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LED TECHNOLOGY FOR DRINKING WATER PURIFICATION

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Summary: Water supply systems are one of the most important life support systems of society. The existing methods of water purification and disinfection are not able to meet modern requirements for the quality of drinking water and do not fully meet the requirements for energy efficiency due to the use of ineffective equipment and technologies. The purpose of this paper is to find effective ways to reduce the effect of harmful organisms in the water on humans by disinfecting it, using light radiation of a certain intensity and spectrum of radiation. The task of the paper is to assess the effect of LED sources of ultraviolet light on harmful organisms in the water and to determine the radiation spectrum that will have the greatest impact on them. According to the results of the study, a mathematical model of the process of radiation exposure to harmful organisms in the water, and the identification of the conditions for the effective use of disinfecting installations were developed. The practical value of the obtained results lies in the possibility of the practical application of LED ultraviolet light emitters for the purification of drinking water at any stage of water preparation and at various levels of water supply.
Keywords: drinking water, LED technology, water treatment.

1. INTRODUCTION

One of the most urgent problems affecting every inhabitant of our planet and the future of humankind is to meet the requirements for high-quality drinking water. According to such world organizations as WHO, UNICEF, UNESCO, United Nations, and others, this problem is much larger than we can imagine. So in 2010 the UN General Assembly clearly recognized the human right to water and sanitation. Everyone has the right to an adequate, uninterrupted, safe, physically accessible, and affordable water supply for personal and domestic needs.

According to the WHO, 5.3 billion people used safe water services in 2017, which means they have an improved water source where they live, available when needed, and pollutant-free. The remaining 2.2 billion people in 2017 were without reliably managed water services:

– billion people with basic services, that is, an improved water source that takes less than 30 minutes to access,

– 206 million people with a limited, improved water source that takes more than 30 minutes to access,

– 435 million people receiving water from unprotected wells and natural sources,

– 144 million people withdrawing untreated surface water from lakes, ponds, rivers, and streams.

In addition, the world still retains clear geographical, socio-cultural, and economic inequalities, not only between rural and urban areas but also in cities and towns, in which people living in poor, informal, and illegal settlements usually enjoy more limited access to improved drinking water sources than other residents.

In general, according to WHO, UNICEF, UNESCO, and the United Nations:

– 2.21 billion people lack access to safe drinking water (WHO / UNICEF, 2019),

– more than half of the world's population or 4.52 billion people lack access to safe sanitation and hygiene services (WHO / UNICEF, 2019),

– 297,000 children under five die each year due to inadequate sanitation, poor hygiene, or unsafe drinking water (WHO / UNICEF, 2019),

– 2 billion people live in water-stressed countries. (UN, 2019). Water scarcity already affects four out of every 10 people (WHO, 2019),

– 80% of wastewater is returned to the ecosystem without treatment (UNESCO, 2017).

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In 2017, 71% of the world's population (5.3 billion people) used a safe drinking water supply that is community-based, accessible when needed, and free from contamination (WHO).

In the least developed countries, 22% of health facilities lack water, 21% lack sanitation, and 22% lack waste management services. (WHO)

The economic and social implications of this phenomenon are that when water comes from improved or more readily available sources people spend less time and effort physically sampling it, allowing them to engage in other, more productive work. It could also lead to increased human safety by limiting a long and risky search for water. Better sources also mean lower health costs as people will be less sick, they would not have to bear medical costs, and they will become more physically active and more economically productive.

Given that children are particularly at risk of water-related illnesses, access to improved water sources means less time for them to access water, better health, and more regular school attendance, which would positively impact their lives in the long run.

Climate change, increasing water scarcity, population growth, demographic change, and urbanization already pose challenges to water supply systems. Given the above, it can be assumed that by 2025, half of the world's population will live in areas characterized by a shortage of quality water. Currently, one of the important solutions to the problem is the reuse of wastewater for the recovery of water, nutrients, and energy. At present, countries are increasingly using wastewater for irrigation. In developing countries, it accounts for 7% of the total irrigated land area. However, their irrigation is usually performed incorrectly, thus creating health risks.

The use of water sources for drinking water and irrigation will continue to develop, with a greater emphasis on groundwater and alternative sources, including wastewater. Climate change will lead to greater fluctuations in rainwater harvesting. To ensure the availability and quality of water, it is necessary to improve the regulation system of all water resources.

2. ANALYSIS OF METHODS AND TECHNICAL MEANS OF WATER PURIFICATION

Another way to solve the problem of the increased high-quality drinking water production is to bring the quality of the water used to the sanitary and hygienic standards. It should be noted that at present there are no technical means for water purification that would meet all the requirements and ensure stable water purification.

