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DETERMINING THE EFFICIENCY OF USING LED SOURCES OF ULTRAVIOLET RADIATION FOR IONIZATION AND DISINFECTION OF ROOM AIR

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This paper reports a study into the possibility of using LED systems of ultraviolet radiation for air ionization and disinfection of air and indoor surfaces in the presence of people. It has been established that UV LED lamps with 120° opening angles have parameters under which radiation intensity does not exceed 30 J/m^2 at distances of 2 meters. Based on experimental data, a methodology for designing the placement of lamps in the room was devised, which meets the requirements of the SBM-2015 standard and the European Directive 2006/25/EU. The use of LED emitters with a total intensity of up to 25 J/m^2 increases the concentration of aero ions. The background concentrations were 140–180 cm^{-3} (positive) and 160–190 cm^{-3} (negative). The minimum permissible level is 500 cm^{-3}. As a result of irradiation, the concentrations were 1100–1460 cm^{-3} (positive) and 1260–1470 cm^{-3} (negative). The influence of the recirculator-air purifier on the concentration of aero ions has not been established. The ionization process began immediately after turning on the irradiation systems in the entire volume of the premises (4–5 meters from the source). The dynamic equilibrium of aero ion concentrations was established within 10–15 minutes after the irradiation was switched on. The presence of a large number of people (up to 0.97 m^2 per person) did not affect the concentration of aero ions. Under the combined effect of ultraviolet radiation and a recirculator-air purifier, the number of mold fungi colonies decreased by 20 times. Under the influence of only ultraviolet radiation – by 2.3 times. The decrease in the number of microbes under the combined effect was 1.6 times, and under the effect of only ultraviolet radiation – 2.8 times

Keywords: LED systems, ultraviolet radiation, air ionization, air disinfection, debacterization, environmental improvement

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1. Introduction

Aero ion concentrations and the presence of bacteria, fungi, and viruses in indoor air are an important indicator of the quality of the environment in which people live. These parameters are regulated by the European standard SBM-2015 [1]. Compliance with regulatory requirements is especially important under the conditions of the Covid-19 pandemic and seasonal increases in the incidence of acute respiratory diseases and influenza. Under the modern conditions of Ukraine, ensuring proper indicators of the quality of the production environment and everyday life is of particular importance due to the crowding of people in civil defense storage facilities. A significant number of such storage facilities are adapted premises, where there are no effective systems for improving the environment. Traditional means of air ionization – devices based on the use of high-voltage discharges, have side effects – uncontrolled generation of ozone and nitrogen compounds. Even modern ultrasonic ionizers [2] have limited maintenance volumes, require air ion dispersion by a fan, and require a long time to normalize air ion concentrations. Powerful low-pressure mercury lamps are used to disinfect premises [3]. But they also generate ozone and have high intensities of ultraviolet radiation. Therefore, it is forbidden to use them in the presence of people. Currently, the latest technologies for disinfecting air and surfaces in rooms using monochrome ultraviolet radiation of relatively low intensity from LED sources are being actively implemented. This makes it possible to use them in premises for the permanent or temporary stay of a large number of people. At the same time, it is necessary to comply with the requirements for their safe use in accordance with IEC 62471:2006. [4]. Therefore, this area requires experimental studies to obtain quantitative data on the intensity of radiation, changes in concentrations of aero ions, and the number of potentially harmful microorganisms under the influence of ultraviolet radiation.

