SAFETY OF THE USE OF ULTRAVIOLET BACTERICIDAL LED LAMPS

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Abstract
Given the rapid development of technologies in the field of ultraviolet LEDs, there was a need for their detailed research, especially their impact on the human body. The paper analyzes the state of the field of bactericidal radiation using ultraviolet LEDs. Special attention was paid to the photobiological safety of ultraviolet radiation. As a result of a theoretical study, general recommendations for bactericidal installations with ultraviolet LEDs were determined.

Keywords: ultraviolet, bactericidal installations, LEDs, blue light safety, photobiological safety.

INTRODUCTION

The speed of development of the LED lighting industry is constantly growing. The first impetus was the creation of the world's first blue LED by Japanese scientists Isamu Akasaki, Hiroshi Amano, and Shuji Nakamura. For their incredible invention and decades of work, they received the Nobel Prize in Physics in 2014. This very moment is a turning point in the industry and accelerated the development of LED ultraviolet lighting tenfold. One of the latest breakthroughs in this field was the creation of aluminum nitride-based diodes that can emit light in the ultraviolet range with a wavelength of 210 nm at the research laboratory of Nippon Telegraph and Telephone Corporation under the direction of Dr. Yoshitaka Tannyasu. Their use is able to ensure distributed disinfection of a significant number of contaminated elements located on a significant plane. Experiments conducted by Japanese scientists confirmed the possibility of using ultraviolet LED light sources to disinfect surfaces and the environment even from viruses.[1]

Thus, we now have LEDs that emit in the most effective for disinfection wavelength range with a peak of 254 nm, which is the most optimal option for obtaining the maximum bactericidal effect. Fig. 1 shows the spectrum of sunlight, where the wavelength range of disinfection cleaning is separately highlighted, as well as the wavelengths of the peak of bactericidal efficiency (254 nm) and the shortest wavelength of existing LEDs in the world (210 nm).

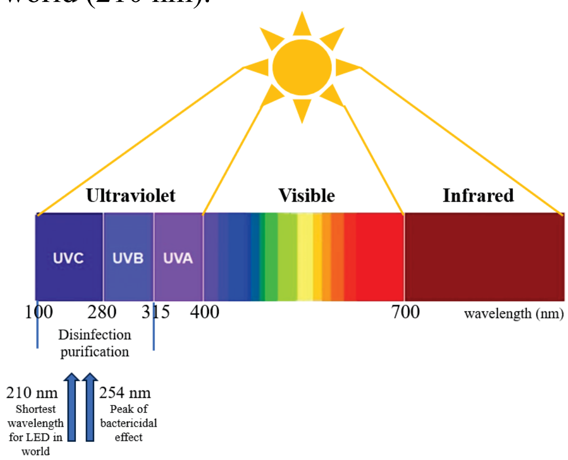

Fig. 1. *Spectrum of sunlight showing disinfection cleaning range, peak bactericidal efficiency and lowest wavelength of existing LEDs*

All this was caused by the growing demand of society for mobile, safe and effective means of disinfection that could protect a person from the negative effects of the environment. One of the first challenges was the pandemic. In addition to this, the increase in the number of wars, armed conflicts and environmental disasters in the world has also increased the demand for disinfection systems that can be used in the presence of people. This is due to the fact that the use of civil protection premises, which are used in case of emergency situations, involves the presence of a large number of people in an extremely small area. This leads to negative trends in the deterioration of air quality - its deionization, increased concentrations of aerosols due to breathing, etc., even under the condition of regular functioning of ventilation systems. In addition, some people can be carriers of various infections. This requires air disinfection.

But scientists face the problem of photobiological safety of such installations, and the latest research by the US Energy Efficiency and Renewable Energy Administration, which was published in their CALiPER report [2] in September 2023, confirmed the need for detailed research and increased requirements for such systems. Thus, it was determined that the radiometric characteristics of bactericidal ultraviolet (GUV) products show striking discrepancies between the claims of manufacturers and the actual characteristics of the product. This, in turn, affects the safety and efficiency of such systems and makes increasing the accuracy and reliability of these devices a primary problem.