For example, in Ukraine, the bulk, namely, 2/3 of Ukrainians consume water from rivers, lakes, and reservoirs, and 1/3 receive water from underground sources.

The water purification scheme (Figure 1) at Ukrainian enterprises is traditional and consists of the following main stages:

– dosing of reagents;
– mixing;
– upholding;
– filtration;
– secondary disinfection;
– supply to consumers.

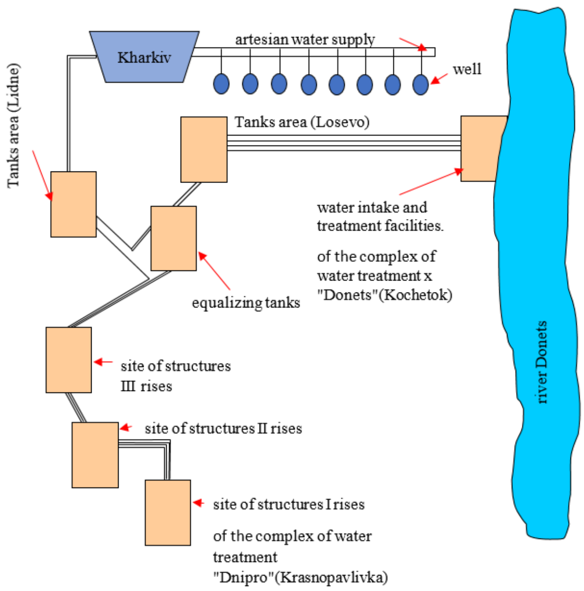

Figure 1. Scheme of water purification in Kharkiv

Most enterprises in Ukraine use chlorination, and rarely ozonation, to disinfect water. A typical scheme for the preparation of drinking water is shown in Figure 2. It should also be noted that the treatment equipment in most cases is very energy – intensive, and is in a state of extreme wear requiring urgent reconstruction, which in turn greatly affects the quality of water purification.

The main problems in such wastewater treatment plants are:

– the need to reduce the content of dissolved organic matter in water;

– the formation of organochlorine compounds that harm the human body;

– the need to remove various contaminants of anthropogenic origin;

– increasing the efficiency of water disinfection concerning various groups of microorganisms;

– treatment of flushing water, filters, and sediments formed.

Tables 1 and 2 show the characteristics of the quality of drinking water in Kharkiv obtained using a typical treatment scheme. Similar data were obtained in other cities of Ukraine [7].

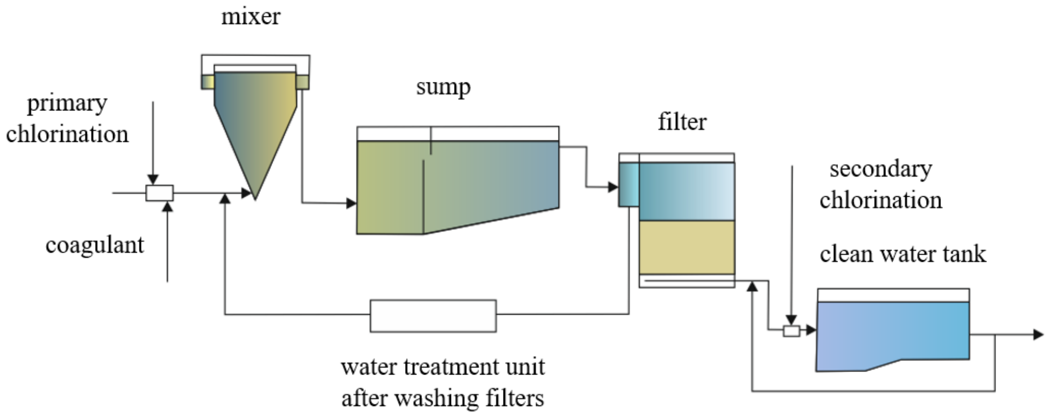

Figure 2. Typical drinking water supply scheme in Ukraine

Table 1. Characteristics of drinking water in the city of Kharkiv

Indicators	Unit of measurement	Kharkiv	DSTU 7525: 2014	DSanPiN 2.2.4-171-10	WHO and EU
Coloration	hail.	ten	20	20	15
Turbidity	mg / dm3	0.5	2.5 NOM	0.5 (1.5)	2.0
Hardness	mmol / dm3	6.8	7.0 (10)	1.5-7.0	1.0-2.0
Alkalinity	mmol / dm3	5.2	6.5	0.5-6.5	not the norm.
Oxidizability	mgO / dm3	6.5	2	4	2
Aluminum	mg / dm3	0.12	0.2 (0.5)	0.2 (0.5)	0.2
Iron	mg / dm3	0.3	0.2	0.3	0.2
Sulfates	mg / dm3	185	250 (500)	250 (500)	250
Chlorides	mg / dm3	52	250 (350	250 (350)	250
Nitrates	mg / dm3	1.9	45	45	Thirty
Dry residue	mg / dm3	695	1000 (1500)	100-1000	<1000