2. Literature review and problem statement

So far, a number of studies have been carried out on the use of ultraviolet light-emitting diodes for improving the environment of people. In work [5], only the coverage of the area of the room by radiation is considered for geometric reasons without providing quantitative characteristics. Paper [6] shows the principle possibility of using ultraviolet light-emitting diodes in the presence of people, but a sufficient volume of quantitative data is not provided. Paper [7] shows the possibility of air ionization using an ultrasonic emitter. Ionization occurs due to the baloelectric effect. But the materials of the work show an extremely limited radius of influence of the ionizer. Study [8] shows the results of determining the sources of air ionization by technical means (personal computers, air conditioners, etc.). At the same time, the effect of electrification of surfaces due to the triboelectric effect on the concentration of ions is shown. The design of an ultrasonic air ionizer with adjustable ionization polarity is proposed. The disadvantage of the device is the need to use a fan to distribute aero ions. This limits the service area and promotes the recombination process of aero ions and their deposition on suspended particles. It is known that ultraviolet radiation has frequency characteristics that bring it closer to ionizing radiation in the spectrum of electromagnetic waves. Therefore, it is advisable to investigate the possibility of air ionization using ultraviolet light-emitting diodes.

Work [9] provides a schematic arrangement of LEDs in a room for air disinfection but does not provide quantitative data on the effectiveness of the application. Study [10] concerns the use of ultraviolet radiation to improve the indoor environment without providing information about the sources of radiation. Evaluating data on air disinfection of educational premises is provided in [11]. It has been shown that under the influence of ultraviolet radiation, the number of bacteria on surfaces decreases. These data require clarification and generalization from the point of view of spatial-temporal changes in the number of pathogenic organisms and the influence of radiation on the degree of electrification of surfaces, which is critical for concentrations of aero ions in indoor air.

It is necessary to determine the possibility of using LED systems of ultraviolet radiation in the presence of people based on the current maximum permissible radiation intensities. It is necessary to obtain data on changes in concentrations of air ions under the influence of LED ultraviolet radiation in the entire volume of the room. It requires the determination of the reduction in the number of colonies of disease-causing organisms on the surfaces of the premises' equipment. The implementation of these tasks will provide an opportunity to design the placement of LED systems for improving the environment, which will be safe for people and acceptable in terms of efficiency.

3. The aim and objectives of the study

The purpose of this work is to substantiate the effectiveness of the use of LED systems of ultraviolet radiation for improving the environment of people. This will provide an opportunity to ensure regulatory concentrations of aero ions in the air and disinfect indoor surfaces when people gather.

To accomplish the aim, the following tasks have been set:

– to investigate the intensity of ultraviolet radiation of LED systems and provide space-time criteria for their use in the presence of people;

– to investigate the effect of ultraviolet radiation of LED systems on air ionization and provide quantitative data on the dynamics of concentrations of air ions of both polarities in rooms;

– to investigate the effect of ultraviolet radiation of LED systems on indicators of microflora in the premises.

4. The study materials and methods

The object of research is the intensity of the radiation of LED systems of ultraviolet radiation, the change in the concentrations of aero ions of both polarities in the indoor air, and the change in the number of colonies of disease-causing organisms on the surface.

The hypothesis of the study assumes that the ultraviolet radiation of LEDs under certain conditions (distances) can correspond to the maximum permissible values safe for people. The radiation of LEDs is sufficient to increase the concentrations of aero ions and reduce the number of disease-causing organisms.

When conducting the study, it was assumed that ultraviolet radiation affected the entire volume of the room and irradiated the surfaces with the same intensity.

The research was carried out using LED UVC T5-5W-275NM open-type ultraviolet radiation sources (TOV Azimut, Kamianske, Ukraine). The rated power of one lamp is 5 W. The predominant length of radiation is 278.6 nm. The radiation propagation angle relative to the longitudinal axis of the lamp is 120°.

In the process of conducting research, the methods of natural measurements were used.

Measurement of physical parameters of ultraviolet radiation was carried out by UV-C "Argus-06", UV-B "Argus-05", UV-A "Argus-04" radiometers. Energy illuminance was measured with the Tensor-51 device. Aero ion concentrations were measured by an air ion counter MAS-01.

The measurement of the electric field strength of surface charges was carried out by the VEZ-P electrostatic charge meter. Relative humidity and air temperature were measured by a certified combined device "CX 601 D".

