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RESEARCH ARTICLE

Quality control of instruments for measuring the characteristics of bactericidal UV radiation

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Abstract
Objectives. Quality control of instruments for measuring bactericidal irradiance of ultraviolet (UV) radiation is based on studying the main metrological characteristics. These characteristics include: angular and spectral sensitivity; linearity range; and absolute calibration in irradiance units. Deviations of the angular sensitivity of measuring instruments from the ideal cosine characteristic can significantly impact error estimation. They can also lead to the distortion of measurement results and a significant difference in instrument readings. The aim of this work is to enhance accuracy in resolving metrological problems of determining irradiance of bactericidal radiation.
Methods. An effective method of resolving this problem is to introduce correction coefficients for the angular sensitivity of radiometers, spectroradiometers and dosimeters. The values are calculated based on the results of measurements on the goniometer when testing measuring instruments. An important role is played by computer models and digital twins of measuring instruments based on the results of studies of the metrological characteristics of radiometers by means of software. This includes modeling the measuring task.
Results. The study of angular dependence of bactericidal UV radiometer sensitivity complemented by an analysis of measurement results obtained by other authors allows determining the value of the angular sensitivity correction coefficients by the deviation of the angular sensitivity of the irradiance measuring instruments of bactericidal radiation from the standard cosine dependence.
Conclusions. Deviations of the angular dependence of bactericidal radiation UV radiometer sensitivity from the cosine characteristic lead to a significant underestimation of the irradiance measurements results from extended emitters. An effective solution is the use of digital angular sensitivity correction coefficients to measure the irradiance of bactericidal radiation determined during tests. When assessing the quality of radiometers, spectroradiometers and dosimeters for bactericidal radiation, incomplete control of the main metrological characteristics of the measuring instruments creates risks of serious errors in the measurement results of bactericidal irradiance.

Keywords: angular sensitivity correction, radiometers, spectroradiometers, spectral sensitivity, bactericidal installation

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НАУЧНАЯ СТАТЬЯ

Контроль качества средств измерений характеристик бактерицидного УФ-излучения

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Резюме
Цели. Контроль качества средств измерений бактерицидной освещенности ультрафиолетового (УФ) излучения основан на исследовании основных метрологических характеристик, включающих угловую и спектральную чувствительность, диапазон линейности, абсолютную калибровку в единицах энергетической освещенности. Наибольшее влияние на предел допускаемой погрешности оказывают отклонения угловой чувствительности средств измерений от идеальной косинусной характеристики, приводящие к искажению результатов измерений и существенной разнице в показаниях приборов. Целью работы является повышение точности средств измерений при решении метрологических задач определения энергетической освещенности бактерицидного излучения.
Методы. Эффективным методом решения проблемы является введение коэффициентов коррекции угловой чувствительности радиометров, спектрорадиометров и дозиметров, значения которых рассчитываются по результатам измерений чувствительности на гониометре при испытаниях средств измерений. Большую роль играет использование компьютерных моделей и цифровых двойников средств измерений на основе результатов исследований метрологических характеристик радиометров с использованием программного обеспечения, включающего моделирование измерительной задачи.
Результаты. Исследование угловой зависимости чувствительности бактерицидных УФ-радиометров на гониометре и анализ результатов измерений, полученных другими авторами, позволяют по отклонению угловой чувствительности средств измерений энергетической освещенности бактерицидного излучения от стандартной косинусной зависимости определить значение коэффициентов коррекции угловой чувствительности.
Выводы. Отклонения угловой зависимости чувствительности УФ-радиометров бактерицидного излучения от косинусной характеристики приводят к существенному занижению результатов измерений энергетической освещенности от протяженных излучателей. Эффективным решением проблемы является использование коэффициентов цифровой угловой коррекции чувствительности средств измерений энергетической освещенности бактерицидного излучения, определяемых при испытаниях. При оценке качества радиометров, спектрорадиометров и дозиметров бактерицидного излучения неполный контроль основных метрологических характеристик средств измерений создает риски серьезных ошибок в результатах измерений энергетической бактерицидной освещенности.

