Early Adoption of UV-C Light Emitting Diode Technology for Water Disinfection

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ABSTRACT

UV-C light emitting diodes (LEDs) emit invisible radiation with wavelengths ranging from 200 nm to 300 nm; hence, they are suitable for germicidal applications. Commercial assimilation of UV-C LEDs for water disinfection has long been thought to be unfeasible mostly because of the relative immaturity of these devices. Though UV-C LEDs are still early in their development cycle, their application for water disinfection is very effective when integrated with a novel and very efficient reactor design. Development of such a system requires an integration of hydrodynamics, optics, thermal management, and electronics. This paper reports the multi-physics co-design of such a system.

Keywords: UV-C; LEDs; Light Emitting Diodes; Water Disinfection; Energy Efficiency; Germicidal.

Conventional reactor efficiencies mandate that implementation of a UV-C LED based system is prohibited until the cost of UV-C LEDs decreases by at least 100X to a cost-to-optical power output ratio of less than \$1/mW. Male-specific bacteriophage MS2 (MS2), which is the surrogate of choice for test validation of *Cryptosporidium parvum* and *Giardia lambia* cysts, requires approximately 10X the UV dose over current inactivation methods of *E. coli*. In addition, Dot Metrics Technologies' (Dot Metrics) experimental results with UV-C LEDs show that 4-log inactivation of MS2 requires a UV dose of approximately 70 mJ/cm^2 (1), which is consistent with the doses required by mercury (Hg) lamps. Despite these factors, the application of UV-C LEDs for water disinfection is a reality today. In fact, the world's first commercial UV-C LED water disinfection system – UV Pearl™ - was officially introduced on May 1st, 2012 by Dot Metrics' business partner Aquionics. This was made possible by Dot Metrics' novel approach of optimizing the reactor design for UV-C LED sources.UV-C LEDs are light emitting diodes that emit invisible radiation with wavelengths ranging from 200 nm to 300 nm when a current is applied to them; hence, they are suitable for germicidal applications. UV-C LEDs have shown promise in replacing Hg discharge-based technology in many water disinfection applications. UV-C LEDs can be used to perform the same functions as Hg-based UV lamps; however, they are an environmentally friendly alternative to the latter because they do not contain heavy metals, and do not require special handling or disposal. Moreover, their pseudo-instantaneous on-off operation (as low as 9 ns with gigahertz back-end electronics), and their reduced footprint (typically 0.3 mm^2 to 0.5 mm^2) enables higher degrees of design freedom for applications where size, voltage, rapid operation, and architecture constraints have prohibited the use of conventional mercury lamp technology. In other words, UV-C LEDs enable a paradigm shift in the collective technological conscience as to the design of UV water disinfection systems.

Commercially available, individual UV-C LED chips typically provide less than 3 mW of optical power, however multi-chip packages can be assembled used to increase the optical output power to value > 120 mW.