The measurement of the intensity of ultraviolet radiation of LED systems was carried out in a special darkened laboratory room (illumination level<1 Lk). Aero ion concentrations, the presence of microorganisms and fungi were measured in three rooms with volumes of 160, 102, and 110 m^3. In the absence and presence of people. One of the premises is a control room. LED lamps were located under the ceiling at a height of 3.3 m evenly, with overlaps of the opening angles of the entire surface of the premises (Fig. 1).

Fig. 1. Location of LED systems in the room (5 pcs.)

Test systems produced by R-Biopharm AG (Germany) were used to detect the total number of microorganisms and molds.

5. Results of investigating the effectiveness of the use of LED sources of ultraviolet radiation

5. 1. Studying the spatial dependence of the intensity of ultraviolet radiation of LED sources

The study of the characteristics of ultraviolet radiation of the LED system LED UVC T5-5W-275NM was carried out at an air temperature of 20 °C, relative air humidity of 40 %. The electromagnetic background at frequencies of 50 Hz and 10 kHz–300 MHz was lower than the sensitivity of measuring devices PZ-50 and PZ-31. Background values of electromagnetic radiation in the range 300 MHz–30 GHz did not exceed 0.2 μW/cm^2.

Determination of the spectral composition of ultraviolet radiation showed that the predominant wavelength is 278.6 nm (radiation was performed on the Inventfine CMS 3000 S/VV device). The radiation intensities of LED systems are given in Table 1.

The measurements given in Table 1 show that at a distance of 2 m from the radiation source, the lamps can be used in the presence of people for 8 hours, which corresponds to the duration of the working day.

The radiation intensity was measured depending on the angle relative to the normal of the lamp axis (Table 2).

From Table 2, it can be seen that at the limit of the opening angle of 120°, the radiation intensity is sufficiently low, and outside the angle it is insignificant. Therefore, in practical application, the placement of individual lamps should be intersections of radiation directional diagrams.

To design the placement of sources of ultraviolet radiation on the ceiling of the room, it is advisable to use the pattern of decreasing radiation intensity from a distance in the direction perpendicular to the axis of the lamp (Table 1).

As can be seen from Fig. 2, the change in radiation intensity corresponds to the function:

$$I = I_0 e^{-2.9r}, \quad (1)$$

where I_0 is the maximum output intensity.

The experimental value, which corresponds to an intensity of 550 mW/m^2, can be ignored due to the proximity to the lamp where people cannot stay. The rest of the experimental data correspond well to the approximation dependence.

Table 1

Dependence of radiation intensity on the distance to the LED system

Distance from the lamp, m	UV radiation intensity, mW/m^2			Exposure value, J/m^2		Permissible UV irradiation time, minutes
	UV-C (200–280 nm)	UV-B (280–315 nm)	UV-A (315–400 nm)	With UV irradiation for 480 minutes (8 hours)	Exposure limit values	
0.05	550	37	70	13939	30	1.03
0.2	128	11	15	3242		4.5
0.5	32	–	–	806.4		17.8
1.0	9.5	–	–	240.8		60.0
1.5	4.5	–	–	114.0		126.3
2.0	1	–	–	25.3		480
2.5	–	–	–	–		–
The distance at which the intensity of UV radiation is less than the sensitivity of the measuring device	2.1 m	0.5 m	0.5 m	Not regulated		

Note: the "–" mark corresponds to values lower than the sensitivity of the device

Table 2

Dependence of the radiation intensity of the LED system depending on the angle of propagation of the rays