Ключевые слова: коррекция угловой чувствительности, радиометры, спектрорадиометры, спектральная чувствительность, бактерицидные установки

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INTRODUCTION

The use of bactericidal irradiation facilities in medicine, photobiology, photochemistry, and pharmacology, especially during the COVID-19 pandemic, has shown the need for increased requirements for the quality control of ultraviolet irradiators, as well as means of measuring energetic and effective bactericidal irradiance.[1]

Tubular low-pressure mercury lamps are used in bactericidal complexes as the sources of ultraviolet (UV) radiation. More than 60% of the radiation flux falls on the resonance line with a wavelength of 253.7 nm, located in the range of maximum bactericidal action of UV radiation from 230 to 300 nm [1]. The advantages of using low-pressure mercury lamps are associated with the position of the maximum bactericidal action of UV radiation on destructively modified DNA and RNA damage corresponding to a wavelength of 265 nm. Currently, along with low-pressure mercury lamps, bactericidal UV irradiators based on xenon pulse emitters, LEDs, and high-pressure mercury lamps are increasingly being used [2].

CHARACTERISTICS OF BACTERICIDAL RADIATION MEASURING INSTRUMENTS

In order to ensure the quality of bactericidal irradiation facilities, the main radiometric characteristics need to be monitored. This includes: the spectral density of the radiation flux of bactericidal radiation; energy illuminance; exposure dose; photobiological hazard; and the rate of decrease of the bactericidal radiation flux. Radiometers, spectroradiometers and dosimeters are used as measuring instruments to control one of the main characteristics of UV emitters: energy effective bactericidal illumination [3–5].[2] Problems relating to the formation of metrological characteristics of measuring instruments of bactericidal effective illuminance are related to the legislative and technical documents. These documents are also based on the research of national metrological institutes and contain requirements for the quality assurance of measurements.[3, 4, 5, 6]

An integrated approach to quality management of measuring instruments for measuring the characteristics of the bactericidal UV radiation includes:

- optimization of quality control methods for UV radiometers during the lifetime of measuring instruments with the use of digital technologies during verification and calibration;
- risk and opportunity management in the measurement of bactericidal irradiance through the characterization of measuring instruments related to the practical measurement task;
- development of methods for statistical quality control and consumer evaluation of bactericidal irradiance measuring instruments;
- application of computer models for assessing the quality of measuring instruments when confirming conformity to existing technical regulations and standards.

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[1] Clark M., Zuber R., Ribnitzky M. *Far UV-C Germicidal Sources: Measurement Challenges and Solutions. UV Solutions*. 2022. https://uvsolutionsmag.com/articles/2022/far-uv-c-germicidal-sources-measurement-challenges-and-solutions/. Accessed November 01, 2023.

[2] Miller C.C. *UVC Measurement Methods & UVC Documentary Standard Development.* National Institute of Standards and Technology. Washington, DC: U.S. Department of Energy; 2022. https://www.energy.gov/sites/default/files/2022-02/ssl-rd22_miller_guv.pdf. Accessed November 01, 2023.

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[5] R 50.2.018-2001. GSOEI. *Measuring instruments of ultraviolet radiation characteristics of bactericidal irradiators. Methods of verification*. Moscow: Gosstandart; 2001 (in Russ.). https://docs.cntd.ru/document/1200029414. Accessed November 01, 2023.

[6] *Ultraviolet air disinfection*. Techn. Report CIE Central Bureau. Vienna. Austria: 2003.

Non-compliance with the requirements of standards and recommendations during practical measurements can lead to differences in the readings of devices of different types, as well as to a loss of accuracy and reliability of measurement results. The technical committees on standardization of the Federal Agency for Technical Regulation and Metrology are responsible for the development of standards and recommendations covering methods of quality control of measuring instruments of bactericidal radiation characteristics.[7] The main metrological characteristics determining the quality of measuring instruments of bactericidal radiation include: angular dependence of radiometer sensitivity; spectral dependence of sensitivity; linearity range; as well as absolute calibration in units of energy illumination. These can be compared to the state primary standards related to the approved state verification schemes.