Table 2. Characteristics of drinking water in the cities of Ukraine

Indicators	Unit of measurement	Kharkiv	Dnipro	Zapori-zhzhia	Odessa	Mikolaiv	Kiev
Coloration	hail.	ten	20	sixteen	nine	8.0	15.0
Turbidity	mg / dm3	0.5	0.8	0.6	0.3	0.5	0,4
Hardness	mmol / dm3	6.8	4.0	3.6	4.0	3.5	3.5
Alkalinity	mmol / dm3	5.2	3.0	2.6	3.0	3.0	3.0
Oxidizability	mgO / dm3	6.5	9.0	7.5	2.0	7.5	5.0
Aluminum	mg / dm3	0.12	0.17	0.1	0.13	0.12	0.18
Iron	mg / dm3	0.3	0.2	0.2	0.1	0.1	0.15
Sulfates	mg / dm3	185	108)	45	50	185	41
Chlorides	mg / dm3	52	39.9	40	28	51	39
Nitrates	mg / dm3	1.9	2.2	1.0	0.003	0.2	0.3
Dry residue	mg / dm3	695	380	318	311	285	288
Water supply source		Siverskiy Donetsk, Dnipro	Dnipro	Dnipro	Dnister	Ingulets, Pivdeniy Bug	Dnipro, Desna

Thus, according to most indicators, the quality of drinking water in Ukraine differs significantly from the WHO and EU requirements. Therefore, we can conclude that the methods of water purification currently used are ineffective. One alternative solution is the use of ultraviolet radiation for water purification. The technology of ultraviolet irradiation for the disinfection of various environments and surfaces has been used for a long time. Ultraviolet light can indeed be an insurmountable barrier against all known microorganisms, including its effectiveness against microorganisms resistant to chemicals. However, for the UV equipment to effectively solve the set task, it is necessary to correctly select the power of bactericidal radiation, providing the necessary disinfection effect. In particular, for the disinfection of domestic and municipal wastewater, a UV dose of at least 30 mJ/cm2 should be used. However, in practice, the water matrix is so unique that a given dose can be either more than sufficient or less than necessary [1]. Ways to improve water disinfection systems and water treatment, in general, should be sought in new methods involving the use of more flexible and energy - efficient systems. Analysis shows [2] that high technical and economic indicators are provided by bactericidal installations based on LED light sources, which, along with the improved energy characteristics, also provide dispersing the installation of bactericidal action and multi-stage disinfection of water. At the same time, studies of water disinfection processes and determination of requirements for germicidal installations based on ultraviolet LED light sources have not yet been carried out. This applies to lighting and electrical calculations of bactericidal installations based on LED light sources. Their absence hinders the introduction of LED water purification systems into the existing water disinfection schemes and determines the low energy and lighting efficiency of such installations. To avoid a secondary contamination by microorganisms, we are considering a distributed water disinfection system based on the use of energy-efficient ultraviolet LED light sources. As studies have shown this hinders the repeated development of microorganisms, since when organic cells of various bacteria are exposed to ultraviolet radiation of spectral composition from 200 to 400 nm cell destruction is observed (Figure 3).

Since the purpose of the ultraviolet radiation installation is to neutralize bacteria, only photons with an energy capable of breaking the bond of protein molecules by radiation with a wavelength of λ < 300nm should have bactericidal properties in them (Figure 4).

The analysis of the spectrum of bactericidal action of installations (Figure 4) leads to the conclusion that the greatest efficiency of bactericidal installations is provided by light sources with a wavelength of 205 - 315 nm. In the research laboratory of the Nippon Telegraph and Telephone Corporation, under the leadership of Dr. Yoshitaka Tannyasu, an aluminum nitride-based LED has been created, which allows emitting light in the ultraviolet range with a wavelength of 210 nm [3]. This creates conditions for solving the problem under consideration. However, the widespread introduction of such light sources in bactericidal installations is hindered by the lack of programs and methods for the lighting design of installations based on them.