Distance from the lamp, m	UV radiation intensity, mW/m^2			Exposure value, J/m^2		Permissible UV irradiation time, minutes
	UV-C (200–280 nm)	UV-B (280–315 nm)	UV-A (315–400 nm)	With UV irradiation for 480 minutes (8 hours)	Exposure limit values	
0.5 (in the center of the beam)	32	–	–	806.4	30	17.8
0.5 (at the border of the beam with an opening angle 120°)	15	–	–	380		37.9
0.5 (outside the beam with an opening angle 120°)	–	–	–	–		Not regulated
1.0 (in the center of the beam)	9.5	–	–	240.8		60.0
1.0 (at the border of the beam with an opening angle 120°)	6.0	–	–	152		94.7
1.0 (outside the beam with an opening angle 120°)	–	–	–	–		not regulated

Note: the "–" mark corresponds to values lower than the sensitivity of the device

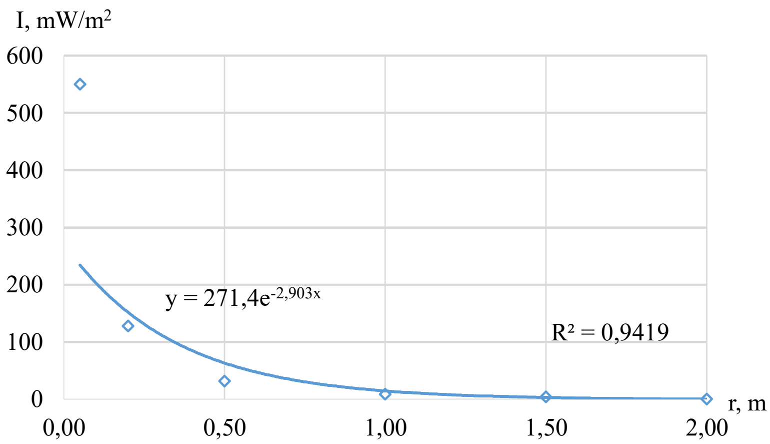

Fig. 2. Dependence of the intensity *I* of ultraviolet radiation on the distance to the source (*r*)

The opening angle of the lamp is 120°, that is, on both sides of the perpendicular from the lamp to the floor, the angle is 60°. The radiation intensity for each point of the opening angle is defined as:

$$I = I_0 e^{-2.9\frac{h}{\cos\alpha}}, \qquad (2)$$

where α is the angle between the "ceiling-floor" perpendicular and the direction to the point of determination of radiation intensity, *h* is the distance from the ceiling to the plane where people are located.

Taking as a basis the intensity of radiation, which exceeds the sanitary norm (up to 30 mW/m^2), the length of the intersection zones of the radiation directional diagrams of neighboring lamps, which ensure acceptable radiation intensities on the entire plane of people's stay, is calculated.

Based on the height of the ceiling and the length of the intersection of the directional diagrams, the distance between the lamps on the ceiling is chosen.

5. 2. Studying indoor air ionization by LED systems of ultraviolet radiation

The study of the dynamics of aero ion concentrations was carried out in three adjacent rooms. Room No. 1 is a control room. In room No. 2, there are 5 LED systems (Fig. 1); in room No. 3, there are additionally 2 ozone-free recirculators for cleaning with mercury lamps isolated from the environment, by Philips. Recirculators were located at a level of 0.8 m from the floor. Air is pumped through recirculators by a fan. The characteristics of the premises are given in Table 3.

The characteristics of the equipment with which the premises were equipped are given in Table 4.

The ultraviolet radiation systems are located under the ceiling in such a way that the intensity of ultraviolet radiation at the level of the table surfaces did not exceed 1 mW/m^2, which amounted to a total radiation dose of up to 20 J/m^2. The measurements were performed at an air temperature of 19–20 °C and a relative humidity of 60–62 %.

The results of measurements are given in Table 5.

