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Communication

Efficient Disinfection of Tap and Surface Water with Single High Power 285 nm LED and Square Quartz Tube

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Abstract: A small water disinfection system based on the combination of a strong single 25 mW LED with a wavelength of 285 nm and a short quartz tube with an outer rectangular cross section is presented. For the disinfection tests clear tap water and slightly turbid and yellow pond water are contaminated with high concentrations of *Escherichia coli* bacteria. These water samples are exposed to the germicidal 285 nm LED radiation while they flow through the quartz tube. The portion of surviving germs is determined by membrane filtration for different water qualities and flow rates. For clear tap water the bacteria concentration can be reduced by at least three orders of magnitude up to flow rates of about 20 L/h. In pond water the maximum flow rate for such a reduction is less than 3 L/h. These high disinfection capabilities and the small size of this system, allow its integration in medical systems for point of use disinfection or even its application in the Third World for decentralized water disinfection powered by small solar cells, because this disinfection capacity should be sufficient for small groups or families.

Keywords: single high power 285 nm LED; square quartz tube; point of use disinfection; light guide

1. Introduction

Clean or at least germfree drinking water is one of the most important commodities in the world. In industrialized countries, water is often disinfected in large central plants by the use of chlorine or ozone [1]. One major problem applying these methods is the possible microbial recontamination on the way to the customer. Thus, the water is most likely not sterile when it comes from the tap, but for example, is loaded with *Legionella* or other pathogen microorganisms [2,3]. That is even often true for water installations in dentist´s or doctor´s practices or hospitals [4–7].

The situation is much worse in the Third World, where an estimated 1800 millions of people [8] have to drink water contaminated with *Escherichia coli* each day and about 750 million human beings are not connected to any water infrastructure at all [9] and cover their own water requirements using freely accessible surface water from rivers, lakes and ponds with potentially high bacterial concentrations. This situation leads to the high number of about 3000 deaths per day [10] due to infected water.

For these people the so-called SODIS (Solar Water Disinfection) technique is usually recommended [11]. According to this method water should be filled in transparent plastic bottles and then placed in the sun for at least 6 h. The UV-A part of the solar radiation is expected to inactivate most of the pathogens in this time. However, this technique has many practical disadvantages like the long disinfection time and the need for intense sunlight. Furthermore Mäusezahl *et al.* [12] proved that it is not as successful as one has hoped for. Therefore, another technique would be desirable, which provides inexpensive and reliable germfree water around the clock whenever the need arises.

Small disinfection systems that are based on the absorption of UV-C radiation affecting the DNA of all microorganisms could become a solution for the drinking water situation in rural areas of the Third World. The germicidal effect of UV-C light is known for a century now [13]. In these past hundred years, the UV-C light was mostly generated by mercury (Hg) discharge lamps that emit 254 nm radiation. However, these light sources have many disadvantages, like limited lifetimes and highly toxic mercury and the need for high voltages, especially when applied in the Third World where solar power is sometimes the only available energy source.

The use of UV-C LEDs would be more advantageous in comparison. They are driven by low voltages, are very small and nontoxic. In the past, these LEDs were very expensive and even had a shorter lifetime than Hg lamps. Meanwhile, they have matured and reach life times of 10,000 h and beyond [14]. Their most important disadvantage is the still existing low optical output power in the range of one or only a few mW per single LED. For this reason several systems with multiple LEDs were proposed in the past. However, in combination with a straight quartz tube that acts as a light guide, this low power radiation of a single LED can be used very efficiently [15]. Such systems could not only be used in the Third World [16]. Because of their small size, they could also be integrated in existing medical systems and perform a disinfection at the place and in the moment when the water is used ("point of use disinfection"). This assumption is supported by several positive studies [17,18].

A first system that was able to disinfect 1 L/h with a 1.5 mW UV-C LED while running through a round quartz tube has already been presented in [19] and tested with tap water that was contaminated with *Escherichia coli*. For higher flow rates than 1 L/h, the germ concentration could still be reduced, but only by much less than the 3 orders of magnitude that are usually referred to as disinfection.

In this paper an advanced system is presented and tested with contaminated tap water and surface water to investigate the system for potential Third World and medical applications. The tests are performed with *Escherichia coli* because of the importance of pathogen *E. coli* strains for causing diarrhea—especially for children [20]—and because many waterborne pathogens like *Vibrio cholerae*, *Enterococcus* spp., *Shigella* spp., *Cryptosporidium* spp. and *Giardia* show a similar or even lower resistance to UV-C radiation [21].