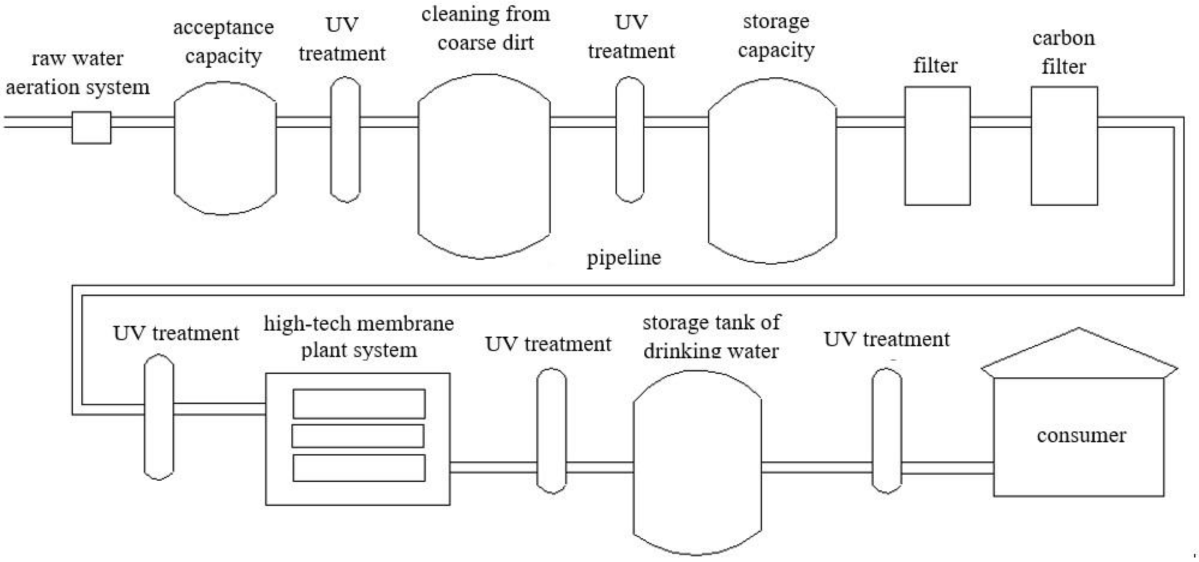

Figure 3. Structure of a water purification system using LED light sources

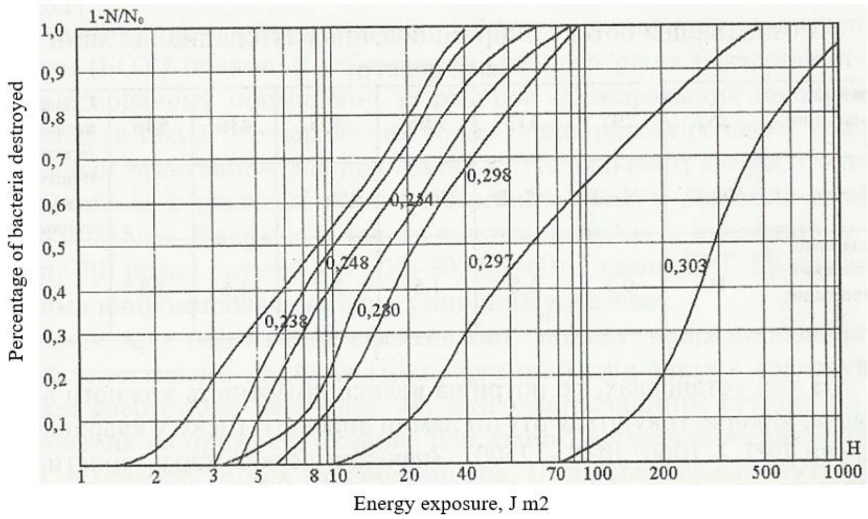

Figure 4. Spectrum of the effectiveness of the bactericidal action of radiation

The analysis of the literature investigating the issue under consideration indicates that when calculating light installations based on LED light sources, the traditional approach to calculating the light distribution of a single element that shines cannot be applied. It is necessary to calculate the entire area within which the elements are located and to take into account the interaction of these elements in creating an overall light distribution, and their interaction with the environment as well. Due to the insufficient knowledge of the regularities of the light distribution of LED light sources, and the low accuracy of their description, the calculation of the characteristics of lighting devices based on them, as well as lighting installations, is rather difficult and does not solve this problem.

The structural model of visualization of the light space created by LED light sources can only be realized for individual LEDs today. A lack of technical and methodological support for visualization of the lighting based on LED light sources causes low efficiency of lighting systems developed on their basis.

