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UV DISINFECTION TECHNOLOGIES FOR WATER, AIR AND SURFACE TREATMENT

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ABSTRACT

A review of the main modern achievements is presented in development, production and application of UV bactericidal lamps and irradiating installations with their use to disinfect water, air and surfaces. It is shown that LIT NPO takes a worthy place among most large-scale global manufacturers of such lamps and installations.

Keywords: UV radiation, UV irradiation, mercury lamp, amalgam lamp, UV radiating diode, UV installation, UV station, LIT NPO

The history of artificial UV radiation using comprises more than 100 years. For example, the fact that UV radiation disinfects water and air was known and began to be used at the end of the XIX and at the beginning of the XX centuries. However, understanding the fact that UV radiation is a unique tool to initiate or carrying out many physical and chemical processes on the surface and inside different environments only appeared within the seventies – nineties. It was time when, on the one hand, the range of tasks in chemistry, biology, medicine, material science, ecology, etc., where chemical methods were either powerless or expensive, or not eco-friendly, became obvious, and on the other hand, nature of many chemical, physical and biological processes became clear at the atomic and molecular level.

At present, technologies based on UV irradiation dynamically develop in industry, medicine, municipal services, power engineering, agriculture, etc. due to serious investments into developments and industrial production of modern powerful high-effective UV radiation sources and irradiating devices based on them. This in its turn is caused by these technologies application scope increase in the above-named fields [1].

The problem of disinfecting natural and sewage water became a development drive of UV irradiation use during the last 25 years. Its scope exactly motivated the leading world institutes and lighting companies to raise quality level of UV radiation sources development and production. New types of these sources were created, which provided new abilities of UV radiation in other fields as well.

A need of industrial water disinfection by non-chemical methods arose at the turn of the eightieth – ninetieth of the last century, when chlorine and its derivatives total harm for people and nature during the traditional chlorination of natural and sewage water was revealed. Strict standard limitations of chlorine derivatives concentration in water on the one hand, and general hygienic requirements, including microbiology (viruses, etc.), which significantly increased in the ninetieth, on the other hand, forced to change both general technological approaches to cleaning natural and sewage water, and approaches to the disinfection [2–5].

Municipal services and industries began to test and accustom ozonization, micro-, ultra- and nano-filtration commercially. UV treatment, replacement of liquid chlorine with more safe chlorine agents and combinations of these technologies pro-

Fig. 1. UV disinfection system of the Northern waterwork (St. Petersburg) of 1,584,000 m^3/day productivity (number of lamps type ДБ 350 is 3888 with total power consumption equal to 1.36 MW)

Fig. 2. UV disinfection station of surface water (Budapest, Hungary); number of lamps type ДБ 350 is 600, total power consumption is 210 kW

Fig. 3. UV disinfection station of the Kuryanovsky treatment facilities (Moscow)*;* number of lamps type ДБ 600 is 6120, total power consumption is 3.7 MW

Fig. 4. UV disinfection station of waste water (Beijing); number of lamps type ДБ900НО is 864, total power consumption is 700 kW

vide an improvement of water purification quality, its sanitary and ecological safety [6].

For the last years, this experience and practice exactly turned UV irradiation from the technology of little expenditures and special application conditions into economically effective basic technology of deep water disinfection, which is widely applied both: independently, and in a combination with other above-named technologies. For this purpose, it was needed to develop and master manufacture of large-scale industrial installations based on powerful UV radiation sources, to create stations of preparing drinking and sewage water treatment of any productivity.

Examples of the correspondent solutions are waterworks of St. Petersburg, Nizhny Novgorod, Budapest, New York and many other cities. In 2003–2008, Vodokanal SUE of St. Petersburg implemented a comprehensive upgrade of the water disinfection system. A modernisation result became creation of the world's largest system of UV stations, which encloses water supply of St. Petersburg and its suburbs [7]. Fig.1 [1] shows one of nine UV systems for preparation of drinking water in St. Petersburg: the Northern waterwork (the largest one in Europe).

The largest in the EU project of UV disinfection station in a system of drinking water preparation is implemented in Budapest (Hungary). Productivity of the station is 600 thousands m^3/day, Fig. 2 [8].

