Efficiency of Point-of-Use Water Disinfection Using Deep UV Light Emitting Diode Technology

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ABSTRACT

The use of Deep Ultraviolet Light Emitting Diodes (DUV LEDs) is emerging as a state of the art technology for point-of-use water disinfection. Sensor Electronic Technology, Inc. (SETi) has taken the lead in the design and fabrication of compact DUV lamps based on III-Nitride semiconductors (GaN, AlN, InN and their alloys). These semiconductor-based DUV light sources offer narrow spectral power distribution (<12 nm FWHM) with peak emission wavelengths from 227 nm to 340 nm. CW optical output power of up to 100 mW (at 275-280 nm wavelengths) can be achieved using a single, hermetically sealed lamp with a footprint of about 1 square inch.

This technology has been incorporated into a design for a chemical free water purification system. SETi fabricated and tested a compact DUV LED point-of-use water purification system. We demonstrated reduction of *E. coli* bacteria concentration by 6 LOG for 0.5 liter/min flow and 4.5 LOG reduction for 2 liter/min flow. SETi also tested *Enterococcus* bacteria and achieved a 4 LOG reduction for 0.5 liter/min flow.

Keywords: UV disinfection, E.coli, Enterococcus, light emitting diodes, point-of-use water purification

1 INTRODUCTION

Clean water is an essential resource for human civilization that is rapidly becoming scarce. Most water purification treatments involve highly reactive chemicals, such as chlorine, that create unhealthy organic by-products. The use of ultraviolet light has begun to garner attention as a safer and more sustainable form of water purification. Currently, the only sources of ultraviolet light are low and medium pressure mercury lamps. These are brittle, sensitive to temperature change, and contain hazardous materials. The use of Deep Ultraviolet Light Emitting Diodes (DUV LEDs) provides for a safer alternative. DUV LEDs are mercury free, compact, durable, and require low-voltage to operate (i.e. batteries, solar panels). This is important to note as society is switching to more environmentally safe and economically sustainable technology. Using DUV LEDs, Sensor Electronic Technology Inc. has designed and tested a prototype DUV LED point-of -use (POU) water purification chamber. Microbial testing was performed in compliance with EPA and NSF drinking water testing guidelines. Water disinfection tests were performed at multiple flow rates and power levels using *E.coli* and *Enterococcus*. No pre-filtration was performed and the micro-organisms were subject to various UVT levels. Throughout testing, constant optimization of the DUV LED water chamber was carried out in order to increase its germicidal efficacy.

2 DUV LED WATER PURIFICATION CHAMBER

The DUV LED water disinfection chamber was designed to be 3 inches in diameter and 6 inches long with 4 UVCLEAN® TO-3 LED Lamps on one end. Each lamp was rated to deliver up to 80mW output optical power at peak wavelength of 272-273 nm. Uniform optical power distribution inside the chamber was verified through numerical simulations. The LED lamps were powered by a customized power supply allowing independent intensity control of each lamp.

3 POINT-OF-USE DUV LED WATER DISINFECTION

3.1 Microbial characterization and testing

Microbial research by SETi was primarily focused on micro-organisms that serve as indicators of contaminated water. *E.coli* and *Enterococcus* were selected as bacterial candidates. Both are found in human fecal matter and serve as prime examples of water contamination. *E.coli* (ATCC 11303) and *Enterococcus* (ATCC 10541) were obtained from American Type Culture Collection. Each bacterium was independently grown in LB Broth™ to mid-log phase. The solutions were then diluted multiple times and from each dilution, an aliquot was taken and placed on an agar Petri-dish. The agar plates were then incubated for 24 hours at 37 ºC. After incubation, two colonies of each bacterium were placed in test-tubes with LB Broth for 24 hours at 37 ºC and were then used for preparation of bacterial concentrations for testing. The concentrations for *E.coli* ranged from $2x10^4$-$2x10^6$ while *Enterococci* concentrations ranged from $1.5x10^3$-$2.3x10^5$ in a final volume of 2 L of deionized H_2O. The suspensions were mixed vigorously and multiple dilutions from each 2 L suspension were made in order to determine the initial concentrations of *E.coli* and *Enterococcus* before UV irradiation.

The solutions were then placed into a funnel controlled by a valve from which the flow rates had been previously established. Three different flow rates were used in the water disinfection experiment: 0.5 LPM (0.13 GPM), 1

LPM (0.26 GPM), and 2 LPM (0.53 GPM). Output current and voltage were monitored during each experiment. Multiple experiments were run with currents ranging from 100mA-500mA per lamp at increasing intervals of 100mA. Once the UV treated samples were collected, further dilutions were made in order to determine the *E.coli* and *Enterococcus* survival concentrations post-irradiation. Post-irradiation determination was conducted immediately in order to minimize the possibility of light-reactivation.

