UV LEDs for Water Treatment: Research Overview and Perspectives

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What's good about UV LEDs?

Light emitting diode (LED) at germicidal UV radiation (< 300 nm), termed UV LEDs hereafter, keep growing in the market. In general, UV LED products have been increasing the output power, extending the lifetime, and some are even challenging the cost reduction. It seems the past prediction based on "Haitz's Law" was too optimistic unfortunately, but the situation has been changing so rapidly. UV LEDs are now on track for practical applications.

UV LEDs are mercury-free, small in size, warm-up-free, resistant to frequent on/off cycle and selective in peak emission wavelengths. How would these features be good for water treatment? First of all, it is an international trend to reduce or strictly control the use of mercury in general. UV LEDs can meet such social preferences. More specifically to water treatment, barriers against mercury leakage at severe accidents are no longer needed for UV LEDs, which can lead to a simple system design overall.

As for the size, UV LEDs pose a typical size of 3 to 4 mm^2 for a single package, which allows flexible design and layout in reactors. Several studies have developed unique UV LED apparatuses for water disinfection (Chatterley and Linden 2010, Bowker et al. 2011, Würtele et al. 2011, Oguma et al. 2013, Jenny et al. 2014) and each adopted different design concepts. For example, we have designed a prototype of ring-shaped apparatus, as in Fig. 1 (Oguma et al. 2016a, b), which was originally motivated to develop something hardly possible with mercury lamps. The ring shape is just one of the trials, but such flexibility in the reactor design is to be noted as one of the charms of UV LEDs. Thinking that UV LEDs currently demand higher cost per output power ($/Watt) than mercury UV lamps, how to optimize the reactor design or how to maximize the performance with limited number of UV LEDs is one of the key factors for practical applications.

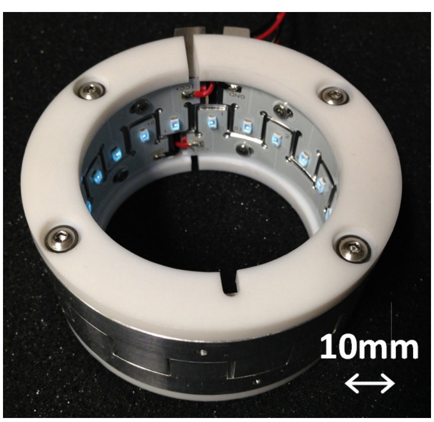

Figure 1. A ring-shaped UV LED apparatus (Oguma et al. 2016a)

UV LEDs do not require warm-up before stabilization, and frequent on/off cycling does not damage the device, namely does not shorten the life time of UV LEDs as it does with mercury UV lamps. These features allow intermittent operation which is preferable for on-demand use, such as point-of-use (POU) and point-of-entry (POE) water treatment options and also good for systems with high-fluctuation in water demand, such as community-based water supply with limited connections.

As for POU/POE applications, growing cities in developing counties are of concern. Cost is an issue for now but not forever. Scientists have done intensive field surveys on water quality and water use behaviors in Asia, including Hanoi in Vietnam and Kathmandu in Nepal, and noted that rapid urbanization results in limited access to centralized water supply systems and urges people to use decentralized water sources, such as unprotected dug well and private water vendors. Water from such sources is occasionally contaminated with microorganisms. Moreover, even in centralized public water supply systems, water quality deteriorates with significant decay of residual chlorine in the distribution network and rooftop storage tanks, highlighting an apparent need of POU/POE treatment at households. In fact, people are taking several coping strategies including POU/POE installation (Do et al. 2014, Gragai et al. 2017) (Fig. 2). A survey revealed that about 76% of residents in central Hanoi were taking POU

Figure 2. A multicartridge POU apparatus commonly found at households in Hanoi

treatment at home (Do et al. 2014), while some POU apparatuses in use were not working as a barrier against microorganisms. UV LED can be a smart add-in option for such systems.

Community-based small water supply systems are another potential target of UV LED application. Such water systems typically use nearby streams or groundwater as the source, followed by a simple filtration and chlorination only. In Japan, health-related incidents associated with drinking water in the past 30 years were mostly associated with disinfection failure, and 44% of it was happening at private (including community-owned) small water systems (Fig. 3). Simple, effective, feasible and sustainable measures are needed at small systems where both human and financial resources are limited. Systems are to be designed for operation and maintenance not by skillful engineers but by the users at their own responsibility.

