$$\Omega = \frac{\pi\gamma^2}{4}. \tag{5}$$

Therefore, the luminance of the light source in the field of vision can be determined by the formula:

$$L = E\frac{4}{\pi\gamma^2}. \tag{6}$$

Taking into account the last formula for the acceptance angle of 11 mrad, the coefficient between luminance L and illuminance E will be approximately 10000.

To measure the spectral density of the light sources in the UV and the visible range of the spectrum, a double monochromator is used. It provides an opportunity to reflect both bandwidth and wavelength accuracy, which is important for analyzing the assessment of photobiological security. One of such monochromators is the Czerny-Turner monochromator (Fig. 5) [9]. Spherical mirrors are used in the monochromator. The optical radiation of the light source passes through the entrance slit and falls on the spherical mirror S_1. The diffraction grid decomposes the beam at separate wavelengths, and the mirror S_2 focuses on the expanded optical radiation on the output slit. The diffraction grid determines the wavelength that is transmitted to the output slit.

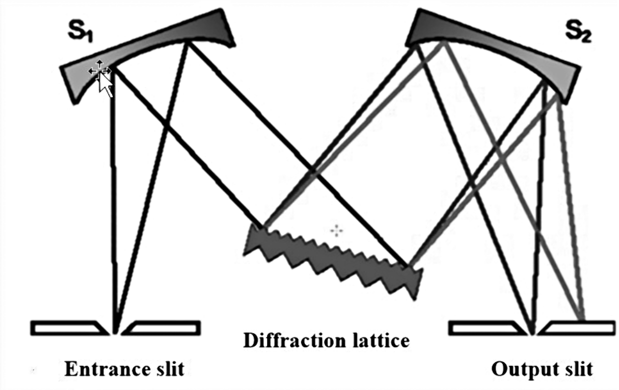

Fig. 5. Principle of Czerny-Turner monochromator

In [5], an experimental setup was proposed for the determination of photobiological radiation safety indicators based on a dual monochromator. In particular, for the determination of spectral irradiation, an installation is used, in which, as a radiation receiver, an Ulbricht sphere with a diameter of 150 mm and an optical winding of 7 mm are used. This sphere is connected to the monochromator by optical light guide. The calibration was carried out with a bandwidth of 5 nm, a step size of 1 nm. Using a PC, an evaluation of the corresponding spectral density function and the corresponding wavelength range was performed (Fig. 6).

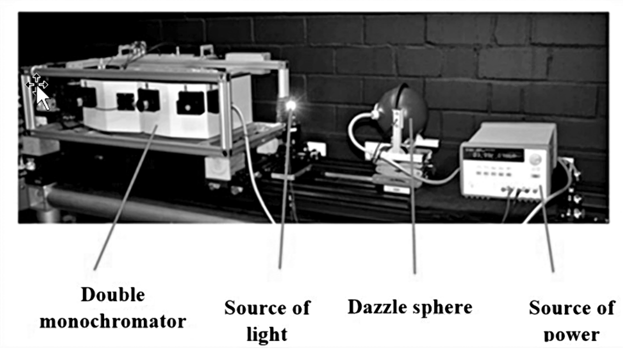

Fig. 6. Experimental installation for measuring the intensity of radiation [7]

To measure the spectral luminance, a dual monochromator with a calibrated quartz halogen lamp with a capacity of 50 W with a throughput of 5 nm and a step size calibrated to 1 nm is used. Measurement is carried out with a diaphragm of 7 mm with an input optics located in front (Fig. 7).

