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WATER PURIFICATION WITH LASER RADIATION

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Abstract. In the report an assessment has been made of the possibilities for disinfection of drinking water from bacteria and viruses causing diseases, and in some cases death. The effect of ultraviolet radiation on microorganisms is examined. Also the report analyzes disinfecting of water with the help of UV lamps, LEDs and laser sources from the UV-range. Some advantages and disadvantages of water purification technology have been identified using the mentioned UV sources.
Keywords: disinfection; drinking waтer; UV sources; laser

Introduction

Water is an extremely important product for human existence as well as for our planet. Available water resources of the planet are a natural resource that cannot be easily renewed. Therefore, the issue of obtaining clean drinking water today is extremely topical and is of paramount importance to all humanity.

Today there are regions in the world where more than 50% of the local population has no access to clean drinking water, Fig. 1. In some countries, the limited availability of water resources is due to specific climatic conditions and in

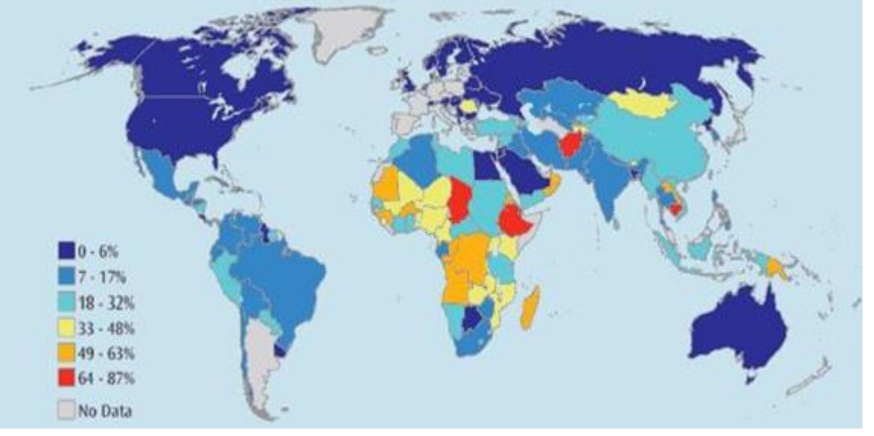

Figure 1. Water in the World

other countries, despite the availability of water resources, the water is unfit for direct drinking due to heavy rainfall during the year and related floods and pollution (Mauser, 2007). In these cases it is extremely important to implement water disinfection measures. Such actions are all the more necessary in the event of crisis situations such as: military conflicts, military missions, earthquakes, floods, droughts, etc.

Disinfection of water

The disinfection is a water purification technology that destroys or deactivates microorganisms. In as early as 1878 British researchers Downs and Count observed that the bacteria stop to multiplying when being exposed to sunlight for longer periods of time. Today, we already know that the ultraviolet UVC short-wave range is detrimental to bacteria and viruses (Chang et al., 1985; Hofmann et al., 2004).

UV rays are electromagnetic waves with wavelengths in the range of 100 nm to 400 nm. This range is conventionally divided into four sub-ranges UVA (315 – 400 nm), UVB (280 – 315 nm), UVC (200 – 280 nm) and VUV (100 – 200 nm), Fig. 2. Ultraviolet radiation from the range of UVC (200 – 280 nm) that comes to our planet from space is absorbed in the atmosphere so that bacteria and viruses are not resistant to this radiation. Therefore, radiation with such wavelength is also suitable for water disinfection, Fig. 3.

Advantages of this disinfection method are: (i) does not change of water taste and smell; (ii) does not pollute the environment; (iii) chemicals are not used; (iv) very short time to implement the technology; (v) simple implementation; (vi) active on persistent microorganisms after chlorine treatment; (vii) easy service and maintenance; (VIII) low operating costs.