What about UV LEDs? Scientists have made a preliminary field test at a remote community in Japan using a flow-through UV LED apparatus and obtained much encouraging data to further explore this application option. Challenges for community water supply are the issue not only in Japan but in many countries including the US (Barstow et al. 2014), and scientists have been sharing expertise between Japan and Canada under the cooperative support by Japan Science and Technology Agency and Natural Sciences and Engineering Research Council of Canada. Such international collaboration is very much needed to promote research and strengthen the knowledge base, leading to the proposal of best solutions that fit local needs.

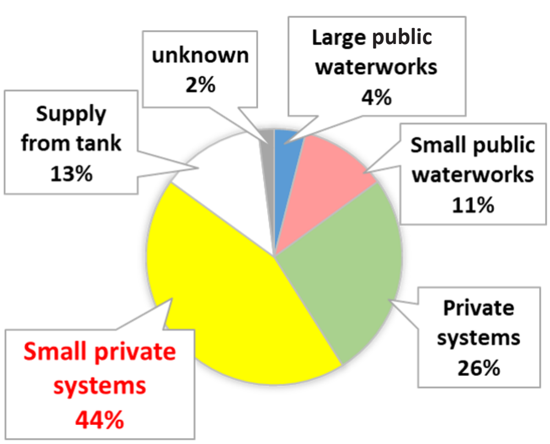

Figure 3. Share of facilities causing health-related incidents in Japan in 1983-2012 (Kishida et al., 2015 with modification)

With regard to the variety in the emission wavelengths of UV LEDs, how to pick up the "right" one is a question. Thus, responses of key microorganisms to different wavelengths, namely action spectra, is important. Action spectra differ among species and strains, but most species typically show a relative peak in inactivation efficiency at approximately 260 to 265 nm (Beck et al. 2015). Meanwhile, in general, LED technology offers higher wall-plug-efficiency, defined as the germicidal emission output per electrical energy input, at longer emission wavelengths in the germicidal UV range. Then, which wavelength to select? To answer this simple question, we have applied UV LEDs at different emission wavelengths to several pathogens including *Pseudomonas aeruginosa*, *Legionella pneumophila* and human adenovirus serotype 5, in comparison with indicator species of *Escherichia coli*, *Bacillus subtilis* spores and coliphages MS2 and Qβ. The results indicate that, in general, 265 nm UV LED is better than 280 nm UV LED in the fluence-based inactivation efficiency, while 280 nm UV LED is more efficient than 265 nm UV LED based on the electricity consumption required to achieve 3 log inactivation of all microbial species tested (Rattanakul and Oguma 2018).

Another interesting result is that, to inactivate adenovirus, a 285 nm UV LED is better than low-pressure UV lamp (254 nm) in the fluence-based inactivation efficiency (Oguma et al. 2016a). As such, examining the spectral sensitivity of key microbial species, as has been done in the context of polychromatic medium-pressure UV lamp, is now important for UV LED applications.

In line with the comparison of microbial species, a flow-through UV LED apparatus was applied to indigenous heterotrophic bacteria in tap water, and the profiles of heterotrophic plate count (HPC) after UV LED exposure were tracked for seven days, aiming to see the microbial stability of treated water during storage (Oguma et al. 2018). The results showed that UV LED reduced HPC right after exposure and, although HPC increased during storage regardless of preceding UV LED treatment, HPC in UV-treated water was lower than that in non-treated samples up to five days of storage.

It was also noted that heterotrophic bacteria in tap water samples formed yellow, white and pale pink colonies, and white colonies became dominant after UV LED treatment and storage (Fig. 4). A phylogenetic analysis based on 16S rRNA gene sequences revealed that yellow colonies were closest to *Novosphingobium* sp. while white and pale pink colonies were both closest to *Methylobacterium* sp., indicating that UV LED exposure can result in the selection of UV-resistant species like *Methylobacterium*. Such selective force by UV exposure should be common to any other UV technologies, but it can be a particular concern with POU

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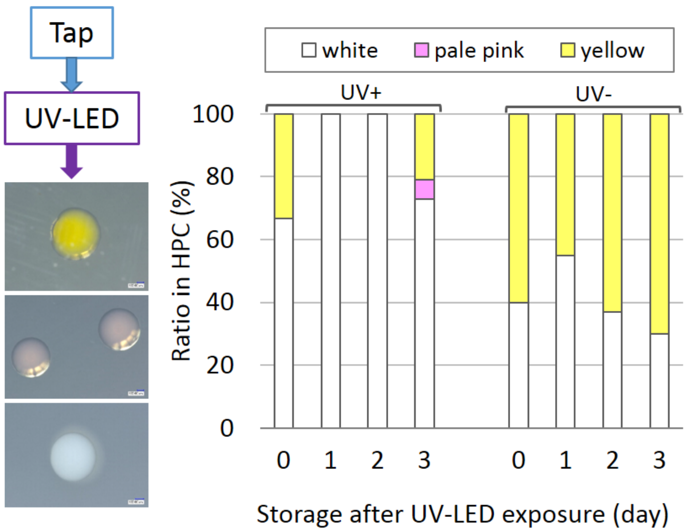