An analysis of publications devoted to modeling a light space using LED light sources, and describing methods for calculating the light distribution of light sources and lighting devices (LF) based on them, showed that publications are mainly devoted to describing LED light sources according to the conditions of a specific problem [4-5]. This does not allow the use of the developed models for any type of light distribution of light sources.

Real lighting devices consist of the n-th number of LEDs providing various designs and technical solutions for their design. Therefore, to determine the optimal number of LEDs and their relative position in the joint venture at the design stage, it becomes necessary to simulate the light distribution of the joint venture and creation of a technique for synthesizing installations with specified properties.

To identify the general patterns of creating a light space by LED lighting devices, it is necessary, based on the study of the light intensity curves (LSI) of the existing LED light sources, to establish the general patterns of their light distribution and development of mathematical models of the characteristics of LED SPs.

To achieve this goal, the authors have developed a synthesis technique for lighting devices based on the known luminous intensity curve (LSI) of a single LED light source. To form the luminous intensity curve of a device based on LEDs, a model of the form [6] was used:

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

where I '(λ) - light intensity distribution SP; I (λ) - luminous intensity distribution of one LED (LED) N is the number of LEDs in the device; I0 - axial luminous intensity of one LED; 2θ0.5 - angle of illumination of one LED; K - coefficient that takes into account the distribution of luminous intensity from the optical element of the light device.

Modeling of light distribution of LEDs was carried out on the basis of Lambert-type curves using spline approximation as the most effective description of this process. Finding the desired spline - a function that describes the distribution of the luminous intensity of an LED light source in space, is reduced to solving a system of linear algebraic equations. To this purpose, the Light Power software has been developed, which provides for the calculation of the LIC of LED devices with an arbitrary arrangement and orientation relative to a certain center of the LED, as well as for each state of the transmission environment. Figure 5 shows an algorithm for calculating the parameters and characteristics of lighting devices based on LED light sources.

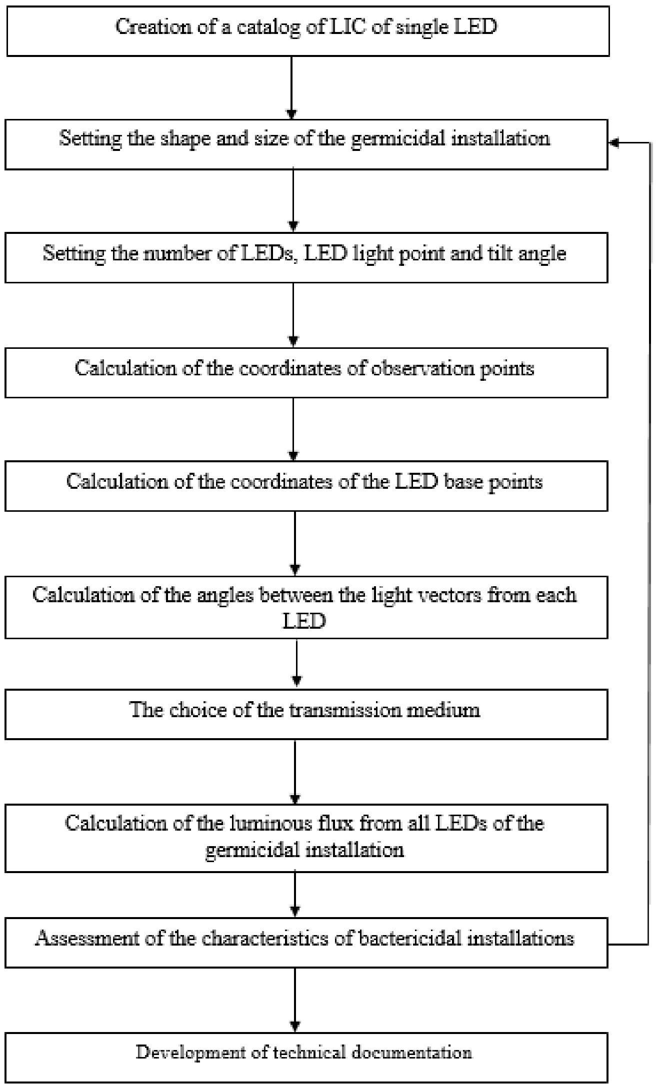

Figure 5. Algorithm for calculating germicidal installations with LED light sources

The calculation result is a graph of light distribution in the plane where the observation points are located. The graph is a luminous intensity curve (LSI) in an arbitrarily chosen plane passing through the axis of the lamp. The magnitude of the luminous intensity in this dependence is the result of the addition of the luminous forces at the observation point, from all the LEDs located in the LED lamp (LEDL). The angle is defined as the angle between the axis of the lamp and the beam to the observation point. To calculate the luminous intensity, the law of the squared distance I = E · L2 is used. To calculate the LSI of the LEDL, the LSI of single LEDs is used. Considering current conditions, the LSI LEDS is a cubic spline of approximation obtained on the basis of experimental measurements for a single LED. The LSI of the modeled LEDL is calculated in two stages.