The system still employs a single LED but with strongly increased optical output of 25 mW. The outer cross section of the flow tube has a square shape that should lead to a more homogeneous intensity distribution, and the corners on both ends of the quartz tube could become alternative spots for mounting LEDs in future systems, with the advantage of being less sensitive for air bubbles or dirt in front of the LED that could reduce the disinfection success.

2. Experimental Section

2.1. Experimental Setup

The main components of the disinfection system depicted schematically in Figure 1 are the 25 mW (@350 mA or 6.5 V), 285 nm UV-LED type UV-HD02-002 of Nikkiso Ltd. (Tokyo, Japan) and a customized quartz tube produced by QSIL GmbH (Langewiesen, Germany) with a length of 100 mm, an inner diameter of 12 mm and a square outer cross section of 16×16 mm^2. A 13° reflector type OPC1-1-COL-WD of Dialight Lumidrives (Long Marston, Great Britain) guarantees that most of the LED radiation is coupled into the quartz tube, as shown in Figure 1. The optical power behind the reflector and in front of the quartz tube is 17.7 mW. The optical axis is parallel to the flow of the potentially contaminated water, of which flow rate is controlled manually via the roller pump Masterflex of Heidolph Instruments GmbH & Co.KG (Schwabach, Germany).

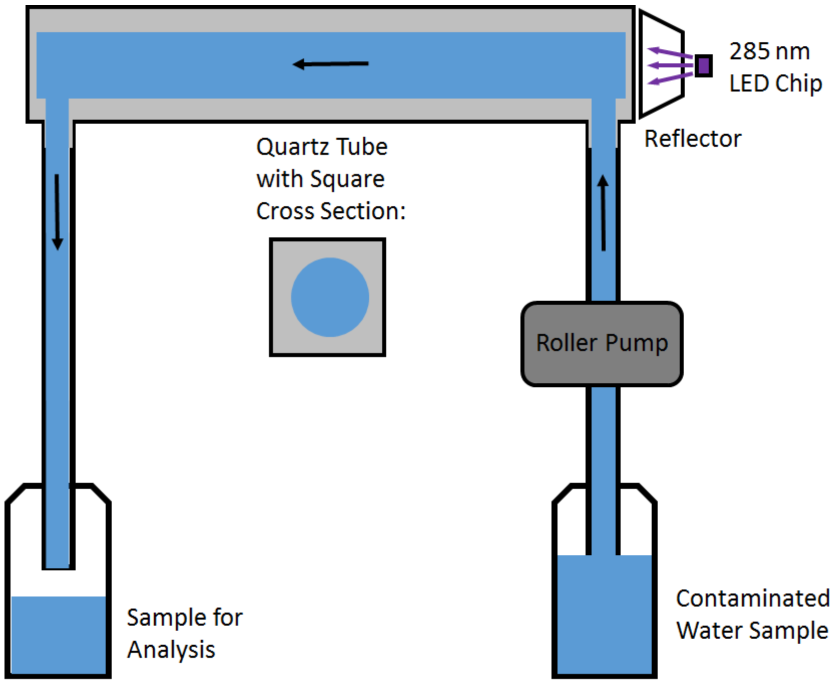

Figure 1. Schematic setup of the disinfection system.

As mentioned before, this water filled quartz tube acts as an efficient light guide for the LED radiation. Almost no UV light can leave the system due to total reflection at the walls of the tube, which generates high efficiency disinfection rates [15]. Furthermore, this system should be equipped with an ultrasonic transducer at a free end of the tube for biofilm removal inside the tube [22].

2.2. Measurement Procedure and Analysis

For these investigations, two different drinking water compositions were chosen: A quite clear solution of tap water with 0.9% NaCl and slightly turbid and yellow surface water of a local pond in Ulm, Germany. Several liters of each test water sample were contaminated with a concentration of about 200,000–300,000 colony forming units (CFU) of *Escherichia coli* (*E. coli*, DSM Strain No. 498) per mL. The pond water was analyzed but not sterilized before adding the *E. coli* bacteria, because the original germ concentration was found to be insignificant compared to the high *E. coli* concentrations.