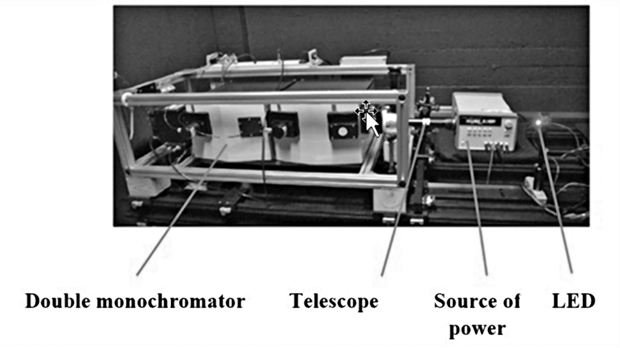

Fig. 7. Experimental installation for measuring the spectral density of radiation [7]

For the measurement of photobiological safety indicators, BELGIMTA LLC “Cersis Analyst” (Belarus) offers the installation of Phoebus-1 [10]. The structure of the installation includes a spectrum diode and a tube unit. An integrating sphere with a light guide are used as the radiation receiver. From the source of light, the light through the registration system is transmitted to a monochromator with a CCD receiver. With the help of software, the spectral density of energy illuminance is calculated, and the limit dose according to the risk groups of standard IEC 62471 is determined. The lamp unit is intended for placement of test and reference lamps. It is a light-proof box consisting of three sections. In the first section there is a test lamp. In the second section is a light bulb FEL-1000, designed for calibrating the photometer. In the third section, the Oriel lamp is placed, with which the calibration of the spectroradiometer is performed.

Conclusions

1. Research of photobiological optical radiation exposure is a relevant problem, as the analysis of a number of publications shows that optical radiation can affect the hormonal and overall health. The medium blue light makes phototoxic effects, which lead to a gradual irreversible loss of visual functions. It has been shown that the synthesis of melatonin is regulated by the amount of light that gets into the eye. In some studies, it is argued that the blue component of the radiation of solid-state light sources can negatively affect the structure of the brain and effect bactericidal action. All this requires comprehensive research, development of national standards for photobiological safety and the creation of specific photometric facilities.

2. Summing up the indicators of photobiological influence of optical radiation, three main factors can be distinguished: spectral composition of light, duration of action and luminance of a light source in the corresponding spectral range.

3. To determine the level of damage to the retina of the eye, it is necessary to determine the size of the irradiated surface of the retina by a light source that is limited to the angle of the eye. The size of the acceptance angle is associated with eye senses that distribute the radiation source’s power across the retina, but it does not depend on the size of the light source.

4. In the experimental installations for the study of spectral density of radiation, which is the main indicator of photobiological radiation safety in accordance with IEC 62471, scientists shall use two methods: standard and alternative. In the standard method, the acceptance angle is determined using the field board, which is installed in front of the detector, and in the alternative one, the field panel is installed in front of the source of radiation. In this case, for measuring spectral density and radiation of light sources in the UV and visible range of the spectrum, the best option is to use double monochromator.

Вимірювання фотобіологічних показників випромінювання джерел світла

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Анотація

Проведено аналіз наукових публікацій і досліджень щодо фотобіологічної безпеки штучних джерел світла. Встановлено, що оптичне випромінювання може впливати на загальний і гормональний стан організму. У першу чергу це пов’язано з синтезом мелатоніну в організмі людини. Основним критерієм для обліку меж фотобіологічної небезпеки випромінювання є інтегральна енергетична яскравість на поверхні ока або шкіри людини. Встановлено, що енергетична освітленість сітківки ока прямо пов’язується з інтегральною енергетичною яскравістю джерела світла, яке знаходиться в полі зору. Головною характеристикою фотобіологічного впливу випромінювання джерел світла є спектральна щільність, яка дає змогу оцінити такі можливі небезпеки випромінювання, як тепловий вплив випромінювання на сітківку та її фотохімічне пошкодження. Для визначення критеріїв фотобіологічної безпеки випромінювання джерел світла необхідно створювати спеціальні фотометричні пристрої. У свою чергу дослідження фотобіологічних показників випромінювання ламп і лампових систем передбачає створення специфічного обладнання і розробки спеціальних методик вимірювань, обробки та обліку даних. У статті розглядаються стандартний та альтернативний методи визначення фотобіологічних показників оптичного випромінювання. Ці методи дають можливість визначити головні чинники фотобіологічного впливу випромінювання джерел світла, такі як спектральний склад світла, час дії випромінювання і яскравість джерела світла у відповідному спектральному діапазоні. Розглянуто метрологічні особливості вимірювання і обробки результатів при стандартному і альтернативному методах. Встановлено необхідність створення національного стандарту фотобіологічної небезпеки джерел випромінювання та його гармонізації з міжнародним стандартом IEC 62471, який вимагає ряду досліджень та широкого впровадження під час сертифікації, в першу чергу, твердотільних джерел світла.