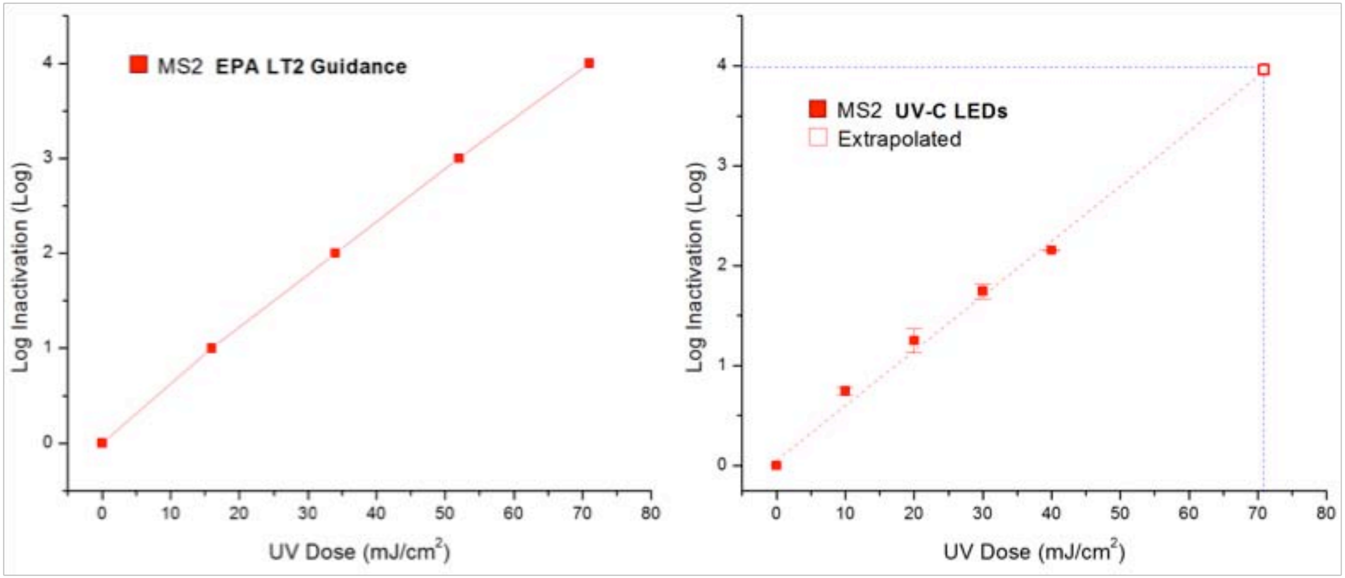

Figure 1. Log inactivation in MS2 as reported by EPA LT2 guidance (left), and as experimentally determined by Dot Metrics Technologies with UV-C LEDs (right).

UV-C LEDs can be can be packaged in a variety of configurations, including watertight hermetic, with packages having a diameter ranging 5 mm to 5 cm. A typical UV-C LED operates with a rapid (< 1 s with ordinary electronic drivers) power-on time at around 6 V and 20 mA. These efficiencies make UV-C LEDs ideal candidates for battery or solar powered applications. Table I illustrates a comparison of UV-C LED and Hg technology.

Table I. Comparison of UV-C and Hg Technology (Low Flow Rate - Low Volume)

Attribute	*Conventional Mercury Lamp*	*UV-C LED*
Efficiency	< 2 gpm/Watt	> 20 gpm/Watt*
Mercury Content	20 – 200 mg	None
Warm up Time	2 – 15 minutes	< 1 s
Zero Flow Limit	10 – 60 minutes	No limit
Architecture	Cylindrical tube	Versatile
Voltage Current	110 – 240 V AC 0.5 – 2.0 A	6 – 12 V DC 0.02 – 0.2 A
Power Consumption	14 – 230 W	0.1 – 10 W
Flow Rate	< 100 gpm	Currently < 5 gpm
*As measured in the UV Pearl™ system for RED.		

This paper presents recent breakthroughs and current initiatives that can advance the industrial adoption of UV-C LED water disinfection systems. Dot Metrics has developed a proprietary technology that compensates for the low optical power output of UV-C LEDs, while leveraging their strengths to allow an early assimilation of UV-C LEDs into new markets. In addition, Dot Metrics has introduced the use of a novel modeling technique in conjunction with the co-design of a proprietary, optically optimized reactor chamber that homogenizes photon flux and ensures liquid quasi plug-flow. The design also incorporates real time water transmittance and absorption sensing for intelligent operational control of the system. As a result, maximized particle residence time and optimized photon flux resulted in a revolutionary, very efficient water disinfection system.

Development of UV-C LEDs is expected to take a similar track to that of blue and red LEDs, and their efficiency is expected to surmount the wall plug efficiency of Hg lamps in the coming years. The wall plug efficiency (WPE) of LEDs (including UV-C LEDs), which is defined as the optical power output divided by the electrical input power, is ever-increasing. Currently, the best demonstrated WPE of UV-C LED is 8% (2) with increasing efficiencies expected as semiconductor material control issues are resolved, and novel light extraction techniques are introduced and refined. Red LEDs came onto the market in the mid 1970's and incrementally increased efficiency until the mid-1980s when their development accelerated through both manufacturing and materials innovations. The result is that red LEDs currently have a WPE of over 80%. Blue LEDs were affected by semiconductor material constraints that many considered insurmountable, however these fundamental challenges were resolved by Nakamura in the early 1990's, and blue LEDs currently feature WPE's of over 80% (3,4). Near UV LEDs, which are affected by semiconductor material constraints and light extraction challenges similar to that of UV-C LEDs, have recently reached a WPE of over 35% (5).