Table 3

Characteristics of the premises in which the research was performed

Room	Volume, m^3	Height, m	Area, m^2	Number of persons	Volume per person, m^3	Area for one person, m^3	Availability of air purification products
No. 1	160	3.3	48.6	50	3.2	0.97	Without air purification
No. 2	102	3.3	31.2	26	3.9	1.2	UV LED lamps
No. 3	110	3.3	33.5	34	3.2	0.98	UV LED lamps+ recirculators

Table 4

Technical characteristics of ultraviolet radiation sources and air purification

Room	LED sources of UV radiation			Air recirculators		
	Number of lamps, pcs	Power, W	Intensity of UV-irradiation on the table surface, mW/m^2	Quantity, pcs	Power, W	Air exchange efficiency, m^3/h
No. 1	–	–	–	–	–	–
No. 2	5	25	1	2	15	58
No. 3	5	25	1	–	–	–

Table 5

Air ion concentrations in test rooms

Room No.	Concentrations of air ions, cm^{-3}	
	n^+	n^-
1	140–180	160–190
2	1100–1320	1290–1470
3	1290–1460	1260–1430

According to [1], the minimum permissible concentration of aero ions of each sign was 500 cm^{-3}. Therefore, the obtained results can be considered satisfactory. A comparison of the concentrations of aero ions in rooms 2 and 3 shows that air recirculators do not have a significant effect on this indicator (taking into account the large passport error of the aero ion counter – up to 40 %).

The dynamic equilibrium of concentrations of aero ions of each sign in the entire volume of the room (at least in the areas occupied by people) is established within 10–15 minutes. This fact requires an acceptable interpretation from the point of view of determining the mechanism of air ionization.

The occurrence of ions in indoor air during UV irradiation from an LED lamp with maximum intensity at a wavelength of 278.6 nm cannot be related to direct photoionization of molecules. Indeed, the energy of the photon corresponding to this wavelength is $h\nu$=4.45 eV, while the ionization energies of the molecules of the main air gases O_2 and N_2 are significantly higher and amount to 12.07 eV and 15.58 eV, respectively. Stepwise photoionization is also impossible due to the lack of electronic states of O_2 and N_2 molecules with the energies necessary for this process. Another mechanism of ionization in the case when the radiation frequency is insufficient for the absorption of one photon to lead to its appearance is multiphoton ionization with the simultaneous absorption of several photons. For it to occur, however, a photon flux density comparable to that occurring in a laser beam and which cannot be provided by a conventional source of UV radiation is required.

In this case, energetically possible and playing the main role is, apparently, associative ionization – the formation of a molecular ion O_2^+ and an electron from colliding oxygen atoms excited as a result of photon absorption: $O+h\nu=O^*$; $O^*+O^*=O_2^++e$. This process can occur if the energy of excitation of atoms combined with the energy of molecular ion formation (dissociation) exceeds the ionization energy of the O_2 molecule. In addition, the radiation lifetime of the corresponding excited electronic state of the atom must be greater than the interval between collisions. It is known that the oxygen atom has a metastable level of 2^1S_0 with an excitation energy of 4.19 eV and a lifetime of 0.7 s (the lifetime of resonant excited electronic states of the oxygen atom is 10^{-7}–10^{-9} s). The dissociation energy of O_2^+ is 6.65 eV. Thus, the total excitation energy of oxygen atoms and dissociation energy are 15.03 eV. This energy is sufficient for the described reaction in the presence of UV radiation with a wavelength of 296 nm, which is present in the spectrum of the LED lamp used.

Under normal conditions, atomic oxygen is practically absent in the lower layers of the atmosphere. Its appearance is possible due to the dissociation of the O_2 molecule during the collision of molecules $O_2^*: O_2+h\nu=O_2^*;\ O_2^*+O_2^*=O_2+O+O.$ excited by photons. Indeed, the excitation energy of one O_2 molecule due to the absorption of UV radiation with a wavelength of 270 nm during an electronic transition $^3\Sigma_g^- \to {}^3\Sigma_u^+$ is 4.59 eV [12], and the dissociation energy of O_2 is 5.12 eV. Note that both reactions can occur in the immediate vicinity of the lamp, where the intensity of UV radiation is maximum and, accordingly, the photon density is sufficiently high. This is due, on the one hand, to weak absorption at the indicated electronic transition and, on the other hand, to the need to prevent the loss of excitation of molecules due to radiation in the gaps between collisions.