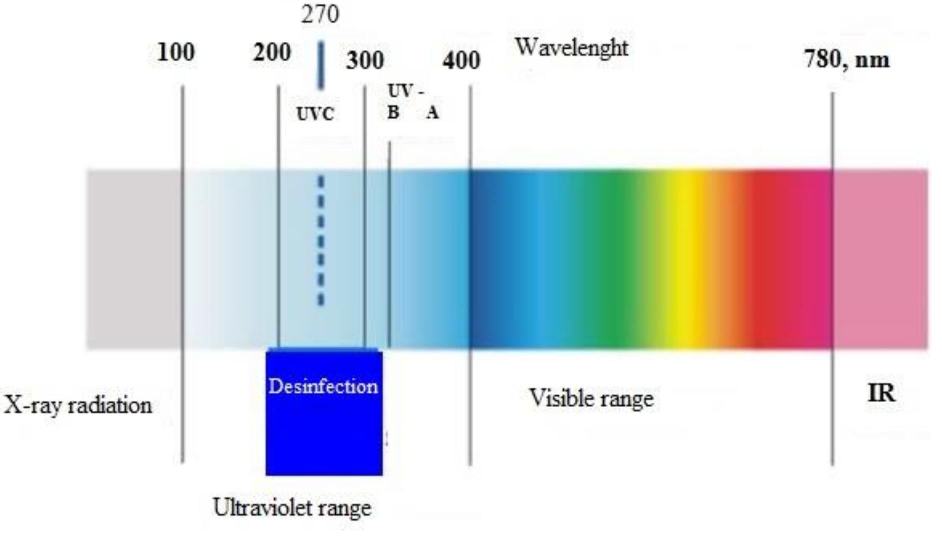

Figure 2. Electromagnetic waves

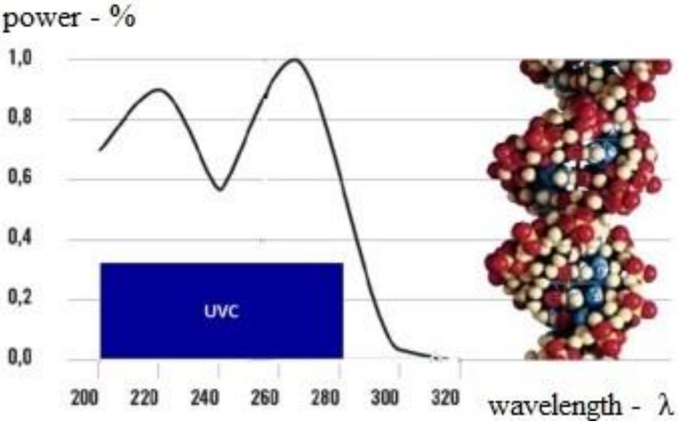

Figure 3. The most effective range is between 200 nm and 280 nm[1)]

Fig. 3 clearly shows that the most effective range is between λ = 200 nm and λ = 280 nm, as it outlines two pronounced maxima at 220 nm and 270 nm. It is important to note that radiation from this range can also be artificially created. From the three ultraviolet ranges A, B and C those below the UVC range are with the highest photon energy. This radiation interacts strongly with the proteins and can act on the living cells. Ultraviolet radiation attacks DNA (Deoxyribonucleic acid) of the bacteria and prevents them from multiplying. Before the impact of ultraviolet radiation on DNA becomes clear, we will recall that DNA consists of a nucleotide chain and a built-in polynucleotide. In turn, each nucleotide consists one of four nucleobases (adenine, guanine, cytosine and thymine), monosaccharides (Deoxyribose) and a phosphate group (Phosphorus). The molecule has two major chains that are linked to one of the nucleobases. The mechanisms in the cell can divide the double strand of DNA, and so each single strand can serve as a matrix for creating a new chain almost identical to the previous one.

Destruction of microorganisms (disinfection) is the result of the process of radiation absorption by the nucleic acids that are located around the cell nucleus. Absorption produces a photochemical reaction, resulting in a change in the structure of the nucleic acid. This leads to inactivation of the microorganism and its ability to propagate. In this process, ultraviolet radiation acts primarily on the thymine base, which cleaves the covalent bonds between the C5- and C6-atoms to form new C5- and C6- atoms in the vicinity, forming thymine dimer, Fig. 4. Ultimately the chain of DNA can no longer be divisible.