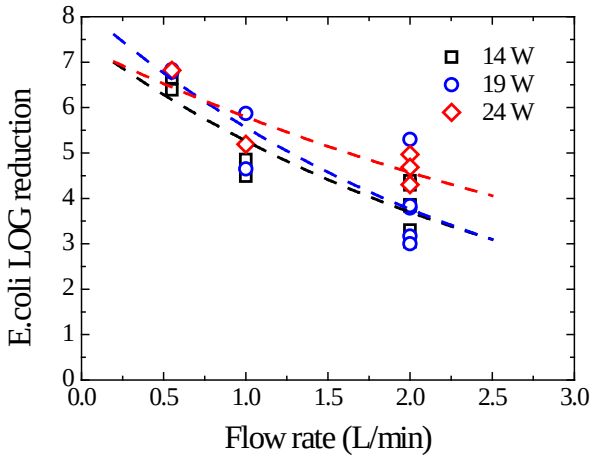

Figure 1: E.coli LOG reduction as a function of flow rate for DUV LED disinfection unit.

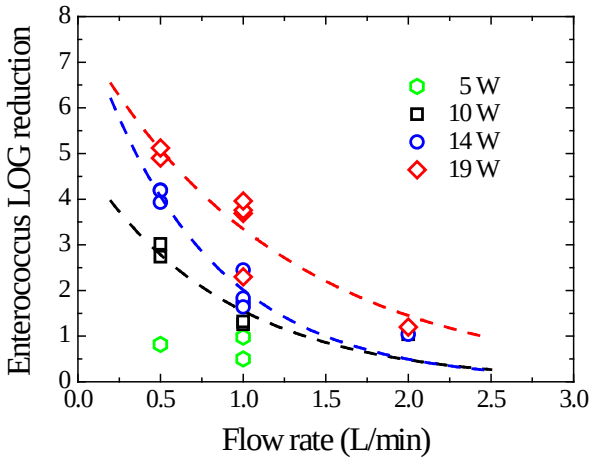

Figure 2: Enterococcus LOG reduction as a function of flow rate for DUV LED disinfection unit.

Determination of *E.coli* was conducted by using Colilert-18™ and Enterolert™ (IDEXX Laboratories Inc.) for Enterococcus. Both methods were approved by the US EPA [1] [2]. The irradiated solutions are then diluted by deionized water into final volumes of 100mL and then mixed with their respective reagents. Then the solutions are poured into Quanti-Tray/2000, sealed, and place into the incubator at 37 ºC for 18-24 hours. LOG reduction values were calculated (N_b/N_a), with N_b and N_a representing the before and after concentrations. The LOG reductions as a function of flow rate are seen in Figures 1 and 2.

At flow rates of 0.5 L/min (8gal/hr) we achieved more than a 6 LOG reduction of viable *E.coli* concentrations at an input electric power of only 14 W. At higher flow rates, >4LOG reduction was achieved at an input power of 24 W. As shown in Figure 2, at 0.5L/min (8gal/hr) almost 5 LOG reduction was measured for *Enterococcus* at an input power of 19W.

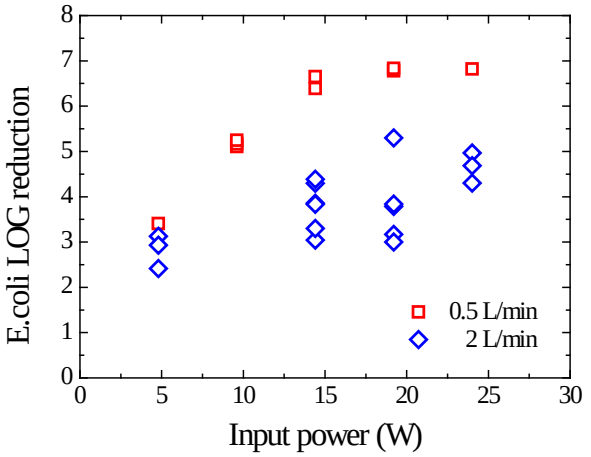

Figure 3: E.coli LOG reduction as a function of input power for DUV LED disinfection unit.

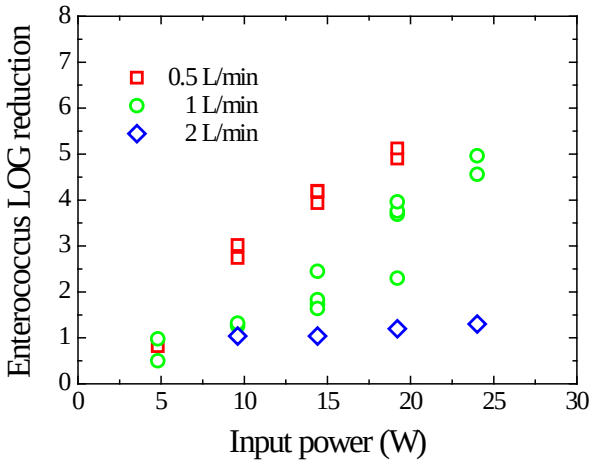

Figure 4: Enterococcus LOG reduction as a function of input power for DUV LED disinfection unit.

As seen from Figure 3, at 0.5L/min the LOG reduction of *E. coli* started to saturate with increasing input power (i.e. optical power). This indicates nearly complete inactivation of the bacteria in water. At higher flow rates LOG reduction increased almost linearly with the input

power. Achieving >6 LOG reduction for both bacterial strains is expected at input powers ~ 50W.