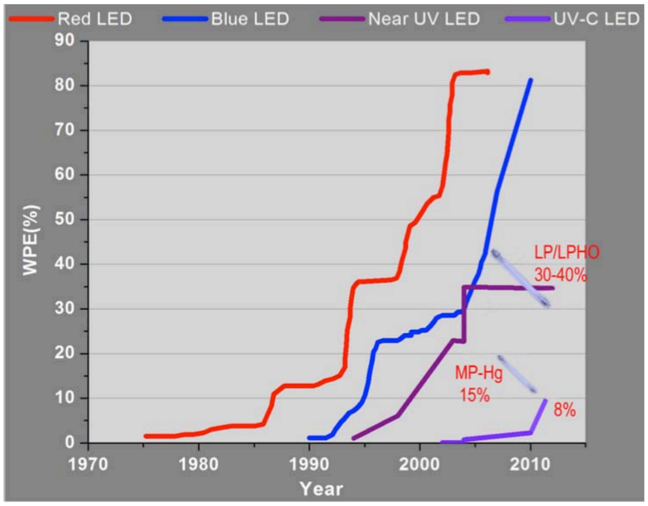

Figure 2: Historical LED wall plug efficiency shown with those of current medium pressure (MP), low pressure (LP), and low pressure high output (LPHO) mercury arc lamps .

THERMAL DESIGN OF A COOLED SOLID STATE UV-C LED SOURCE

Recently, experimental UV-C LEDs have demonstrated > 10% (2) external quantum efficiency (EQE); nonetheless, currently available commercial UV-C LEDs exhibit single digit external quantum efficiencies and therefore readily produce excess heat, which must be removed. Currently their external quantum efficiency (EQE) is below 4%; hence, their optical power output is limited because >90% of the input electrical power is converted into heat (phonons), not photons. The EQE range of UV-C LEDs –as reported in the literature- is presented in Figure 3.

Proper thermal management of optical semiconductor devices improves performance and lifetime (6, 7). This is particularly important for UV-C LEDs. Optical output intensity and device lifetime can be particularly improved for those UV-C LEDs whose heterostructure is fabricated with a solid state, crystalline ternary alloy of aluminum, gallium, and nitrogen (AlGaN) which is typically affected by deleterious high defect densities. Non-cooled UV-C LEDs will quickly rise to high temperatures triggering self-deterioration and causing premature device failure. Packaged UV-C LEDs that are coupled to an improper thermal management system (i.e. an inadequate heat-sink) are provided with minimal heat exchange while still being subjected to high thermal stress; this is true even when operation takes place in low ambient temperature environments. The overall performance enhancement of UV-C LEDs subject to proper thermal management is illustrated in

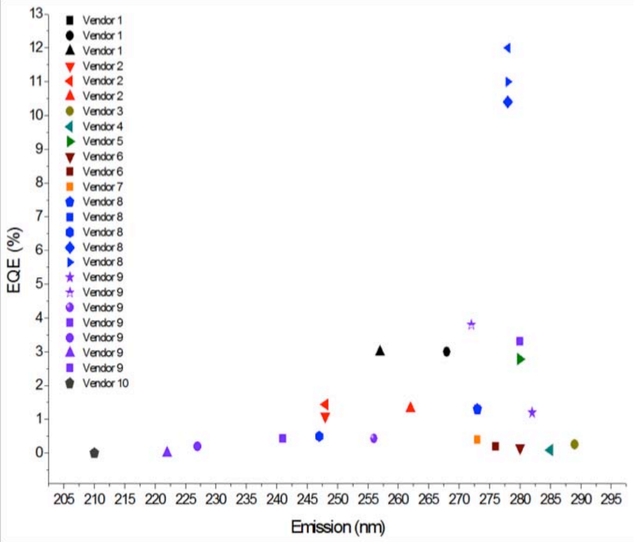

Figure 3: Published UV-C LED EQE values from various manufacturers.