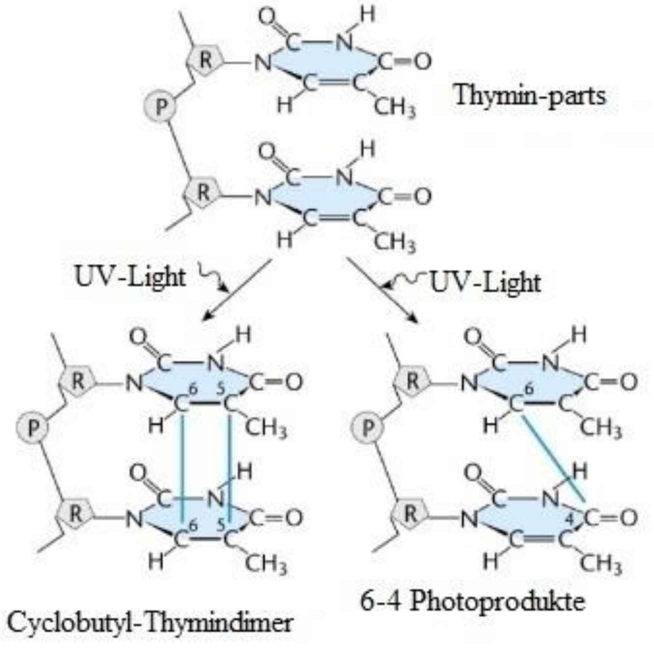

Figure 4. The chemicals and process

Assessment of the UV dose

When disinfecting drinking water with UV light, to assess the required radiation intensity, the known concepts of chemical technology (a contact time with disinfectant – CT) are followed. Here, a required UV dose is inserted instead of the CT. The UV dose is defined as a falling UV energy per unit area. The UV dose is a product of UV intensity *I* and exposure time *t* (similar to the CT concept). The intensity of ultraviolet rays is typically measured in milliwattts per square centimeter (mW/cm^2), and the action time is measured in seconds. Thus, for the UV dose, mWs/cm^2 is obtained. The UV dose is often expressed in millijoule per square centimeter (mJ/cm^2), as 1 mWs = 1 mJ.

There are several different models to evaluate the UV dose required to deactivate microorganisms. The simplest model used to calculate UV intensity is the radial model that is successfully used for UV lamps:

$$I(r) = (P_L / 2\pi r) . (e^{-ar})$$

where: P_L is the UV radiation power per unit length of the lamp, mW/cm; *r* – distance to the source, cm; *a* – ase UV absorption coefficient of water, 1/cm. *a* = 2.303; *I*(*r*) – UV intensity at distance to source, mW/cm^2.

Using manufacturer's UV radiation data about P_L, dimensions for purification device, UV reactor and assuming water quality variables related to the absorption coefficient *a*, UV intensity *I* (*r*) could be calculated via above formula. This model can be used to provide a rough estimate of the disinfection ability when suitable data are missed.

UV radiation sources

UV lamps

Three types of UV lamps are commonly used as water disinfection systems: low pressure (LP), low pressure high output (LPHO) and medium pressure (MP). This separation is based on the mercury vapor pressure at which the lamps work. Lamps LP and LPHO operate at mercury vapor pressures of $1.3*10^{-4}$ – $1.3*10^{-6}$ bar, giving monochromatic UV light with λ = 253.7 nm. MP lamps work at much higher mercury vapor pressures of $1.3*10^{-1}$ – 13 bar, emitting polychromatic UV light at higher intensities. Fig. 5 shows a schematic of the lamp LP, LPHO and MP. In principle, there is no difference in the disinfection capability between these three groups of lamps, but each has its own advantages and disadvantages. For example, compared to LP lamps, MP lamps have a higher bactericidal output, and fewer lamps are typically required for a given application. LP and LPHO lamps operate at temperatures from 40 °C to 200 °C and MP lamps operate at much higher temperature ranges from 600 °C to 900 °C. LP lamps have the lowest consumption, and LPHO and MP lamps require higher power.

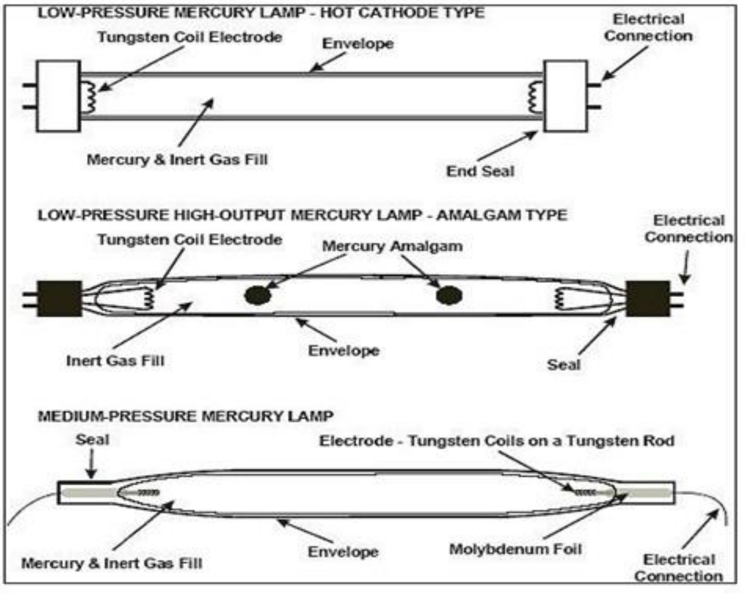

Figure 5. Scheme of the lamp used

Since all ultraviolet lamps contain mercury, breakage of the UV lamp during operation may result in the release of 5 – 50 mg of mercury in the water.