EXPOSITION

Existing research has previously focused on the effects of ultraviolet radiation at a wavelength of 254 nm, as this wavelength is the most effective in fighting viruses, but despite the development of technology and the appearance of safer LED lamps, the negative effects of ultraviolet radiation on the body of humans and mammals in general have remained. Therefore, with the advent of shorter wavelength LEDs with a wavelength of 222 nm, more studies have appeared that try to prove the effectiveness and greater safety of such light sources.

The first indications for the use of UV-C to kill microbes appeared in the 18th century.[3] Ultraviolet radiation (UV-C), with a range of 100-280 nm (peak 254 nm), is absorbed by RNA and DNA bases. This causes the inactivation of microorganisms by disrupting the process of DNA replication. In general, this process disrupts cellular function, leading to the death of bacteria and inactivation of viruses. [4-6] However, the ability of ultraviolet radiation to neutralize bacteria, viruses and fungi depends on its intensity, wavelength and duration of exposure.[7]

Usually, UV-C radiation is used to disinfect air and water. The use of low-pressure mercury vapor lamps, which usually emit light at a wavelength of 254 nm, has been effective, but their harmful effects have become a problem and an obstacle to widespread adoption, and the UN ban has pushed inventors to new developments. It is because of this that the need for LED sources arose. So, according to research, such light sources can inactivate from 90 to 100% of viruses and bacteria.

Many scientific studies show that the effectiveness of UV devices depends on the duration of exposure and exposure time. The destruction of microorganisms by UV light was more effective when the distance between the light source and the microorganisms was shorter and the exposure time was longer. Researchers such as Yang J et al [8] reported that efficacy was higher when the distance from the UV-C device was 1 meter compared to 2 meters and 3 meters, and when exposure time was 15 minutes compared to 10 minutes and 5 minutes. These studies point to the key factor that the inactivation of organisms depends on the dose of exposure.

It is known that the radiation emitted by the original germicidal lamp with a wavelength of 254 nm poses a potential threat to human health. This can lead to problems such as corneal irritation, conjunctival irritation (known as photokeratoconjunctivitis) and skin irritation such as erythema, swelling, burning and other symptoms. The World Health Organization recognizes UV-C as the most harmful to the skin compared to other components of solar radiation. [6,9,10]

In terms of biophysical principles, like other ultraviolet radiation, UV-C can theoretically be carcinogenic through the same mechanisms that make it an effective bactericidal agent. Long-term exposure to radiation can damage the DNA of the human body due to dimerization of pyrimidines. [10,11]

However, different wavelengths of UV light affect skin tissue differently. Waves with a longer length can penetrate deeper into the skin tissues. UV (315-400 nm) can penetrate deep into the dermis, while UV-B (280-315 nm) is absorbed more superficially by the epidermis, and UV-C (100-280 nm) mainly affects the outer layer of the skin , including the stratum corneum.[12] Because of this last fact, only a limited amount of UV light can penetrate the deeper layers of the skin. The protection provided by the stratum corneum and epithelial tissues can significantly reduce the risk of carcinogenesis caused by UV-C radiation compared to UV-B radiation. Also, scientific studies confirm that UV-C is less likely to cause skin cancer compared to UV-B.[13-16]

A recent study of 330 healthcare workers working with the SARS-CoV-2 pandemic found that 16.7% of them were directly exposed to UV light. This situation raises concerns about his safety. [17] Researchers including Narita K et al [18] demonstrated that a single exposure of mouse skin to UV-C at a wavelength of 254 nm (75 mJ/cm²) resulted in the formation of CPD in the outer epidermal layer, which then assumed a flattened shape. Thereafter, UV-C was detected in the stratum corneum only 24 hours after exposure. This study provides interesting information that, even if 254-nm UV-C radiation can have a mutagenic effect on cells, the normal turnover processes of these cells can regulate the consequences of its exposure. There is currently no evidence that short-term use or single exposure to 254-nm UV-C is associated with a risk of carcinogenesis. However, it is important to distinguish it from the situation with prolonged exposure.