Transmission spectra of the water samples where determined by an absorption spectrometer type Specord 250 plus of Analytik Jena AG (Jena, Germany) and the LED emission was measured by an UV-Vis spectrometer type SensLine AvaSpec 2048 XL of Avantes BV (Apeldoorn, The Netherlands).

The water samples were pumped through the quartz tube with different flow rates: 1 L/h, 3 L/h, 6 L/h, 9 L/h, 12 L/h, 15 L/h, 18 L/h and 21 L/h. Behind the quartz tube, the samples were collected and the surviving bacteria concentrations were determined by membrane filtration as described in the international standard "Water quality—General guidance on the enumeration of micro-organisms by culture (ISO 8199:2005)" [23] with membrane filters and nutrient pads type Endo of Sartorius AG (Goettingen, Germany). For each flow rate, water quality samples were taken at least in triplicate with the LED turned on and also with the LED turned off. These samples without UV radiation where used to determine the reference bacteria concentrations.

3. Results and Discussion

The emission spectrum of the 285 nm LED, and the transmission spectra of the different water samples are presented in Figure 2. At the LED peak wavelength of 285 nm the pond water transmission is only about 50% for a sample thickness of 10 mm. This leads to a penetration depth of about 13 cm for the tap water and 11 mm for the pond water. It should be noted that this pond water transmission value for 285 nm varied between 50% and 85% depending on the spot where the water samples were taken. Intentionally, less transparent water was sampled. For illustrating the wavelength dependence of the germicidal effect of the LED radiation, an expected DNA absorption spectrum for *E. coli* is shown in Figure 2 that was calculated by the UV spectrum calculator tool of Integrated DNA Technologies Inc., (Coralville, IA, USA) [24].

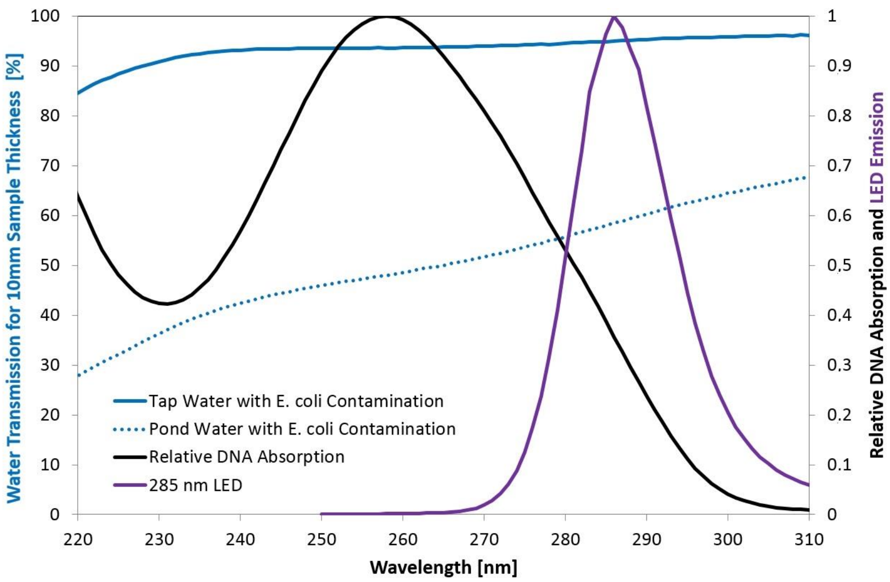

Figure 2. Transmission spectra of the different water samples for 10 mm sample thickness, together with the relative DNA absorption for *E. coli* calculated with [24] and the emission spectrum of the Nikkiso 285 nm LED. (The arrows indicate the corresponding axis.)

The measured disinfection success for the different water qualities and flow rates can be found in Figure 3. It is supplemented by an estimated disinfection rate based on a very simplified model, data shown as continuous curves. This model assumes that a dose of about 10 mJ/cm^2 of 285 nm radiation leads to a 10 times reduction of *E. coli*. This assumption is based on results of about 6 mJ/cm^2 found in [25] for a 275 nm LED multiplied with the DNA absorption ratio at 275 nm and 285 nm of 1.7. The actual radiation dose in the presented setup is estimated with respect to the measured water transmission and with the assumption of a plug flow. This is done by calculating an average irradiance intensity and an average exposure time. The radiation dose is the product of both values. This is an oversimplification that does not consider the real velocity profile but gives an impression of the relative dependence of the disinfection success of the flow rate.