The risk and the adverse health effects that may result from such a situation make us look for other alternative sources of ultraviolet radiation.

LEDs

There is a new alternative for water disinfection by the use of ultraviolet rays from UV-LEDs that do not use mercury as in UV lamps and show promise as effective UV disinfection devices (Mori et al., 2007; Vilhunen et al., 2009). It is a technology which opens a great future, especially a fast developing application and mobile systems in third world countries. Interesting possibilities are also provided for the supply of such disinfection reactors to solar panels.[2)]

Currently, a variety of LEDs emitting ultraviolet light are available on the market. The first ones were launched in 1990 with gallium nitride-based diodes (GaN), which had been successfully applied in water purification systems against microorganisms. Fig. 6 shows a graph of the dependence of modern commercial LEDs on wavelength.

If we compare the low pressure mercury lamps with the LEDs, we will see that it is largely beneficial to use the LEDs, despite the high 40% efficiency of the mercury lamps. For example, the lifetime of mercury lamps is about 8,000 operating hours, while for LEDs it is tens of thousands of hours.

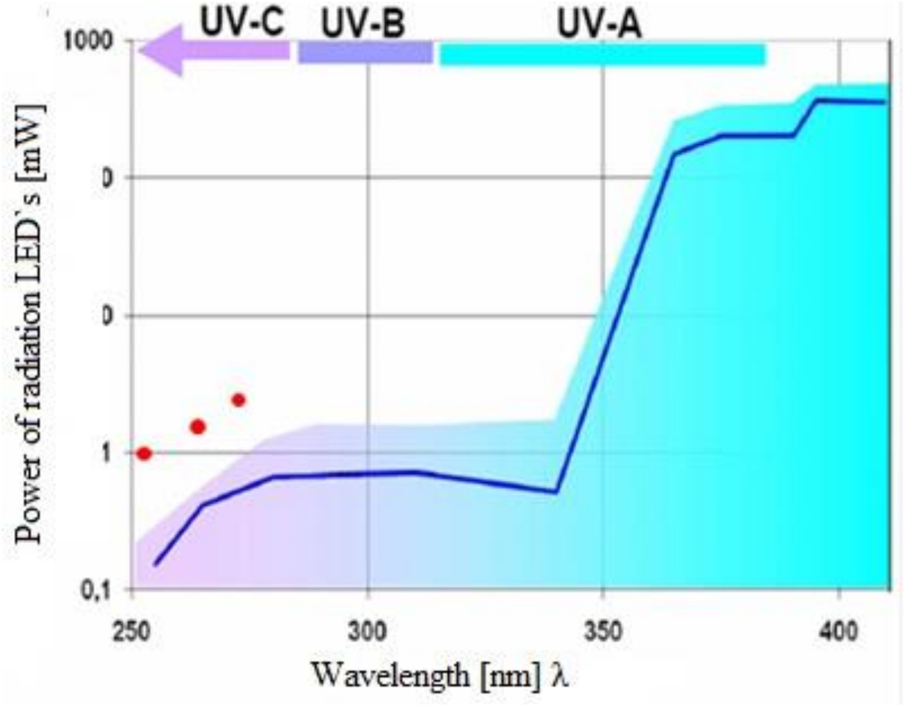

Figure 6. Power of LED's radiation vs. wavelength[3)]

Another significant advantage of LEDs is their small size and ability to be deployed in mobile systems as they are supplied with direct current and are independent of the power grid. They can also be adapted to work with autonomous photovoltaic systems.

Laser

Laser sources form another modern source of UVC radiation (Table 1). Solid-state lasers are suitable for the purpose of disinfecting drinking water. For example, Ti: Saphir lasers emitting at λ = 800 nm, using the fourth harmonic of the frequency (λ/4) or the third harmonic (λ/3) provide radiation respectively in the ranges 175 nm – 275 nm and 233 nm – 366 nm. Excimer lasers form another type of lasers emitting in this UVC range. For example, KrF laser with λ = 248 nm and KrCl laser with λ = 222 nm. One of the most common industrial lasers Nd: YAG laser (λ = 1060 nm) is also appropriate if its fourth harmonic of its primary radiation length (λ/4) is obtained, producing output radiation of 266 nm.