When assessing the quality of radiometers, spectroradiometers, and dosimeters for bactericidal radiation, the incomplete control of basic metrological characteristics of measuring instruments can create risks of serious errors in the results of measurements of energetic bactericidal irradiance. The deviation of relative spectral sensitivity of radiometers from the relative bactericidal efficiency of UV radiation can significantly impact the accuracy of measuring instruments for bactericidal radiation characteristics. In works on quality assessment of measuring instruments for bactericidal radiation characteristics in the national metrological institutes, special attention is paid to one of the most important characteristics: the angular dependence of sensitivity. Deviation from the ideal cosine characteristic is the primary cause of errors in measurement results [6–8].

METHOD FOR MEASURING THE ANGLE DEFINITION OF THE BACTERICIDAL UV RADIATION RADIOMETERS SENSITIVITY

Resolving matters relating to the correction of the angular dependence of the sensitivity of measuring instruments is especially important when controlling the energy illumination from several radiation sources. It is also significant when evaluating the bactericidal efficiency of extended UV emitters and dimensional panels. When UV radiation falling on the receiving surface of the radiometer deviates from the normal, the radiometer signal decreases. This is because the projection area of the photodetector in the direction of the incident flux decreases in accordance with the cosine relationship. The problems of ensuring accuracy and reliability of the results of practical measurements of energy illumination of bactericidal radiation are associated with the fact that commercially available radiometers have angular dependence of sensitivity. This can differ significantly from the ideal cosine dependence of sensitivity. Various types of goniometers are used to control the angular sensitivity of radiometers, spectroradiometers and UV dosimeters [9].

The required angular correction of the sensitivity of short-wave UV radiation receivers in radiometers, spectroradiometers and dosimeters is a technically difficult task, requiring the development of special devices. Figure 1 shows the angular dependence of the sensitivity of various types of germicidal UV radiometers No. 1, No. 2, and No. 3, as well as the ideal cosine dependence of the sensitivity cos φ [7, 10].

As shown in the diagrams, the decrease in sensitivity of radiometer No. 2 reaches 50% at an angle of incidence of radiation φ on the receiving surface of the radiometer of 30°. At an angle of incidence of 45°, the decrease in sensitivity reaches 75%. The sensitivity of radiometer No. 1 is completely absent at angles of incidence exceeding 75°. This limits its application in water treatment systems at short distances from the radiator. In the area of large angles of incidence of radiation (with a sharp decrease in the levels of radiometer signals proportional to sensitivity) the influence of scattered radiation on the results of measurements of the relative angular sensitivity of the radiometer increases significantly.

A general view of the goniometer for measuring the dependence of the radiometer sensitivity on the angle of incidence of UV radiation is shown in Fig. 2.

Deviation $f(\varphi)$ of the angular sensitivity of the UV radiometer $S(\varphi)$ from the standard function cos φ, expressed in percent, is determined by the expression:

$$f(\varphi) = 100\% \, [\cos \varphi - S(\varphi)]/\cos \varphi. \quad (1)$$

Figure 3 shows the results of measurements of deviations $f(\varphi)$ of angular sensitivity of bactericidal radiation radiometers No. 1, No. 2, and No. 3 from the standard cosine characteristic.

Deviations of the angular dependence of the sensitivity from the cosine characteristic are presented in Fig. 3. The deviations of angular dependence of sensitivity from the cosine characteristic indicate a significant underestimation of the results of measurements of energy illuminance from extended emitters when using commercially available UV radiometers of bactericidal radiation. In order to exclude systematic error, coefficients of angular correction of sensitivity must be used which enable the distortion of the results of measurements of energy bactericidal irradiance to be compensated.

[7] https://www.rst.gov.ru/portal/gost (in Russ.). Accessed November 01, 2023.