After prolonged exposure to 254 nm UV light (450 mJ/cm²/day for days 1, 2, 3, 4, 5, 8, 9, 10), observations showed that sunburn and peeling occurred on days 4 and 5 skin However, these side effects subsided after cessation of exposure for 2 days. Cells that expressed CPD were found only in the hyperkeratotic stratum corneum of the skin. At the same time, histological studies revealed the presence of parakeratosis, intracellular edema and epidermal hyperplasia. Recent changes in tissue structure are closely related to the possibility of tumor development, even more so than the level of DNA damage from UV light.[19] Given this, healthcare professionals are advised to avoid constant and direct exposure to UV radiation. If radiation is necessary, they should limit the time and cover exposed areas of the skin with clothing.

Recently, due to the frequent use of UV-C for disinfection and the high safety risk, some studies have tested the theory that light with a narrower wavelength range can kill microorganisms without harming human cells. Since ultraviolet light with a very short wavelength of about 200 nm is intensively absorbed by proteins, in particular peptide bonds, and other biomolecules, its ability to penetrate biological materials is limited. These wavelengths cannot penetrate the stratum corneum of our skin (5-20 micrometers thick), but can penetrate bacteria and viruses because their cells are much smaller than mammalian cells. [20-22] Thus, ultraviolet C light with a narrower wavelength range (200-230 nm) is considered safe for human cells because it is strongly absorbed by bioaerosols but does not reach the nuclei of mammalian cells. [23,24] Also international organizations note that traditional means of disinfection - mercury lamps are prohibited to be used in the presence of people. Therefore, LED light sources are the way out. The only limitation is the location of such emitters at a distance of 2 m from people in compliance with the requirements of biological safety according to EN 62471:2008 IDT and IES 62471:2006.

This is supported by studies using UV light with a wavelength of 222 nm, which suggests that far UV light (207-222 nm) can potentially be used to inactivate microorganisms without harming the skin. There is new evidence that long-range UV radiation at 222 nm penetrates primarily the upper epidermis, but not the basal layer. Also, new data confirm that UV radiation with a wavelength of more than 250 nm (in particular, 270-310 nm) must be filtered in this case. [23,24]

Another study aimed at studying bactericidal light sources showed that the depth of penetration of ultraviolet radiation into the limbal epithelium of the cornea of rats depended on the wavelength. 311 nm UV-B and 254 nm UV radiation reached the basal epithelial cells as well as the central corneal epithelium, while 235 nm radiation reached the middle region. On the other hand, UV-C with a wavelength of 207 and 222 nm reached only the surface layer of the epithelium. The same situation was observed in the case of the limbal epithelium of the pig cornea, where UV-C with a wavelength of 222 nm reached only the surface layer. These results suggest that UV-C with short wavelengths such as 207 and 222 nm were unable to reach the corneal epithelial stem cells. [25]

Another recent study aimed to determine the safety of chronic exposure to 222 nm UV light (450 mJ/cm²/day for days 1, 2, 3, 4, 5, 8, 9, and 10) and found that this radiation did not result in mutagenic DNA damage or changes in the epidermis of the skin of mice. Therefore, the available data confirm the possibility of using far ultraviolet light (207-222 nm) as an effective means of disinfection without negative effects on human health. [18, 26]

But despite all the advantages and possibilities of using such sources for disinfection, in view of recent studies [USA] it was found that the manufacturers of light sources manipulate terminology, use incorrect units of measurement, and the characteristics of the products were very often dubious and unverified. Thus, LED products that should emit UV-C actually emit UV-A, which is unacceptable because it poses a threat to people's safety. In addition, manufacturers inadequately assessed the effectiveness of UV-C radiation and significant differences were observed among similar products. Therefore, the results of this independent study confirmed the need to increase the control of manufacturers, the development of education in the industry, the creation of separate industry standards, special accountability, the need to standardize the methods of measuring the light technical characteristics of LEDs.