Within the industrially developed world, a total transition from chlorination of sewage water to UV disinfection takes place. So in the USA, more than 65 % of sewage water scope is already treated by

[1] The UV lamps and/or the comprehensive irradiating equipment with the lamps presented in this and in all subsequent figures are developed, made, supplied and put in commission by LIT NPO.

Fig. 5. UV irradiation of inner surfaces and air of underground carriages in depot

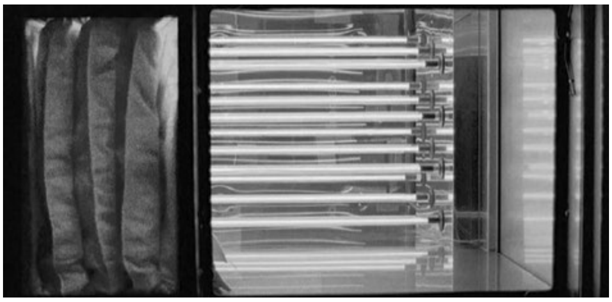

Fig. 6. UV module, which built in ventilation system of up to 15000 m^3/h productivity

UV irradiation, and in Russia it is approximately 30 %.

The world's largest UV system of sewage water disinfection consisting of four UV stations disinfects all municipal sewage water of Moscow with the design productivity of $3 \cdot 10^6$ m^3/day, Fig. 3.

As well intensely, technology of sewage water UV disinfection is introduced in the advanced countries of Asia (Republic of Korea, Malaysia, People's Republic of China). Fig. 4 shows an UV station of 780,000 m^3/day productivity started in Beijing in 2016 [9].

During recent years, one can observe a similar dynamics of UV radiation use for air disinfecting and cleaning, but several years later than water [10–13]. People in the urbanised world, more often are in a closed room: at home, at work, at school, in a high education institution, in transport and even on vacation.

And if earlier buildings and constructions were designed taking into account external air quality with a considerable part of natural ventilation, then now to achieve a comfortable state, air heating and conditioning are widely applied, including a partial recirculation for energy saving. And this requires an essentially new quality of air environment.

Global migrations of population all over the planet, with their concentration in urbanised space, with a long time of people stay in places of mass gathering cardinally aggravated the situation of broadening infectious diseases, which are transferred in airborne way. Flu epidemics within the last thirty years are no more local territorial phenomena.

Earlier, a priority was always given to chemical factors of air environment quality. Now, taking into account the above stated, microbiological factors play an increasing role. Safety of air environment not only by chemical but also by microbiological factors forced to solve problems of economic and effective disinfection of large air volumes separately or within general systems of their cleaning, conditioning, etc.

Therefore from medicine and food industry with traditionally high special requirements for microbiology of air environment, UV disinfection technologies expand to systems of air cleaning of general purpose and to transport. As well as in the water disinfection, more general new tasks caused a necessity to develop these systems. For recent years, a range of irradiating devices for air and surface disinfection was created in Russia. These devices are in particular used for emergency treatment of operating rooms and of other rooms in hospitals, in ventilation systems, as well as at food productions, offices, schools, warehouses and transport, Figs. 5, 6.

Photosynthesis, photocatalysis and photopolymerisation on surfaces, in liquids and gases using UV radiation of different spectral intervals are applied in microelectronics, chemical, pharmaceutic, printing and other industries. And processes of the so-called activated photo-oxidation are widely used to clean gases and liquids out of micro impurities [1, 14].

Studies of photobiological effect of UV radiation are significantly extended (for example, to stimulate growth and increase stress resistance of plants (Fig. 7), and this is not the full list of up to date use of UV radiation as a high-precision influence tool on processes and environments.

The success of UV disinfection technologies, and first of all, of water disinfection, would be impossible without a significant progress of UV radiation sources. For the last twenty years, UV radiation discharge sources in particular showed a huge scientific and technological increase in their development. Such sources of UV radiation as semiconductor UV radiating diodes quickly develop. As it was noticed earlier, the main stimulus of the specified technologies development is the problem of en-

Fig. 7. Platform with UV lamps hung on tractors

vironment disinfection, and the main characteristics of the relevant UV radiation sources and ballast for them are as follows:

- Bactericidal flux;
- Bactericidal efficacy;
- Lifetime of the source;
- Decrease of bactericidal flux by the end of the source lifetime;
- Lifetime, compactness and cost of the ballast;
- Safety, environmental friendliness and adaptability of the source application.

