UV-LED technology: the future of safe and sustainable water disinfection

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Clean drinking water is required for human survival, but still about 785 million people lack access to safe drinking water, including 144 million people who are dependent on surface water (World Health Organization, 2019). Globally, at least 2 billion people have to use source water that is contaminated with faeces, which can transmit diseases such as diarrhea, cholera, dysentery, typhoid, and polio. The WHO estimates that contaminated drinking water causes 485 000 deaths each year (World Health Organization, 2019). Safe, affordable and energy efficient water treatment systems are needed to improve the drinking water supply around the world. Ultraviolet (UV) disinfection is an effective way to reduce the number of microbial pathogens in drinking water and is an option for addressing prevailing drinking water issues which does not require chemicals or generate disinfection by-products. Traditionally this treatment was performed with UV low pressure (LP) and medium pressure (MP) lamps which contain toxic mercury. The UN Environmental program gathered states for signing a convention against use of mercury, the Minamata-convention in 2013, which presently has been signed by 132 countries (UNEP, 2021). In the EU, measures against use of mercury have been implemented, for instance in the directive 2011/65/EU on the restriction of the use of certain hazardous substances in electrical and electronic equipment and further on 2017 in the directive 2017/852/EU on use of mercury. The political ambition is clear that use of mercury should be banned as soon as possible in accordance with the Minamata-convention. The EU commission has a delegated right in 2011/65/EU to permit exemptions from the ban for electronic and electric equipment and has presented a draft, still not decided in June 2021 on total ban of mercury use from 2026 (Ref. Ares(2021)3882317 - 14/06/2021). LP- and MP-lamps, although technically useful, are under pressure to be exchanged for other disinfection methods.

UV-light emitting diodes (LED) are highly interesting as a replacement for mercury lamps to make UV disinfection safer, sustainable and more environmentally friendly to operate. UV-LEDs are operated digitally, meaning that they start emitting photons as soon as they are taken into operation. Thus, they can be switched on and off repeatedly with no lag at all for UV-generation. This is contrary to UV-lamps, which need to be heated up prior to operation. Manufacturers of UV-LED’s have further on increased the manufacturing capacity leading to lower cheaper production costs every year. The price of UV-LEDs has decreased annually by 20-30% the last 5 years. Finally, the energy efficiency, i.e. how large proportion of the supplied electricity that is transferred to UV- photon generation in the UV-LEDs has improved significantly the last 5 years, leading to more energy efficient UV disinfection opportunities. There are three critical steps for an LED to produce light: charge carriers (electrons and electron holes) need to be injected into the active region; the electrons and electron holes must recombine to generate light; the light must be able to exit the semiconductor. All these steps are currently optimized leading to significant improvements in the use of UV LEDs for disinfection. This opens up for new design, new operation possibilities, and potentially changes the conventional way of applying UV disinfection to drinking water. It is interesting to look at wavelength combinations in terms of UVA, UVB and UVC radiation since light in these ranges have been shown to induce damage to microorganisms through different mechanisms. UVA, UVB and UVC represents UV radiation in the wavelength range of 315–390 187 nm, 280–315 nm and < 280 nm respectively, see *Figure 1*. In disinfection, UVC is more efficient and requires a lower UV dose to achieve a certain log reduction compared to UVB or UVA. UVA acts by production of reactive oxygen species (ROS) which mediate the inactivation, mainly targeting membrane lipids and proteins. UVC on the other hand induces direct damage to the DNA by DNA-lesion formation, which inactivates the microorganisms by leaving the cell unable to replicate its DNA. UVB has been found to inactivate the cells using a combination of the effects of UVA and UVC. To this date UVA-LEDs are more energy efficient with better power output than UVB- and UVC-LEDs. Therefore disinfection using UVA-LEDs will be advantageous in an energy perspective despite the lower disinfection rate. The disinfection efficiency can be defined as optical disinfection efficiency, i.e. log reduction per UV dose or electrical disinfection efficiency; log reduction per energy/power input to the LEDs.