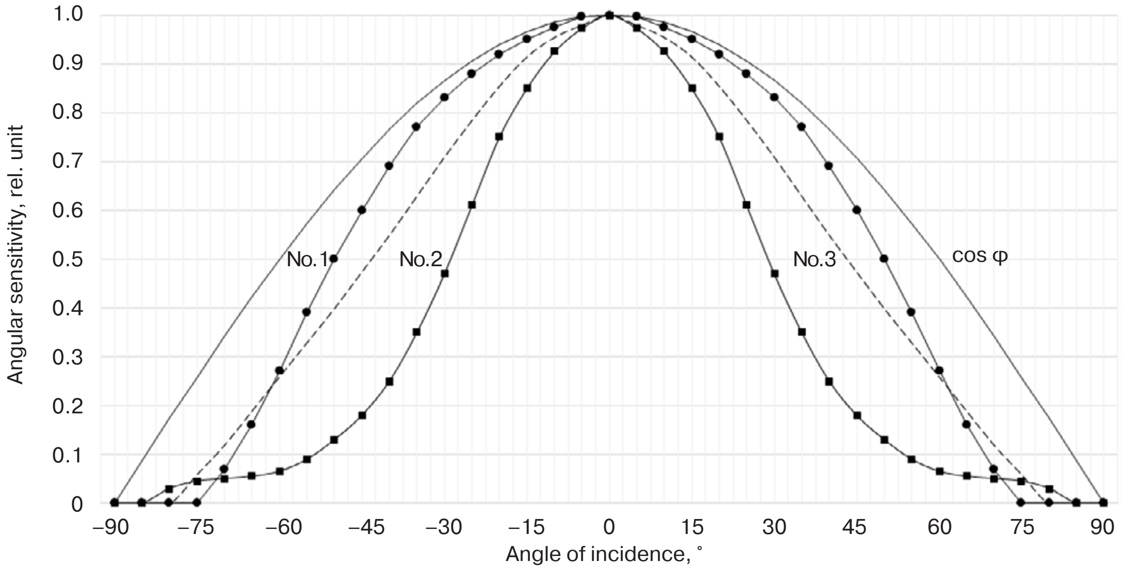

Fig. 1. Angular dependence of sensitivity of different types of bactericidal UV radiometers and ideal cosine dependence of sensitivity

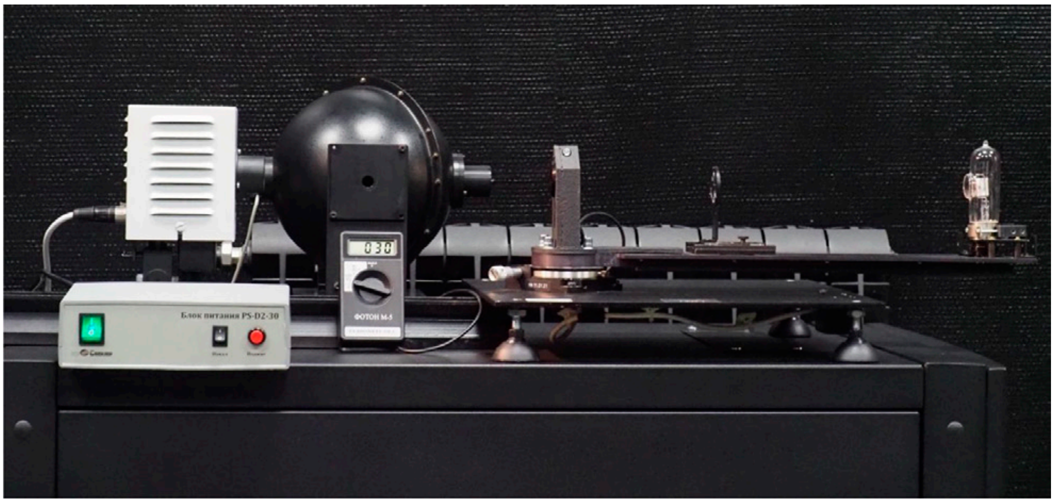

Fig. 2. General view of a goniometer designed for measuring angular sensitivity of bactericidal UV radiation radiometers