5. 3. Investigation of the influence of LED systems of ultraviolet radiation on the indicators of microflora in the room

Biological samples were taken in each room at three points before the room was irradiated and three months after the installation of the equipment (Fig. 3).

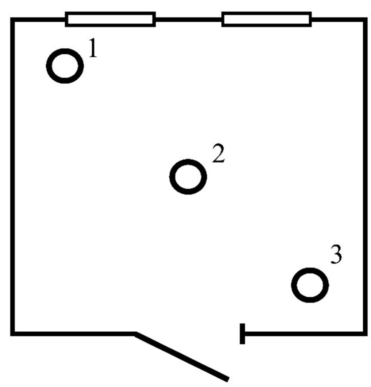

Fig. 3. Indoor biological sampling points

The amount of dangerous microflora was estimated by the number of colonies of forming units (CFU) per 1 decimeter of square surface. The method of washing with tampons was used.

Data on mold fungi in individual points of the premises are given in Table 6.

Table 6

Number of CFU of mold fungi per 1 dm^2 surface area in the tested premises

Date of study	Research points, room No. 3			Research points, room No. 2			Research points, room No. 1		
	1	2	3	1	2	3	1	2	3
Initial data	120	8	10	27	7	9	25	45	36
In 3 months	3	4	0	7	6	6	18	44	27
Effect	Reduction of CFU by 20 times			CFU decrease by 2.3 times			Virtually unchanged		

The data in Table 6 show that the greatest contamination with mold fungi is observed at the point farthest from the entrance door. The greatest effect of CFU reduction is achieved with the combined action of ultraviolet radiation and the use of air recirculators (20 times), with ultraviolet emitters alone (room 2) – by 2.3 times. In control room No. 1, there are practically no changes.

Table 7 gives data on changes in the total microbial count (CFU/dm^2) in the premises.

The data in Table 7 show that the greatest effect is achieved by using only bactericidal ultraviolet radiation (room No. 2). The combined effect of direct ultraviolet radiation and air recirculators gives the best effect. This result is the opposite compared to changes in fungal colonies, although in both cases the effect on the improvement of the environment is significant. There were practically no changes in control room No. 1.

Table 7

Total microbial number in test rooms

Date of study	Research points, room No. 3			Research points, room No. 2			Research points, room No. 1		
	1	2	3	1	2	3	1	2	3
Initial data	80	194	42	66	70	114	33	23	36
In 3 months	77	90	33	23	16	52	40	27	38
Effect	Reduction of CFU by 1.6 times			CFU decrease by 2.8 times			Virtually unchanged		

In general, it can be concluded that in each specific case, taking into account the initial data on the pollution of the premises, it is possible to choose an effective means of improving the environment.

6. Discussion of results of investigating the effectiveness of the use of LED systems of ultraviolet radiation for the disinfection of premises

An increase in the concentration of aero ions and a decrease in the number of colonies of bacteria and fungi in the experimental premises indicate the possibility of using LED systems of ultraviolet radiation to effectively improve the environment of a large number of people.

Experiments have shown that such systems, unlike traditional solutions [3], can be used in the presence of people. At least at a distance of 2 m from the source for 8 hours, the energy exposure does not exceed the maximum permissible level of 30 J/m^2. This meets the requirements of the SBM-2015 standard and the European directive 2006/25/EU.

It is advisable to use such systems in places where a large number of people are permanently or temporarily staying, educational facilities, civil defense storage facilities, etc.