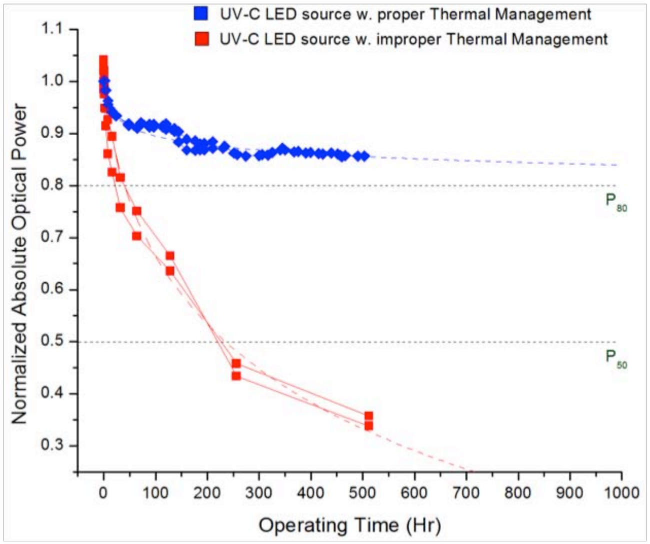

Figure 4: Comparison of UV-C LED sources with and without proper thermal management. Two UV-C LED sources were tested with improper thermal management, shown in red, with a dotted average line.

The use of active heat exchangers is certainly beneficial to this application. Thermoelectric coolers (TECs), which are solid state semiconductor electric heat pumps, are devices that can be employed as the core of a thermal management system. Nonetheless, the use of TECs requires dynamic thermal, electrical, and aging considerations.. UV-C LED die sizes are currently restricted to a few hundred square microns mostly due to poor AlGaN quality (3). The extrinsic property of thermal capacitance, measured in J (kg · K)-1, is therefore low for each die. When the thermal turn-on transient of UV-C LEDs is considered, it will rise sharply due to the high current density in the UV-C LED and the low RC time constant of the thermal properties of AlGaN. Due to these factors, the momentary thermal transient can exhibit intensities more than ten times the average operating temperature of the semiconductor device. Sharp thermal transients occur in micron-scale masses (8), thus high transient heating is highly localized. For multi-chip packaged UV-C LEDs the heat conducted to neighboring dice will be subjected to power blurring due to heat diffusion in all dimensions.

OPTICAL DESIGN OF AN EFFICIENT UV-C LED REACTOR CHAMBER

The electrical efficiency of an UV-C fluid irradiation system will benefit from an efficient use of the UV-C photons emitted from the sources. Similarly, the cost of the system will be abated by decreasing the need for more or higher intensity UV-C sources.

FLUID DYNAMIC DESIGN OF AN EFFICIENT UV-C LED REACTOR CHAMBER

The inactivation rate of a UV-C LED reactor will be highly dependent upon the particle residence time within the reactor chamber. By means of Computational Fluid Dynamics (CFD) studies, Dot Metrics implemented, and developed a novel reactor design, which allows quasi-plug flow rates ranging from 0.1 gpm to above 2.5 gpm, and integrates a prototype of Dot Metrics' UVinaire™. Fluid flow in Dot Metrics' reactor designs was modeled using a combination of Fluent and Star CCM computational fluid dynamics modeling systems. Particles, which simulated pathogenic microorganisms, were released into the reactor chamber and tracked through the system under various fluid flow rates. Histograms of particle residence times in the reactor were generated from the models and were used to predict experimental performance of the reactor. The average particle residence time is described as the volume of the reactor, *V*, divided by the flow rate of the fluid, *Q*. An ideal particle residence time histogram would consist of a delta function centered on *V/Q*. Even small fractions of particles escaping early from the reactor will limit the achievable log inactivation. An early-stage prototype, which was modeled, and then tested experimentally, prematurely released a large percentage of particles, which limited the performance of the reactor to an approximated 2 log reduction value of *E. coli* bacteria at a flow rate of 0.2 gpm shown in Figure 5 (right). A battery of several prototypes were modeled, manufactured and tested during development including an improved prototype design which has the particle residence time histogram given in Figure 5 (left). Note also the distribution of the histogram around V/Q, which is a quick method of predicting performance of the model.