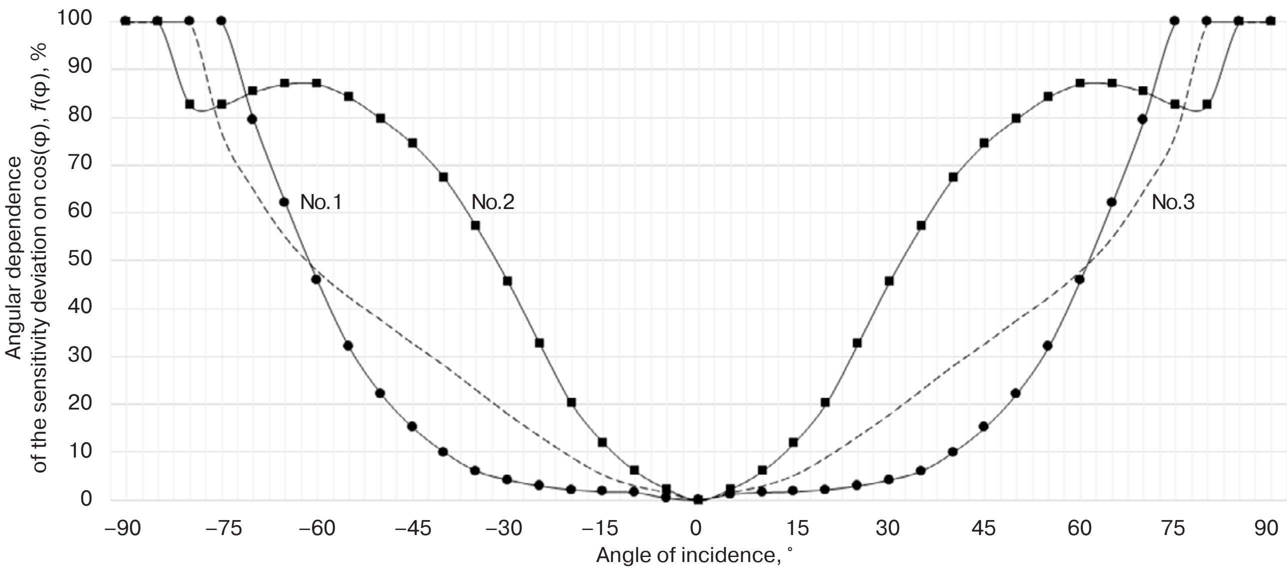

Fig. 3. Deviation $f(\varphi)$ of the bactericidal radiation radiometers angular sensitivity from the standard cosine characteristic

DETERMINATION OF THE COEFFICIENTS OF ANGULAR CORRECTION OF THE UV RADIOMETER SENSITIVITY

The radiometer signal is determined by integrating the energy brightness spectral density (EBSD) over the area of the radiator within the working solid angle, taking into account the spectral and angular dependence of the radiometer sensitivity. The equation describing the signal of a radiometer (spectroradiometer, dosimeter) of bactericidal UV radiation can be represented in the following form:

$$i = N \int_{\Omega_0} \int_{\varphi} \int_{\lambda} \int_{\delta_0} L(\lambda,\delta,\Omega) S(\lambda,\varphi) d\delta\, d\lambda\, d\varphi\, d\Omega, \quad (2)$$

where λ is the wavelength; δ is the radiating area of the UV radiation source; Ω is the solid angle; $L(\lambda, \delta, \Omega)$ is the EBSD of the bactericidal UV radiation source; $S(\lambda, \varphi)$ is the spectral and angular dependence of the radiometer (spectroradiometer, dosimeter) sensitivity); N is the dimension coefficient; δ_0 is the total area of the radiating region of the bactericidal UV radiation source; Ω_0 is the total solid angle determined by the angular dimensions of the bactericidal UV radiation source.

The sensitivity angular correction coefficient $K(\varphi)$ of the radiometers is presented in Fig. 1. This is determined by the results of measurements of the angular dependence of sensitivity. It is intended for the maximum correction of the results of measurements of energy illumination of bactericidal UV radiation arising due to technically imperfect design of diffuse diffusers in the measuring instruments.