At the first stage, a catalog of single LEDs of various modifications is created, from which the device is supposed to be created.

At the second stage, at the observation points, the luminous intensity from all LEDs of the lamp is calculated.

The second stage of the task is carried out in accordance with the developed methodology:

– calculation of the coordinates of observation points depending on the observation angle for a given step of changing the angle,

– calculation of the coordinates of the LED base points for the given LED luminescence points and the angle of inclination of the LED axis to the lamp axis,

– calculation of the angles between the light vectors from each LED and the vector that defines the axis of the LED.

Application of the developed methodology allows calculating the SOC from the LEDL for any conditions of use. Calculation of LSI for LEDL is reduced to the calculation of the luminous intensity at any point of the transmission medium Ai with coordinates (xa, ya, za) in a coordinate system in which the OZ axis coincides with the lamp axis. The origin point is the imaginary center of the lamp luminosity, which can be arbitrarily selected in the area of the diode placement plane. The XOY plane is perpendicular to the OZ axis and the OZ axis passing through the zero point. The direction of the OX axis is freely selectable. The algorithm used in the task for calculating the observation points Ai of the transmission medium is based on the statement that these points are in the XOZ plane.

Method for calculating the coordinates of the glow points of the transmission medium. To calculate the coordinates of the glowing points of the transmission medium, an algorithm for calculating the coordinates was applied, which consists in finding the coordinates of equidistant points of the transmission medium, when rotating them around the origin. In order to use this method, the following values are set:

– distance to calculation points R from the zero point of the coordinate system,

– the step of changing the angle when moving the calculation point around the point of the zero axis OZ. The step is used to calculate the angle between the calculation point and the negative direction of the OZ axis.

The cosine theorem determines the distances to the calculation points and their coordinates.

$$a = - R * \cos(\gamma) \quad (2)$$

Figure 6 shows the geometric interpretation of obtaining the coordinates of the calculation points as a result of rotation of the calculation point around the center of coordinates.

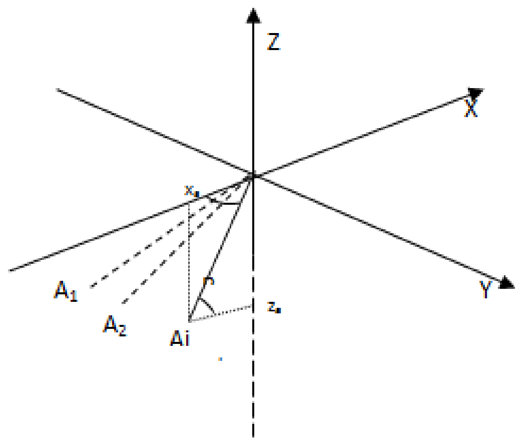

Figure 6. Determination of the coordinates of the point of calculation

The task of the angle of inclination of the LED axis to the lamp axis. The coordinates of two points in space, specified in a specific order, define a single vector. Thus, if you set two points lying on the rays of the axial light intensity of the LED enables setting the direction of the LED axis. The end point of the LED vector must be specified as the coordinates of the optical center of the LED. The starting point of the LED vector can be chosen arbitrarily, but it must necessarily belong to the beam of the axial light intensity of the LED. To determine the coordinates of the starting point of the LED vector in specifying the angle between the axes of the LED and the lamp, we calculate the angle obtained by drawing the plane through the OZ axis and the point of the optical center of the LED. The point of the optical center of the LED, perpendicular to the OZ axis, is restored. Hypotenuse of this triangle will protrude a segment of the geometric ray from the point of the optical center of the LED to the OZ axis. The angle between the hypotenuse and the OZ axis is specified when designing the lamp and is the angle of inclination of the LED axis to the lamp axis. The starting point of the LED vector, based on this construction, is the point of intersection of the hypotenuse with the OZ axis. Denoting the point of the optical center of the LED with coordinates Ds (xs, ys, zs) and using the tangent theorem for a right-angled triangle, we find the size of the leg belonging to the OZ axis in the form:

b = a * tg (γ), (3)

where a is the length of the leg, which can be found from the coordinates of the optical center point of the LED.