Actual log reduction in the reactor was predicted in the following manner: each particle has an associated resi-

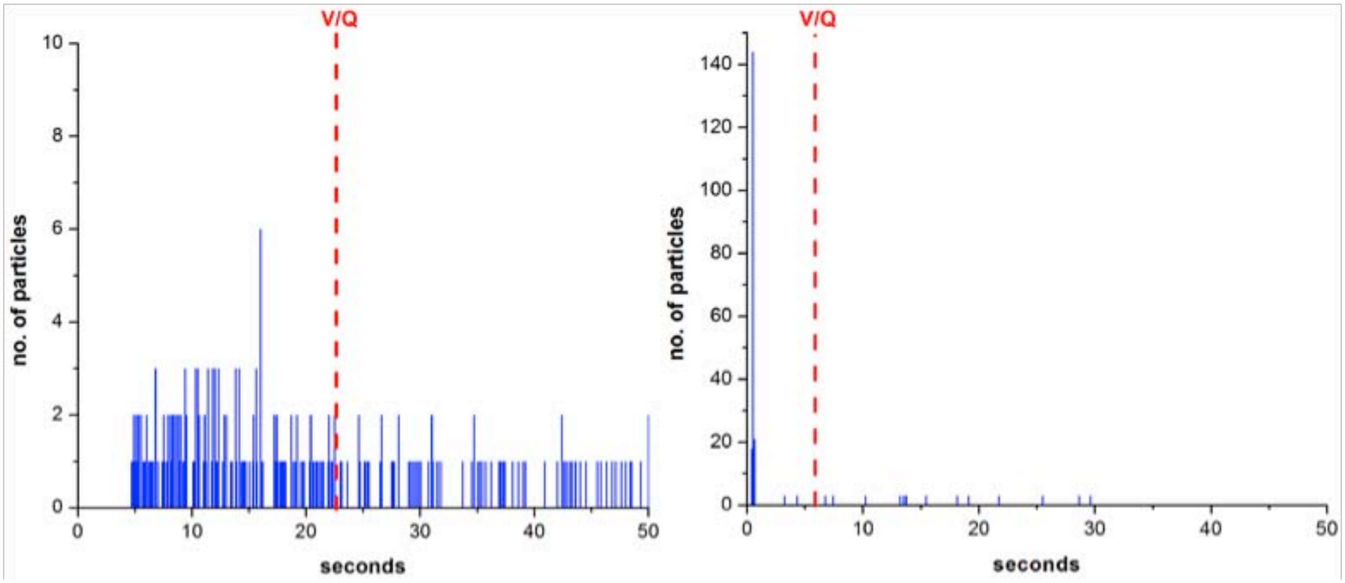

Figure 5: Particle residency results for extreme variations in reactor design including volume, inlet, and outlet dimensions.

dence time, or time spent being irradiated in the reactor. These particles were binned to time bins of a tenth of a second, as shown in Figure 5 (right). A single stage decay model of Chick's law, Eq. 1 was applied to each of the bins to determine the survival fraction of the particles in that bin.

$$\mathbf{S = e^{-kD}} \qquad \textbf{Eq. [1]}$$

The UV rate constant, k, and irradiance, D, were experimentally determined. The predicted log reduction of the system was determined as the log of the ratio of the sum of the surviving particles and the initial number of particles.

BIOLOGICAL ASSAY

The desired product of an effective UV water treatment system is an efficient inactivation rate measure by flow rate and log reduction of viable bacterial colonies. The UVinaire™ monolithic UV-C fixture integrates UV-C LEDs, electronics, sensing, and the thermal management system as described above. The UVinaire™ delivers an engineered flux of photons with an application dependent peak emission wavelength ranging 265 to 280 nm. A beta-prototype of the above design was used to conduct a systematic series of bioassays with *E. coli* surrogates MS2 and T1. Test results indicate 6-log Reduction for the T1 phage at flow rates up to 2 gpm.

Studies to determine wavelength calibrated UV doses for bacteriophages T1 and MS2, and their UV Rate Constants in an optically engineered 3-D UV-flux environment were completed. Experimental results indicated that UV doses delivered by UV-C LEDs with peak emission ranging 265 to 280 nm enables an enhanced log reduction capability with respect to 254 nm UV doses delivered by LP lamps. These tests confirmed that the reactor optical design allows a 24X enhancement over Hg-based lamps in the susceptibility of microorganisms to UV.

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