As expected, the disinfection success varies with the water quality because the more UV radiation is absorbed by the water itself the less is available for DNA destruction. In clear tap water a reduction of three or more orders of magnitude is reached up to flow rates of about 20 L/h. For slower flow rates below 6 L/h one would expect an even stronger germ reduction, but for unknown reasons the disinfection success shows just minor variations between 1 and 12 L/h.

For the slightly turbid and colored pond water only for flow rates of less than 3 L/h a concentration reduction of about 3 orders of magnitude is achieved. For higher flow rates, there is still a significant germ decrease recognizable, but reductions of less than a factor of one thousand are usually not called disinfection.

In both experimental series, the simplified model predicts disinfection rates that are higher than the observed values. That is probably caused by the assumption of a plug flow. The real flow characteristic will be more like a laminar flow, with higher velocities in the middle of the tube, and therefore a reduced exposure to the 285 nm radiation and consequently a reduced disinfection.

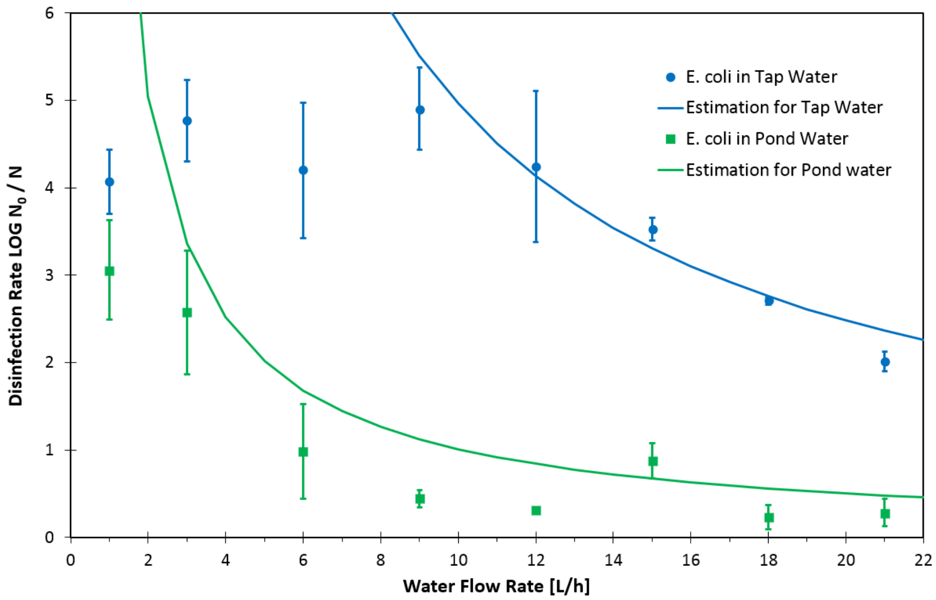

Figure 3. Relative *E. coli* reduction by the 285 nm LED radiation behind the quartz tube. The symbols mark measured values with error bars that show the standard deviation. The continuous curves are estimated by a simplified model.

4. Conclusions and Outlook

The presented system is already sufficient for many applications; e.g., it could be integrated in a modern dentist chair for point of use disinfection for water in the beaker that patients use for rinsing their mouth. Additionally, it could be combined with a solar cell of about 15 × 15 cm^2 and disinfect water for a family in rural areas of the Third World sufficiently. It should be noted that this disinfected drinking water should be consumed without a large delay. Otherwise the surviving germs could recover and proliferate again.

If this disinfection capacity is not sufficient there are two obvious ways to improve the system. The first one would be to choose a LED with a peak wavelength at about 260 nm because there the DNA absorption and germicidal efficiency is higher by a factor of 2.5. However, at the moment the availability of high power 260 nm LEDs is very limited and for surface water the absorption rate is even higher compared to 285 nm radiation.

The second alternative would be to employ more LEDs. As already mentioned in the Introduction, it is not necessary to apply LEDs on the optical axis but it would also be possible to place LEDs even at the corners of the square quartz tube at both ends. Thus, the disinfection capacity could be increased just by the number of employed LEDs. In the past, these LEDs were very expensive with prices of up to $10 k for a single high power 285 nm LED three years ago. However, the price has already dropped by more than a factor of ten, and will probably be below $100 in the near future.

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