Figure 4. UV LED exposure selected UV-resistant *Methylobacterium* sp. (pale pink and white colonies) [Oguma et al. 2018]

applications where UV-treated water is directly consumed without barriers afterwards. The significance and health impacts of such microbial selection is to be explored intensively.

Perspectives for the future

To promote both research and practical applications, standardization of fluence (dose) determination for UV LED systems is very much needed. The question is how to determine the fluence for LEDs having various emission spectra with different peak emission, in a comparable manner for conventional mercury-based UV lamps. Biodosimetry and the concept of reduction equivalent dose (RED) are basically valid for UV LED systems, while some modifications are needed.

Currently, some people consider LED as monochromatic light source while the others take it as polychromatic, resulting in the mismatch of protocol for fluence determination particularly on the wavelengths conversion. Moreover, UV-based technologies for water treatment are all standardized at 253.7 nm so far, but the rationale to do so for UV LEDs is unclear. The 253.7 nm reference may not be needed, or not even scientifically correct for UV LEDs emitting out of this particular wavelength. Further discussion is very much needed in open and international ways.

More for practical applications, just thinking of the replacement of conventional lamps with UV LEDs is not very expansive and attractive. UV LEDs are expected to open the door for new applications, which would eventually stimulate the whole market of UV-based technologies. A paradigm shift is needed. ■

References

Barstow, C.K. et al. (2014) Assessing point-of-use ultraviolet disinfection for safe water in urban developing communities. *J. Water and Health* 12(4), 663-669.

Beck, S.E. et al. (2015) Action spectra for validation of pathogen disinfection in medium-pressure ultraviolet (UV) systems. *Water Research* 70, 27-37.

Bowker, C. et al. (2011) Microbial UV fluence-response assessment using a novel UV LED collimated beam system. *Water Research* 45, 2011-2019.

Chatterley, C. and K.G. Linden (2010) Demonstration and evaluation of germicidal UV LEDs for point-of-use water disinfection. *J. Water and Health* 8, 479-486.

Do, A.T. et al. (2014) Household Survey of Installation and Treatment Efficiency of Point-of-Use Water Treatment Systems in Hanoi, Vietnam. *J. Water Supply: Research and Technology-AQUA* 63(2) 154-161.

Guragai, B. et al. (2017) Effects of inequality of supply hours on consumers' coping strategies and perceptions of intermittent water supply in Kathmandu Valley, Nepal. *Science of the Total Environment* 599-600, 431-441.

Jenny, R.M. et al. (2014) Modeling a continuous flow ultraviolet Light Emitting Diode reactor using computational fluid dynamics. *Chemical Engineering Science* 116, 524-535.

Kishida, N. et al. (2015). Analysis of health-related incidents associated with drinking water in Japan in the last three decades (1983-2012). *J. National Institute of Public Health* 64(2), 70−80. (in Japanese)

Oguma, K. et al. (2013) Application of UV light emitting diodes to batch and flow-through water disinfection systems. *Desalination* 328, 24-30.

Oguma, K. et al. (2016a) Application of UV light-emitting diodes to adenovirus in water. *J. Environmental Engineering*, ASCE 142(3), 04015082.

Oguma, K. et al. (2016b) Effects of arrangement of UV light-emitting diodes on the inactivation efficiency of microorganisms in water. *Photochemistry and Photobiology* 92(2) 314–317.

Oguma, K. et al. (2018) Effects of UV Irradiation by Light Emitting Diodes on Heterotrophic Bacteria in Tap Water. *Photochemistry and Photobiology*, in press. DOI: 10.1111/php.12891

Rattanakul, S. and K. Oguma (2018) Inactivation kinetics and efficiencies of UV LEDs against *Pseudomonas aeruginosa*, *Legionella pneumophila* and surrogate microorganisms. *Water Research* 130, 31-37.

Würtele, M.A. et al. (2011) Application of GaN-based ultraviolet-C light emitting diodes – UV LEDs – for water disinfection. *Water Research* 45, 1481-1489.