Table 1. Laser type and wavelength (µm)

Argon fluoride (Excimer-UV)	0.193	Helium neon (yellow)	0.594
Kryption chloride (Excimer-UV)	0.222	Helium neon (orange)	0.610
Kryption fluoride (Excimer-UV)	0.248	Gold vapor (red)	0.627
Xenon chloride (Excimer-UV)	0.308	Helium neon (red)	0.633
Xenon fluoride (Excimer-UV)	0.351	Krypton (red)	0.647
Heliom cadmium (UV)	0.325	Rhodamine 6G dye (tunable)	0.570-0.650
Nitrogen (UV)	0.337	Ruby (CrAlO3) (red)	0.694
Helium cadmium (violet)	0.441	Gallium arsenide (diode-NIR)	0.840
Krypton (blue)	0.476	Nd:YAG (NIR)	1.064
Argon (blue)	0.488	Helium neon (NIR)	1.15
Copper vapor (green)	0.510	Erbium (NIR)	1.504
Argon (green)	0.514	Helium neon (NIR)	3.39
Krypton (green)	0.528	Hydrogen fruoride (NIR)	2.70
Frequency doubled	0.532	Carbon dixide (FIR)	9.6
Nd YAG(green)		Carbon dixide (FIR)	10.6
Helium neon (green)	0.543		
Krypton (yellow)	0.568		
Copper vapor (yellow)	0.570		

Ultraviolet radiation emitted from the laser source does not use heat or chemical additives of any kind during the purification process. The simple fact is that radiation comes into contact with the microorganism to inactivate the DNA and to render it harmless.

Finally, we could say that there are two main disadvantages to ultraviolet water purification. The first one is related to the treatment of infected or cloudy water – UV radiation cannot penetrate and destroy microorganisms in such water. It could be requiring a water filtration prior to the purification which adds expense to the procedure. Otherwise, much of the UV light is absorbed and the process becomes largely ineffective. The second main disadvantage is connected with no residual treatment. Any microorganisms that the UV radiation missed would remain in the water. It would require a chlorine compound such as chloramine to be added to water purified by ultraviolet radiation after the treatment.

Conclusion

Inactivation of pathogenic microorganisms through wastewater disinfection plays a fundamental role in the protection of public health against waterborne diseases. Disinfection of water with ultraviolet radiation is an effective and well-functioning method. The use of ultraviolet laser light and LEDs, as an alternative to low pressure mercury lamps, ensures environmental and economic efficiency of the technology. In the coming years, research and development in the field of laser diodes and LEDs will develop at a very rapid pace, which will also reveal broad prospects for the creation of mobile drinking water purification systems.

NOTES

1. https://www.heraeus.com/en/hng/the_incredible_power_of_light/uv_disinfection.aspx
2. http://www.osram.de/produkte/uv-ir/uvc.html
3. http://www.heraeus-noblelight.com

REFERENCES

Chang, J.C., Ossoff, S.F., Lobe, D.C., Dorfman, M.H., Dumais, C.M., Qualls, L.G. & Johnson, J.D. (1985). UV inactivation of pathogenic and indicator organisms. *Appl. Environ. Microbiology*, *49*, 1361 – 1365.

Hofmann, R., Andrews, B. & Lachmaniuk, P. (2004). Guidelines for ultraviolet disinfection of drinking water: considerations for Ontario. *J. Toxicology & Environmental Health A, 67*, 1805 – 1812.

Mauser, W. (2007). *Wie lange reicht die resourche Wasser: Der Umgang mit dem blauen Gold.* Frankfurt am Main: Fischer Taschenbuch.

Mori, M., Hamamito, A., Takahashi, A., Nakano, M., Wakikawa, N., Tachibana, S., Ikehara, T., Nakaya, Y., Akutagawa, M. & Kinouchi, Y. (2007). Development of a new water sterilization device with a 365-nm UV-LED. *Medical & Biological Engineering & Computing*, *12*, 1237 – 1241.

Vilhunen, S., Särkkä, H. & Sillanpää, M. (2009). Ultraviolet light-emitting diodes in water disinfection. *Environ. Sci. & Pollution Res. Int.*, *4*, 439 – 442.

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