Studies have proven (Table 5) that the ultraviolet radiation of LEDs effectively ionizes the air and maintains the concentration of aero ions at the proper level (>500 cm^2 of each polarity). The advantage of such systems, compared to traditional ones using high-voltage discharges and ultrasound, is the absence of side effects (generation of ozone, nitrogen compounds) and the need to spread aero ions from the source by directed air movement [8]. The concentration of air ions increases immediately after switching on the lamps. Differences in the concentration of air ions, at least in one room, at distances of 4–5 meters are within the limits of the radiation error. This becomes possible due to the instantaneous distribution of ultraviolet radiation quanta throughout the room and their interaction with air molecules. The dynamic equilibrium of the concentration of aero ions was reached within 10–15 minutes after turning on the devices. Unlike traditional air ionization systems, the presence of people when using ultraviolet emitters does not affect the concentration of air ions. This is explained by the continuous process of air ionization, including in the breathing zone.

In contrast to previous studies [5] on the use of bactericidal systems in primary institutions, this work contains quantitative characteristics of environmental disinfection. It has been proven (Tables 6, 7) that the use of LED ultraviolet radiation is an effective means of reducing the number of mold fungi colonies (up to 20 times) and the microbial number (up to 2.8 times).

The established dependence of the spatial decrease in the intensity of ultraviolet radiation (Fig. 2) makes it possible to determine the location of sources of ultraviolet radiation that is safe for people and acceptable for improving the environment, based on geometric considerations.

But the study has some limitations due to a number of unanswered questions. The mechanism of the air ionization process from the point of view of the physics of atmospheric processes requires research [13]. The relationship between the formation of ions and finely dispersed aerosols in the air, as well as the dynamics of aerosols and dispersed dust as a result of interaction with aero ions, has not been fully elucidated. In the process of human exhalation of warm air, aerosols are formed that interact with aero ions. Determining the degree of air deionization due to such interactions will make it possible to optimize the number, power and placement of sources of ultraviolet radiation. Such information will contribute to the development of more effective methods of improving the environment.

A limitation of the study is also the determination of the effect of ultraviolet radiation on only two pathogenic factors. The difference between the effects of ultraviolet radiation and radiation in combination with air recirculators on fungal colonies and microbial flora requires careful research. This will make it possible to improve the regulations for the use of modern bactericidal air and surface disinfection systems.

The disadvantage of research is the uncertainty of the energy balance of radiation and air ionization. Quantifying such a balance in the future may provide factual material for designing LEDs and UV LED systems with parameters optimal for environmental health.

7. Conclusions

1. It has been established that the use of LED systems of ultraviolet radiation with a predominant wavelength of 280 nm (UV-C) can be used in rooms where people are present. But the distance from the source should be at least 2 meters for a duration of 8 hours of operation. Under such conditions, the safe dose of 30 J/m^2 is not exceeded. The principles of designing the placement of lamps based on experimental data on the decrease in radiation intensity with distance have been determined. This meets the requirements of SBM-2015 standards and European Directive 2006/25/EU.

2. The use of LED systems of ultraviolet radiation is an effective means of air ionization of indoor air. Aero ion concentrations increase from 140–180 cm^{-3} (positive) and 160–190 cm^{-3} (negative) to 1100–1460 cm^{-3} (positive) and 1260–1470 cm^{-3} (negative). At the same time, the ionization process takes place in the entire volume of the room, at least at a distance of 4–5 meters from the radiation sources. The physical mechanism of air ionization in the entire volume of the room, which is mostly associative, has been clarified.

3. The use of LED environmental disinfection systems makes it possible to reduce the number of colonies of mold fungi and bacteria. Under the combined influence of ultraviolet radiation and air recirculators, the number of mush-

room colonies decreases by 20 times, under the influence of ultraviolet radiation alone – by 2.3 times. Microbial pollution in the first case is reduced by 1.6 times, in the second – by 2.8 times. Such a contradiction requires further research on improving the methodology of improving the environment.

Conflicts of interest

The authors declare that they have no conflicts of interest in relation to the current study, including financial, personal, authorship, or any other, that could affect the study and the results reported in this paper.

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Data availability

All data are available in the main text of the manuscript.

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