The study also confirmed the presence of significant differences in radiometric characteristics between different types of products and GUVs. In addition, the lower UV-C radiation efficiency of LED products was confirmed than LPM products. In addition, manufacturers often did not take into account the spectrum and intensity distribution to determine the bactericidal efficiency.

Unfortunately, all this repeatedly proves the lack of standardized lighting and electrical calculations of such systems, which prevents their introduction into existing disinfection systems and causes the low energy and lighting efficiency of such installations. Therefore, in order to identify the general regularities of the creation of light space by LED light devices, the authors have developed a method of synthesis of light devices based on the known luminous intensity curve (LIC) of a single LED light source. A model of the form was used to form the light power curve of the device:

$$I'(\lambda) = F\left(I(\lambda), N, K\right) = F\left(I_0, N, 2\theta_{0,5}, K\right) \quad (1)$$

where $I'(\lambda)$ is the distribution of light intensity of SP; $I(\lambda)$ – light intensity distribution of one LED; N is the number of LEDs in the device; I0 is the axial light intensity of one LED; $2\theta_{0.5}$ – illumination angle of one LED; K is a coefficient that takes into account the distribution of light power from the optical element of the lighting device.

Modeling of light distribution of LEDs was carried out on the basis of Lambertian type curves using spline approximation as the most effective description of this process. Finding the desired spline - a function describing the distribution of light intensity of an LED light source in space is reduced to the solution of a system of linear equations of algebra. For this, the Light Power software was developed, which provides the calculation of the LIC of LED devices with an arbitrary location and orientation relative to a certain center of the LED, as well as for each state of the transmission medium.

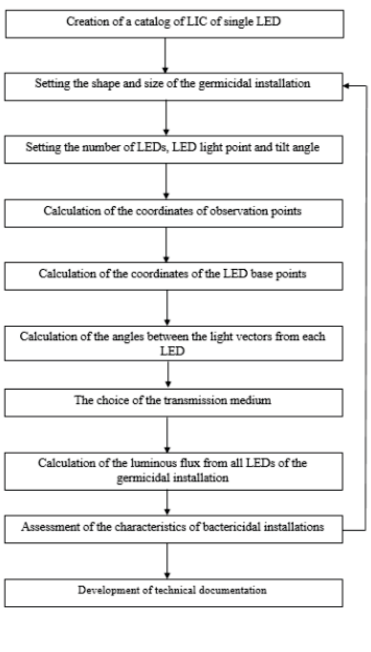

Fig. 2. *Algorithm for calculating bactericidal installations with LED light sources*

In fig. 2 presents the algorithm for calculating the parameters and characteristics of lighting devices based on LED light sources.

The result of the calculation is a graph of light distribution in the plane where the observation points are located. The graph is a curve of luminous intensity (LIC) in an arbitrarily chosen plane passing through the axis of the lamp. LIC of a simulated LED lamp is calculated in two stages: 1) At the first stage, a catalog of LIC of single LEDs of various modifications is created, from which LED lamp is supposed to be created; 2) At the second stage, the light intensity from all LEDs of the lamp is calculated at the observation points.

CONCLUSION

In summary, we can say that due to the ability to inactivate a wide range of microorganisms, ultraviolet radiation can be a promising tool for disinfection in medical facilities, civil defense facilities, etc. So, summarizing, the following basic recommendations can be made for the development and use of ultraviolet LED lighting systems:

1. Use ultraviolet as an additional means of disinfection, taking into account all limitations and effectiveness.
2. For the use of ultraviolet devices in rooms with constant presence of people, it is necessary to use short-wave UV-C in the range of 200-230 nm with filtering of wavelengths above 250 nm. To ensure human safety.
3. When using UV-C systems with a wavelength of 254 nm, people are advised to avoid continuous and direct exposure. Namely, short-term and irregular stay indoors with the use of skin and eye protection.
4. Increasing control of manufacturers, developing education in the industry, creating separate industry standards, special accountability, the need to standardize the methods of measuring light technical characteristics of LEDs.

5. The use of algorithms for the calculation of bactericidal installations with LED light sources, in order to ensure high technical characteristics, safety, efficiency, quality and a high level of product inspection.

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