In the XOY plane, the projection of the optical center point of the diode has coordinates xs and ys, respectively. The vector length from the optical center to the OZ axis is √ (xs2 + ys2). Thus, leg b is defined as:

b = tg (xs2 + ys2). (4)

Coordinates of the point of intersection of the hypotenuse with the OZ axis (0, 0, zs + b). Figure 7 shows the geometric interpretation of the obtained coordinates of the points based on the LEDs.

You can set the coordinates of the starting point of the diode vector simply from the geometric image of the lamp. The task uses the calculation of the coordinates of the origin of the diode vector for each diode of the lamp according to the described algorithm, if the coordinates of the point of the optical center of the diode and the angle of inclination of the diode axis to the lamp axis are specified. When specifying the coordinates of the beginning and end points of the diode vector from the geometric construction of the lamp, the need for the problem of the angle of inclination of the diode axis to the lamp axis disappears.

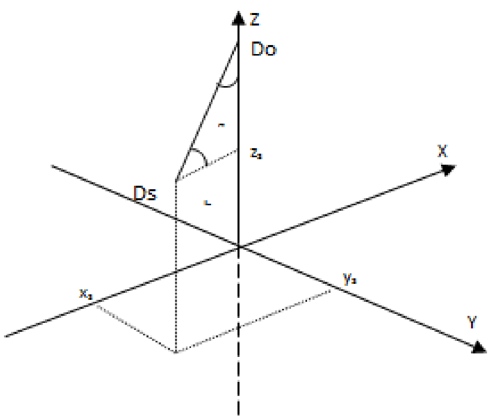

Figure 7. Determining the coordinates of the LED base point

To calculate the luminous intensity from the optical center of the LED to the point of calculation, the angle between the vector specifying the axis of the LED and the vector from the point of the optical center of the LED to the point of calculation is recognized.

The angle between vectors in space is found using the concept of scalar multiplication of vectors in accordance with this, the scalar product of two vectors a (Xa, ya, za) and b (X in, Yb, zb) is the sum of multiplications of the corresponding coordinates of the vectors: ab = xa * Xb + ya * yb + za * zb. On the other hand, the dot product of these vectors is the achievement of the lengths of the vectors multiplied by the cosine of the angle between them:

ab = | a | * | b | * cos (α). (5)

To find the angle between the axis of the LED and the vector from the optical center of the LED to the observation point, the start and end points are determined for each of the vectors. Figure 8 shows a geometric interpretation of obtaining the angle between the vectors defining the axis of the LED diode and the vector from the optical center of the LED directed to the observation point (observation vector). The first vector defines the axis of the LED and is assigned to the beam of the axial intensity of the LED. The vector is drawn from any point lying on the beam of the axial luminous intensity of the Do LED to the optical center of the Ds LED. The second vector is from the point of the optical center of the LED Ds to the observation point Ai.

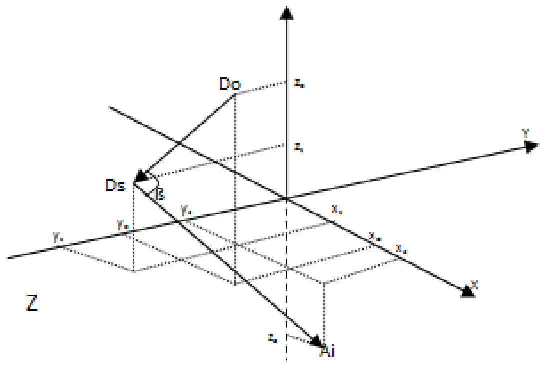

Figure 8. Determination of the angle between the axis of the LED and the calculation vector

The coordinates of the points that define both vectors: Ds (xs, ys, zs) - point of the optical center of the LED; Do (xo, yo, zo) - LED base point; Ai (xi, yi, zi) - the point of calculation (the point at which the total luminous intensity from the LEDs located in the lamp is calculated).