3.2 Ultraviolet Transmission Measurements

A significant factor in reduction in efficacy of the DUV LED purification chamber is the reduction of transmittance of the ultraviolet light within the chamber. This is especially true with higher concentrations of micro-organisms as they can shield and/or scatter the ultraviolet light. *E.coli* and *Enterococcus* UV transmission (UVT) levels were measured using a UV-VIS spectrophotometer. Calibration was performed by using a quartz cuvette containing deionized water with a volume of $1cm^3$ for a baseline measurement. Several *E.coli* concentrations were created in test tubes and placed into individual quartz cuvettes and compared to the deionized water baseline. The results of the *E.coli* UVT are presented in Figure 5 and *Enterococcus* in Figure 6.

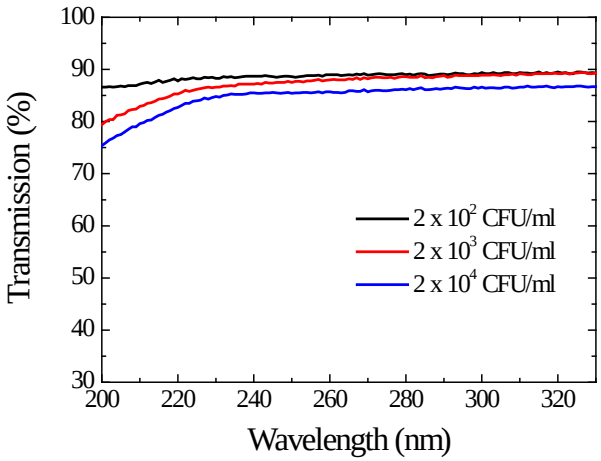

Figure 5: UVT data for DI water with different E. coli concentrations.

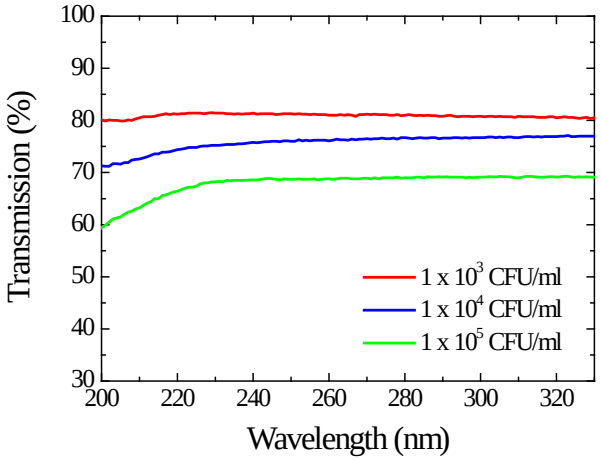

Figure 6: UVT for DI water with different *Enterococcus* concentrations.

Even though *Enterococcus* and *E.coli* are roughly the same size, their UVT differences are evident. This is due to *Enterococcus* being gram-positive, while *E.coli* is gram-negative. The high concentrations of peptidoglycans located within the cell membrane of the Enterococci are believed to be responsible for the lower overall UVT.

3.3 Deep UV Viral Disinfection

The efficacy of the DUV LED chamber on viral inactivation was also studied. *MS2* bacteriophage from the Leviviridae family was selected to represent viral microbes. Viruses are much more difficult to inactivate due to the protection afforded to them by their protein encapsulates. Preliminary test results of flow rate 0.5L/min at 34mW power are shown in Table 1. Difficulty was incurred when attempting to determine MS2 concentrations due to complications in visually observing cell lysis.

Initial Concentration (PFU/mL)	Survival Concentration (PFU/mL)	LOG Reduction
2.30E+01	4.00E-01	1.8
1.27E+05	3.50E+03	1.6
1.50E+02	<1	>2.17
5.30E+01	<0.1	>2.72
1.66E+02	<0.1	>3.22

Table 1: MS2 inactivation at 0.5L/min (8gal/hr) at 34mW.

Successful MS2 inactivation at low flow rate and power indicate the potential for DUV LED viral inactivation. More tests at higher flow rates and increased input power will be conducted in order to improve the systems efficacy to meet NSF guidelines.

4 SUMMARY

The prototype of DUV LED water disinfection unit has shown multiple LOG value reductions in *E.coli*, *Enterococcus*, and *MS2* at minimal electrical input power. Further studies dealing with system design are being conducted to provide uniform UVT levels and achieve performance levels required for drinking water consumer applications. Current DUV LED technology is extremely promising for point-of-use water purification systems where traditional UV stage cannot be used due to high vibration or low operating temperature requirements, such as disaster relief or emergency response systems.

ACKNOWLEDGEMENT

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[1] U.S. Environmental Protection Agency Office of Water. Method 1103: Colilert coliform and E. coli water analysis, EPA 2007.

[2] U.S. Environmental Protection Agency. National Primary Drinking Water Regulations: Ground Water Rule; Final Rule, 71:216 p. 1-88, 11/08/2006