Ключові слова: фотобіологічна безпека; випромінювання; спектральна щільність; кут прийому; стандартний метод; альтернативний метод.

Измерение фотобиологических показателей излучения источников света

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Аннотация

Проведен анализ научных публикаций и исследований по фотобиологической безопасности искусственных источников света. Установлено, что оптическое излучение может влиять на общее и гормональное состояние организма. Основным критерием для учета границ фотобиологической опасности излучения является интегральная энергия яркости на поверхности человеческого глаза или кожи, а для ее определения необходимо создавать конкретные фотометрические устройства. Для исследования фотобиологических показателей излучения ламп и ламповых систем необходимо создавать специфическое оборудование и разрабатывать специальные методики измерений. В статье рассматриваются стандартные и альтернативные методы определения фотобиологических показателей оптического излучения. Эти методы дают возможность определить главные факторы фотобиологического воздействия излучения источников света, такие как спектральный состав света, время действия и яркость источника света в соответствующем спектральном диапазоне. Рассмотрены метрологические особенности измерения и обработки результатов при стандартном и альтернативном методах. Установлена необходимость разработки национального стандарта фотобиологической опасности источников излучения и его гармонизации с международным стандартом МЭК 62471, который требует ряда исследований.

Ключевые слова: фотобиологическая безопасность; излучение; спектральная плотность; угол приема; стандартный метод; альтернативный метод.

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Порівняння сучасних методів оцінювання кольоропередавання джерел світла

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Анотація

Кольоропередавання джерел світла має важливе значення як у сертифікації, так і в практичному застосуванні джерел світла у різних сферах. Індекс кольоропередачі R_a є основним нормованим параметром, що відповідає за кольоропередавання світла та є обов'язковим для сертифікації ламп. Тому важливо, щоб метод вимірювання і розрахунку індексу R_a якомога точніше відповідав візуальній оцінці споживачів.

В Україні з 01.01.2019 р. введено ДСТУ CIE 013.3:2017 "Метод вимірювання та визначення кольоропередавання джерел світла" (CIE 013.3-1995, IDT) на заміну ГОСТ 23198–94 "Лампы электрические. Методы измерения спектральных и цветовых характеристик параметров". Численні наукові публікації свідчать про недоліки стандарту CIE 13.3-1995, це пов'язано з новими дослідженнями в фізіології людського ока та в колориметрії в цілому. Результати цих та інших досліджень було враховано в методі IES TM-30-15, а згодом у методі CIE 224:2017 та в IES TM-30-18.

Проведено порівняльний аналіз методів розрахунку індексу кольоропередачі CIE 13.3–1995 та IES TM-30-15, а також публікацій звітів CIE 224:2017 та IES TM-30-18, в яких враховано неточності попередніх методів. Наведено характеристики, за якими проводився аналіз, основні відмінності методів розрахунку індексу кольоропередачі. Проаналізовано результати світових досліджень щодо нових методів.

В результаті аналізу виявлено, що новий метод IES TM-30-18 має ряд переваг у порівнянні з CIE 13.3-1995. Цей метод враховує всі зауваження попередніх методів та надає користувачам більш детальну інформацію про джерело світла щодо зміщення насиченості, кольору та відтінку.

Ключові слова: індекс кольоропередачі; індекс точності; індекс насиченості.

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Вступ

У зв'язку з широким використанням світлодіодних джерел світла в різних сферах діяльності виникла проблема щодо встановлення вимог до їхніх характеристик та методів випробувань у порівнянні з традиційними, що викликано різними принципами випромінювання, конструкцією та ін. З 2019 року в Україні вступили в дію гармонізовані з європейськими та міжнародними національні стандарти, в яких значною мірою прописані вимоги до характеристик та методи випробувань світлодіодних джерел світла та світильників.