And in our opinion, as UV radiation sources, UV discharge lamps only and in some prospect, semiconductor UV radiators can be used.

As to the latter, we know the following:

- Semiconductor UV radiation diodes of the near UV range are developing now rapidly [15, 16]. At the market, diodes have appeared with wavelengths of (360–395) nm, which supersede, for example, traditional UV MHLs in particular at the market of UV radiation sources for photo hardening of coatings.
- In the semiconductor diodes of UV–C interval, an active study of their application in the systems of disinfecting water, air and surfaces takes place at least in special applications [17, 18]. The first commercially available diodes and devices based on them are appeared, which radiate in a (255–270) nm range [19]. At present, works have been published, which is showing a great success in development of UV–C diodes in (268–278) nm range (in particular, their energy efficiency is declared to be of 5 % and more) [20]. However, semiconductor UV–C radiators come along more slowly than normal light emitting diodes, what is connected with some unresolved physical and technological problems [15].

So, the leader in the UV–C diodes field *Crystal IS* Company (USA) proposes in particular Optan diode of UVC LED8–250–280 type with maximum radiant flux of 10 mW in spectral interval of (250–280) nm with power consumption of 3.6 W. Energy efficiency of the diode is of about 0.28 %. Such low energy efficiency is caused by a variety of reasons, basic of which are non-radiative recombination of charges on the dislocations out of the active layer, discrepancy of the semiconductor lattice and of the substrate constants, stacking faults, and increased ohmic resistance of the *p-n*-junction.

A serious problem of UV light emitting diode development is to obtain high-doped *AlGaN* layers of *n*- and *p*-types with a high concentration of *AlN* and to provide a rather low operation voltage and the low power consumption. One way of this problem solution is use of super lattices and forming an intermediate layer between the substrate and semiconductor to coordinate the lattice constants. This direction work is in progress [21], and the leading manufacturers prepare standardisation of measurement methods of UV–C diode electric and radiometric characteristics under the aegis of the International Ultra-violet Association (IUVA)) [22].

Lifetime of modern UV–C diodes with wavelength of (255–265) nm for example, is rather low as well: of about 1000 h when radiation flux decay to 50 %. Nevertheless, such radiators are already applied, particularly in water transmission measurement devices (τ metres) and in express biotesting devices (devices for bactericidal sensitivity curve measurement (BSCM) [19].

The main UV radiation sources of broad application are discharge UV lamps. They allow obtaining big specific energy-effective radiation fluxes, have rather long lifetime and are rather easy-to-work. Depending on the discharge conditions and on the filling composition of these lamps, they can have continuous and/or linear radiation spectra. Mercury, metal-halogen, hydrogen, excimer and other discharge UV lamps are now manufactured for different applications. Their envelopes are made of rather transparent for UV radiation glasses, most often these are quartz and uviol glasses. By power supply methods, the lamps can be divided into electrode and electrodeless, with continuous and pulse operation modes [1, 23].

At present, electric discharge in mercury vapour with inert gas mixtures is the main source of bactericidal UV radiation [1, 23]. The lamps with such

Fig. 8. Production of amalgam lamps

discharge are divided into LP mercury lamps, amalgam lamps (LP) and HP mercury lamps (according to the domestic classification, which corresponds to the middle pressure discharge lamp term used abroad).

The main comparative operational characteristics of these lamps are given in the Table.

The main advantage of the sources based on the mercury LP discharge is high energy efficiency in the bactericidal spectrum interval, which with optimum discharge parameters of modern powerful lamps is about (35–40)% [24].

HP lamps have a typical band (striped) spectrum corresponding to a considerably smaller efficiency.

As to the amalgam lamps, though they are mercury-containing but are much safer ecologically.