The angular correction coefficient of radiometer sensitivity is equal to the ratio of the signal of an ideal radiometer $i_{id}(\varphi)$, This has a standard cosine dependence of sensitivity to the signal of a real radiometer $i_r(\varphi)$:

$$K(\varphi) = i_{id}(\varphi)/i_r(\varphi). \quad (3)$$

In most cases, the relative EBSD of radiation sources and the relative spectral sensitivity of radiometers do not depend on the direction of radiation of the source, or the angle of incidence of radiation on the photodetector. In this case, the angular sensitivity correction coefficient is determined by the angular dependence of the radiometer sensitivity $S(\varphi)$ and the angular dependence of the source EBSD $L(\delta, \Omega)$ according to the expression:

$$K(\varphi) = \frac{\int_{\varphi} \int_{\Omega_0} \int_{\delta_0} L(\delta,\Omega) \cos\varphi d\delta\, d\Omega\, d\varphi}{\int_{\varphi} \int_{\Omega_0} \int_{\delta_0} L(\delta,\Omega) S(\varphi) d\delta\, d\Omega\, d\varphi}. \quad (4)$$

When the radiometer is used to measure the energy illumination produced by a small-diameter tubular bactericidal emitter, the sensitivity angle correction coefficient $K(\varphi)$ is determined by the following formula:

$$K(\varphi) = \frac{\int_{\varphi} \int_{\delta_0} L(\delta,\varphi) \cos\varphi d\delta\, d\varphi}{\int_{\varphi} \int_{\delta_0} L(\delta,\varphi) S(\varphi) d\delta\, d\varphi}. \quad (5)$$

The use of the angular sensitivity correction coefficient taking into account geometric conditions of measurements enables the systematic error of correction of angular sensitivity of radiometer (spectroradiometer, dosimeter) to be radically reduced. This thus compensates for the technical shortcomings of measuring instruments, and excludes any significant variations of measurement results of energy illumination of bactericidal UV radiation by different measuring instruments.

Table presents the results of calculating the values of the angular correction coefficients of sensitivity of UV radiometers No. 1, No. 2, and No. 3 obtained in accordance with expression (5) for low-pressure mercury lamps. The results depend on the maximum angle of deviation of the incident radiation flux from the normal from 10° to 70° to the receiving surface of the radiometer.

Table. Values of angle correction coefficients of UV radiometers sensitivity

UV radiometers	Maximum deflection angle, °						
	10	20	30	40	50	60	70
Radiometer No. 1	1.01	1.03	1.04	1.05	1.08	1.16	1.26
Radiometer No. 2	1.07	1.13	1.31	1.50	1.70	1.08	2.00
Radiometer No. 3	1.03	1.06	1.13	1.18	1.23	1.31	1.39

The data presented in Table shows that the results of measurements of energy illuminance of bactericidal radiation of mercury tube lamps by radiometers of different types will differ significantly from each other.

These results indicate that, in order to meet the requirements of the normative documents[8] for an angular sensitivity correction error of 4%, the coefficients $K(\varphi)$ for radiometer No. 1 at angles of incidence exceeding 40° need to be used. For radiometer No. 2—at angles of incidence exceeding 0°, and for radiometer No. 3—at

[8] Miller C.C. *UVC Measurement Methods & UVC Documentary Standard Development*. National Institute of Standards and Technology. Washington, DC: U.S. Department of Energy; 2022. https://www.energy.gov/sites/default/files/2022-02/ssl-rd22_miller_guv.pdf. Accessed November 01, 2023.

angles of incidence exceeding 10°. Radiometer No. 1 is characterized by the smallest error of angular correction of sensitivity from those presented in Table. For radiometer No. 2, the coefficients of angular correction of sensitivity at any angles of deviation of the incident radiation from normal must be used.

It is difficult to ensure the accuracy of measurements when the emitters are located in the center of the room and the energy illuminance of bactericidal radiation needs to be measured in the corners of the room. This is also the case when the emitters are located in the corners of the room and the energy illuminance is measured in the center [8]. The influence of the quality of the radiometer's angular response on the measurement results is less in the case when the radiometer is directed to the center of the extended emitter. Here the main contribution to the measurement results is made by UV radiation incident at angles close to the normal with respect to the radiometer's receiving surface. The radiation falling on the radiometer receiving surface at large angles to the normal is also lateral to the peripheral radiating region of the radiometer and its contribution is relatively small.