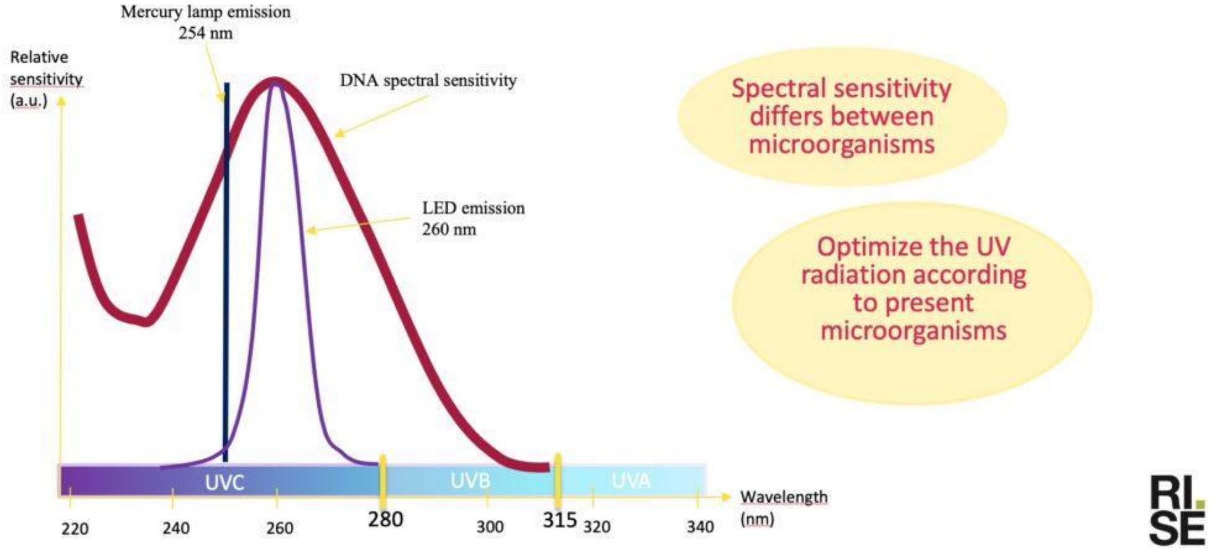

Figure 1. UVA, UVB and UVC with spectrum. From watersprint.com

In order to reach the United Nations' goal of "safe and affordable drinking water for all by 2030" ("Goal 6: Clean water and sanitation," 2015) large engineering efforts and innovation are required and with their compact and robust design, LEDs can contribute to this goal by making water disinfection increasingly available. UV-LEDs are an energy efficient water treatment technology which can be driven by battery or solar energy. They are portable, flexible and can operate at the point source (Lui et al., 2014) as well as being part of the solution for more energy efficient large-scale UV installations for drinking water disinfection and will allow the use of mercury in UV disinfection reactors to be phased out.

Since UV-LEDs have a completely different geometry, size, emission pattern and radiation spectra than low pressure (LP) and medium pressure (MP) mercury lamps it is not convenient nor advantageous to simply use the same standard procedure and reactor geometry as in the conventional UV disinfection system. There has been a restriction in the implementation of UV-LED based disinfection due to a lack of disinfection regulations covering the incorporation of UV-LEDs. That situation is changing and during 2019 the NSF International drinking water treatment standard has been updated to include guidelines on UV-LED based disinfection (LeFort, 2019). A protocol has been presented by Kheyrandish et al. (2018) for fluency determination with guidelines on how to take measures, and adapt UV disinfection procedures, to accommodate UV-LEDs in disinfection tests (see Sholtes et al., 2019). These protocols, together with the NSF International drinking water treatment standard, will ensure comparability between studies and allow the industry to introduce UV-LED disinfection into practice. While regulations and standards are being explored, and the benefits and potential for UV-LED based water treatment are clear, additional understanding of the influence of wavelength and light delivery are required for the technology to mature.

Examples of smart design and UV LED use have been suggested by several researchers. Different microorganisms have different sensitivities for different wavelengths. With UV LEDs, it is possible to combine different wavelengths in the same reactor, thus increasing the disinfection safety in the treatment step in a compact way. The digital operation offers a pulsed light disinfection set-up, which some microorganisms seem to be much more susceptible for. Pulsed light can thus increase the safety of the disinfection and provide a higher log-reduction of the microbial content. If applying pulsed mode, the *intensity could be kept constant* by altering the run time, with a longer runtime applied during pulsed mode to compensate for the dark periods of the pulses. Another way is to keep the *run time constant* by altering the intensity of the light, with higher intensity applied during pulsed mode to compensate for the dark periods of the pulses. A third way is to keep both *time AND intensity constant* by calculating the total dose for each case and compensating the resulting log reduction accordingly. Pulsed mode also improves thermal management of the UV LED and expands its lifetime, yet the optimal frequency seems to vary for different microorganisms. Higher pulse frequencies seem to be more efficient in some studies reaching an optimum below 1000 Hz but more investigations are needed.

A number of reactor design opportunities are available. The small size of the UV LED, compact as a pinhead, allows for all kinds of reactor shapes, such as spherical, cubic, cylindrical or oblong with several new opportunities for hydraulic loads to the disinfection reactor. The photons not absorbed by microorganisms can in some cases be reflected by the reactor chamber material if this enhances UV reflection. Proper materials contribute to radiation uniformity within the reactor and disinfection efficiency. The interplay between UV wavelengths and reactor material should thus be further investigated (Chen et al., 2017; Song et al., 2016; Li et al., 2019).

The UV-LED is a light source that is promising for UV disinfection applications. It is a highly flexible light source that is expected to increase the efficiency of UV disinfection by allowing more customized applications and optimized irradiance usage. Wavelength combinations and pulsed light disinfection should also be tested for UV-LED based disinfection in turbid water and water containing large particles. UV-LEDs achieve higher disinfection efficiency than conventional UV lamps in such conditions (Crook et al., 2015) and it is possible that the radiation pattern, intensity and run time are particularly important for such water. This could be particularly important for prospects of implementing UV-LED for disinfection of wastewater. Point-of-use UV-LED reactors for water disinfection have already reached the market and the implementation of full-scale UV-LED disinfection for drinking water treatment has been implemented. The emergence and application of UV-LEDs in drinking water production, and other water management contexts including re-use applications, will revolutionize the water industry in a way analogous to how LEDs in the visible light range impacted the domestic lighting industry.

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