At present, global manufacturers of LP amalgam lamps of *Philips* (Netherlands), *LightTech/LSI* (Hungary/the USA), Heraeus Noblelight (Germany), LIT NPO (Russia/Germany), etc. offer lamps of 50 to 1000 W power. Their energy efficiency in the bactericidal interval is from 30 to 40 % and useful lifetime is up to 16000 h. In Russia, the leader in the development and manufacture of powerful amalgam lamps is LIT NPO, which has two lamp productions: the first one being the main is in Moscow and operates since 1996, and the second was established in Germany in 2010, Fig. 8. LIT Company manufactures a wide range of UV lamps for water and air disinfection. The most powerful of them is ДБ1000 lamp of 1000 w power. In 2014 production of ozone-generating lamps with radiation in the mercury line of 185 nm is begun for special applications.

Based on these UV LP lamps, installations for water disinfection with unit-productivity from 0.5 to 10,000 m^3/h are produced. Most large-scale manufacturers of them are as follows: *Trojan* (Canada), LIT NPO (Russia/Germany), *Wedeco Xylem* (Germany/ USA), *Halma group* (*Hanovia*, *Aquionics*, *Berson*) (Great Britain/ USA/Netherlands), *Calgon Carbon* (USA) and *NewLand* (PRC).

Traditionally UV HP lamps of (0.1–20) kW are made in *Philips* (Netherlands), *LightTech/LSI* (Hungary/ USA) and *Heraeus Noblelight* (Germany). The leaders of UV installation production using these lamps are *Trojan* (Canada), *Atlantium* (Israel) and *Berson* (Netherlands).

One can notice also other discharge sources of UV radiation, which for a range of reasons were not wide common, for example, xenon pulse and excimer lamps.

The first ones are only used for special disinfection tasks but even there they are applied to a limited extent because of a short lifetime (100–1000) h relative to a low bactericidal efficiency (8–10)% and due to high prices of the lamp-ballast set [25]. Excimer lamps radiate due to disintegration of special molecules being an excited atom system. These molecules can include different atoms (for example XeF^*) or identical (for example, Ar_2^*). Excimer lamp radiation is narrow-band, and maxima of radiation bands depending on the used molecules are within wave length interval of (120–360) nm. Energy efficiency of these lamp discharge depends on the power and can reach 25 % at a low power (of about (10–20) W). Energy efficiency of excimer lamps in the UV spectrum interval is almost twice lower than of UV LP mercury lamps, and with power increase it noticeably decreases. Application of such sources for commercial disinfection is restraining because of low bactericidal efficiency, high cost and complexity of the ballast. In our country, the leader of development and production of such excimer lamps is the Institute of High-Current Electronics of the Siberian Branch of the Russian Academy of Science (Tomsk). And in 2006–2009, a commercially available device for water disinfection *(Instant Trust*) was developed by *Philips Lighting* Company.

Table. Main operational characteristics of UV lamps based on mercury discharge

Parameter	HP lamps	Traditional LP lamps	Amalgam LP lamps
Lamp power, W	2000–20000	15–100	100–1000
Energy efficiency of lamps in the bactericidal interval,%	≈ 10–12	≈ 35–40	≈ 35–40
Lifetime of lamps, h	4000–8000	12000–16000	12000–16000
Formation of by-products in water	possible	impossible	

CONCLUSION

A high efficiency of UV irradiation makes it an irreplaceable element of the modern drinking water preparation system. Introduction of UV irradiating equipment for disinfection of sewage water allows eliminating chlorination at operating treatment facilities, which is potentially dangerous for population and environment. Systems of air and surface disinfection will be inevitably used as well as UV water treatment systems. Their development will require more time and efforts first of all concerning creation of a necessary regulatory basis and introduction of UV irradiation technology itself into medicine, food industry and transport.

The core of any type UV installations is a source of UV radiation. UV LP amalgam lamps have the greatest expansion and development, and their progress for the last twenty years is obvious. The leading world companies produce such lamps of (800–1000) W. Semiconductor sources of bactericidal radiation are also rapidly developed. LIT Company, as well as other UV installation manufacturers, observes with interest and recognises progress in development of such sources, however, do not consider them for the present being competitive with the traditional discharge UV lamps.

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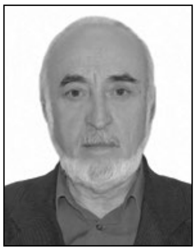

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