The application of interlaboratory comparisons of measuring instruments of the characteristics of the bactericidal radiation produced by tubular mercury lamps allows discrepancies in the measurement results to be identified. Discrepancies can be significantly reduced by using the coefficients of angular correction of sensitivity.[9]

When creating digital doubles of measuring instruments for energy illuminance of bactericidal UV radiation, the use of sensitivity angular correction coefficients in the list of basic metrological characteristics of the radiometer allows the accuracy and reliability of measurement results to be achieved without the development of complex quartz diffusers.

Evaluation of random and systematic errors of measurement results after introduction of angular correction coefficients of radiometer sensitivity is carried out in accordance with GOST R 8.736-2011[10]. The tolerance limit of error of bactericidal radiation radiometers is established in accordance with the requirements of national and international standards. This limit is estimated based on the results of studies of the error components of the main metrological characteristics of UV radiometers (spectroradiometers, dosimeters). They include: angular and spectral dependence of sensitivity; deviation from linearity of sensitivity in the operating dynamic range; and absolute calibration in units of energy illuminance. The limit of tolerance of measuring instruments of energy bactericidal irradiance is 10%. This takes into account the systematic error of angular correction of sensitivity which is not more than 4%.

In order to estimate the random error of the angular sensitivity of the radiometer, measurements on the goniometer are repeated after rotating the radiometer relative to the optical axis. The unexcluded systematic error in the angular correction of the radiometer is estimated by taking the following into account: the angular resolution of the goniometer; the nonlinearity of the sensitivity; the sensitivity threshold of the radiation receiver; the instability of the energy brightness of the transmitter; and the level of scattered radiation.

For spectroradiometers, the problem of providing angular correction of sensitivity is associated with a small angle of view due to the use of diffraction gratings. This makes it difficult to use spectroradiometers in monitoring the characteristics of bactericidal irradiation facilities without an integrating sphere [11, 12].

The most effective step in ensuring quality by reducing the systematic error of means used to measure the characteristics of bactericidal UV radiation is to introduce coefficients of angular and spectral correction of sensitivity These must take into account the complexities of applied measurement tasks when using digital models and digital twins in the future.

CONCLUSIONS

Analysis of the problem of quality control of bactericidal irradiators shows the need to ensure angular correction of sensitivity of radiometers, spectroradiometers and dosimeters. This is associated with a significant revision of methods and means of measuring the energy illuminance of UV radiation, in order to meet the requirements of existing regulatory documents.

An efficient solution to this problem is the use of correction coefficients of angular sensitivity of radiometers, determined during the type approval tests of measuring instruments.

The most progressive method in the future of increasing accuracy when resolving metrological problems of energy illumination of bactericidal radiation will be the use of computer models and digital doubles of measuring instruments. These will be based on the results of studies of basic metrological characteristics of radiometers, spectroradiometers and dosimeters with the use of software for modeling measurement conditions.

[9] Krames M. *The rise of UV-C LEDs*. LEDs & SSL Magazine. July 24, 2020. https://www.ledsmagazine.com/leds-ssl-design/article/14178371/technology-roadmap-shows-uvc-leds-are-onthe-rise. Accessed November 01, 2023.

[10] GOST R 8.736-2011. *State system for ensuring the uniformity of measurements. Multiple Direct measurements. Methods of measurement results processing. Main positions*. Moscow: Standartinform; 2013 (in Russ.). https://docs.cntd.ru/document/1200089016. Accessed November 01, 2023.

The experience of national metrological institutes in Russia and abroad shows the need to enhance accuracy and eliminate the gross errors in measuring energy illumination created by bactericidal facilities based on the use of correction factors of angular and spectral sensitivity of UV radiometers.

Authors' contribution. All authors equally contributed to the research work.

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