The coordinates of the LED vector D (Do, Ds) and the calculation vector A (Ds, Ai) are found using the coordinates of the start and end points of the vector:

D (xs - xo, ys - yo, zs - zo) A (xa - xs, ya - ys, za - zs)

Having determined the lengths of the vectors:

$$|\boldsymbol{D}| = \sqrt{((x_s - x_o)^2 + (y_s - y_o)^2 + (z_s - z_o)^2)}$$
$$|\boldsymbol{A}| = \sqrt{((x_a - x_s)^2 + (y_a - y_s)^2 + (z_a - z_s)^2)} \quad (6)$$

calculate the scalar attainment of vectors using their coordinates:

$$\boldsymbol{DA = (x_s - x_o) * (x_a - x_s) + (y_s - y_o) * (y_a - y_s) + (z_s - z_o) * (z_a - z_s).} \quad (7)$$

The scalar attainment of vectors is calculated using the definition of scalar multiplication:

DA = | D | * | A | * Cos (ß)

Equating the scalar attainments of vectors found in various ways, we find the angle between the vectors:

$$|D| * |A| * \cos(\beta) = (x_s - x_o) * (x_a - x_s) + (y_s - y_o) * (y_a - y_s) + (z_s - z_o) * (z_a - z_s). \quad (8)$$

$$\boldsymbol{\cos(\beta) = ((x_s - x_o) * (x_a - x_s) + (y_s - y_o) * (y_a - y_s) + (z_s - z_o) * (z_a - z_s)) / (|D| * |A|)} \quad (9)$$

Using previously found vector lengths and the arcos function, we find the value of the sought angle between the vector defining the LED axis and the vector from the optical center point of the LED to the observation point. After interpolation using the cubic spline approximation function for the selected LED, we calculate the luminous intensity from a specific LED at the selected observation point. Summing up the value of the received luminous intensities from all LEDs of the LEDL, we obtain the luminous intensity at this observation point.

It should be noted that the developed method for finding the angle between the vector specifying the LED axis and the vector from the optical center point of the LED to the observation point does not depend on the methods for calculating the coordinates of observation points and LED base points. Therefore, it can be applied to any arbitrarily chosen observation points, LED bases and their location environment, which makes the algorithm suitable for calculating the light distribution from LED systems for bactericidal water disinfection.

Figure 9 shows the experimental (-) and calculated (-) LSI at a distance of 1 m from the glow point. The difference between the calculated curves of the real ones does not exceed 10% and is explained by the difference in the parameters of individual LEDs of the SP, as well as their currents and thermal modes.

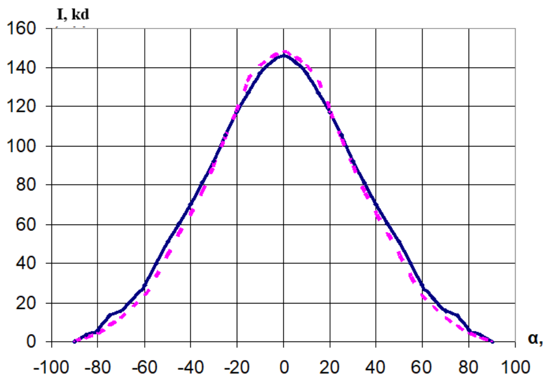

Figure 9. Calculation result

3. CONCLUSIONS

1. The studies carried out allowed to establish reasons for the deterioration of water quality, and installations requirements for its improvement.

2. The requirements have been determined and the design of an energy-efficient bactericidal installation based on ultraviolet LED light sources for multilevel water disinfection has been developed.

4. Investigation of the parameters and modes of the developed bactericidal installation and the conditions for its optimal functioning were given.

5. A technique has been developed for modeling the luminous intensity curve of a LED lamp based on the known luminous intensity curve of a single LED. We have experimentally proved the possibility of its application for calculating and designing bactericidal installations based on a certain number and placement of ultraviolet LEDs.

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ТЕХНОЛОГИЈА ЗА ПРЕЧИШЋАВАЊЕ ВОДЕ ЗА ПИЋЕ

Сажетак: Системи водоснабдевања један су од најважнијих система за одржавање живота у друштву. Постојеће методе пречишћавања и дезинфекције воде нису у могућности да удовоље савременим захтевима за квалитет воде за пиће и не испуњавају у потпуности захтеве за енергетском ефикасношћу због употребе неефикасне опреме и технологија. Циљ рада је пронаћи ефикасне начине за смањење дејства штетних организама у води на човека дезинфекцијом светлосним зрачењем одређеног интензитета и спектра зрачења. Задатак рада је процена утицаја ЛЕД извора ултраљубичастог светла на штетне организме у води и утврђивање спектра зрачења који ће на њих имати највећи утицај. Развијен је математички модел процеса излагања зрачењу штетних организама у води и одређени су услови за ефикасно коришћење дезинфекционих постројења. Практична вредност добијених резултата лежи у могућности практичне примене ЛЕД зрачника ултраљубичастог зрачења за пречишћавање воде за пиће у било којој фази припреме воде у различитим нивоима водоснабдевања.

Кључне ријечи: вода за пиће, ЛЕД технологија, пречишћавање воде.

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