UV disinfection of water: the need for UV reactor validation

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Abstract Disinfection by ultraviolet light (UV) has received wide endorsement as an important contribution to the multiple barrier approach for protection of public health. UV can be used both to disinfect wastewater discharged to the environment, and to disinfect that water when it is picked up again for human consumption. UV readily blocks infectivity by such chlorine-resistant pathogens as Cryptosporidium parvum, Giardia lamblia and Legionella pneumophila. Multiple disinfectant use is now being discussed to broaden the spectrum of pathogens that can be inactivated by using disinfectants in their most strategically advantageous dose and function. Optimizing multiple barrier strategies requires attention to validation of the concepts and technologies involved. UV technology validation ensures that the equipment can deliver the target UV design dose, and that the monitoring/control technology modulates the dose appropriately with changes in water quality or operating conditions. The bioassay approach for UV reactor validation is recommended over analytical and numerical models. Analytical models, which provide an average dose estimate, have been shown to be inadequate. Numerical models, which utilize Computational Fluid Dynamics (CFD) and UV light intensity models to predict reactor performance, can be accurate when used by skilled professionals but require significant validation and/or calibration against bioassay data.

Keywords Bioassay; CFD; dose delivery; UV controls; UV disinfection; UV dose; UV monitoring; validation

Introduction

UV technologies are becoming better recognized as potent tools in our multiple barrier arsenal for protection of public health against pathogens and chemical contaminants in our water. Engineered UV systems for disinfection use predominantly that part of the electromagnetic spectrum that lies between 200 nm and 300 nm. The effectiveness of UV as a disinfectant is a consequence of the UV-induced changes in the pathogen’s nucleic acids including formation of thymine dimers between adjacent thymine base pairs with a consequential interference with pathogen replication. The inability of the pathogen to reproduce itself (as indicated by bacterial growth in cultures or pathogen infectivity assays) is an indication of UV effectiveness. The higher the UV dose applied, the higher the number of damaged sites formed in the nucleic acids and the lower the percentage of cells that survive UV irradiation. The dose required to produce several logs inactivation of microbes can require the formation of hundreds of dimers. Potential risks to public health exist from a broad range of pathogens including protozoan parasites such as Giardia spp. and Cryptosporidium spp., bacteria such as Salmonella spp. and Legionella spp., and viruses such as hepatitis A virus and rotavirus. The relative sensitivity of different organism to UV follows the general order (from most sensitive): Cryptosporidium spp. oocysts, Giardia spp. cysts, vegetative bacteria, viruses and bacterial spores.

Strategies for use of UV disinfection

UV disinfection can be used in several places within the water cycle to protect public health. UV disinfection of wastewater will inactivate pathogens including the protozoan parasites being discharged to receiving waters that are either used for recreational purposes or picked up as source water for a downstream community’s water treatment plant. Human beings are pathogen incubators, and if their waste is treated in a wastewater treatment plant...
that uses chlorine that is not effective against *Cryptosporidium* spp. oocysts or is used at doses that have a minimal impact on *Giardia* spp. cysts, then wastewater treatment plants can become major sources of such chlorine-resistant pathogens in the receiving waters. These protozoan pathogens are extremely sensitive to UV however, and the advantages of UV in protecting water sources is evident.

Within a conventional water treatment plant, the most common location considered for UV disinfection is after the filters. Other locations are possible however, and strategic thinking may eventually dictate that the other sites be equally considered. For example, filters will trap the larger organisms and accumulate them in high concentrations. If the filter backwash water is sent to the municipal wastewater treatment plant, then the above-described problem may result. If the filter backwash water is recycled to the head of the water treatment plant to conserve some of the backwash water, then the return of live cysts may create a process burden and increased risk should a filter breakthrough occur. UV could be used to disinfect the backwash water, but high solids make the process challenging and likely expensive. If UV were used to disinfect the total pre-filter volume after coagulation/flocculation (i.e., source water together with the recycled backwash water), then only inactive cysts would be in the filter, thus reducing burden on process and risk to public health if the filter barrier were to be compromised. UV after the filter will achieve the same result, but there is reason to believe that a multiple barrier approach (UV before and after the filter) would not only be effective but strategically advantageous in promoting production of sludges that are safer to handle and easier to subsequently treat for additional pathogen reduction.

With the wider use of UV, the potential is being recognized to develop multiple disinfectant strategies that provide a higher level of pathogen protection and a level of disinfection redundancy that is compatible with the multiple barrier concept. Primary disinfection has generally been by use of a single disinfectant, but that practice could be changing. Chemical and UV disinfection have their own characteristics, and additionally differences in effectiveness with different pathogens. For inactivating *Cryptosporidium parvum*, some disinfectants (chlorine and chloramines) are practically ineffective, whereas others are better (e.g., chlorine dioxide and ozone), and UV is best.

There is almost an inverse relationship between UV and chlorine in how the two disinfectants target different pathogens. Those pathogens sensitive to UV are resistant to chlorine, and vice versa. This provides a unique opportunity to exploit the disinfectants strengths in a multiple disinfectant strategy within the context of a multiple barrier approach. Such a multiple disinfectant strategy is illustrated in Figure 1, where the dose to achieve 4 logs (99.99%) inactivation of different pathogens with UV and chlorine are plotted against each other. Note the logarithmic scale of the chlorine dose. Bacteria and the majority of the pathogenic viruses of epidemiological concern in potable water are sensitive to low doses of UV and chlorine. The chlorine-resistant pathogens such as *Cryptosporidium* spp., *Giardia* spp. and *Legionella* spp. are readily addressed by low doses of UV, and the more resistant viruses such as adenovirus are very sensitive to chlorine. By selecting a UV dose of 40 mJ/cm² and a chlorine dose of 5–10 mg/L·min, both disinfectants together are providing a multiple and redundant barrier to most of the pathogens, and each disinfectant is providing a barrier to resistant organisms of the other disinfectant.

The multiple disinfectant strategy carries with it another advantage illustrated in Figure 1; namely, that by controlling the protozoan parasites at low UV doses, the higher chlorine doses are no longer required, and as a consequence there is a reduction in formation of chlorine disinfection byproducts.

The regulatory limit for total trihalomethanes (TTHMs) is shown on the graph along with the chlorine dose-dependent production of these compounds in two different water
qualities. The higher the natural organic matter in the water being treated, the higher the TTHM production at any given chlorine dose. Two extremes in water quality are illustrated, and most water qualities will lie between the extremes. When considering that the chlorine dose can be 200–500 mg/L·min at low winter temperatures depending on water pH, there is substantial benefit in being able to use lower chlorine doses to limit TTHM production. Additionally, in order to retard the development rate of the TTHMs, it is best to convert the chlorine to chloramines by addition of ammonia after the required chlorine dose. This brings yet another advantage by creating a third disinfectant (chloramine) that is a better control agent for the biofilms in the distribution system than is chlorine.

**Ideal versus real UV reactors**

UV dose (fluence) is defined as the product of UV intensity (fluence rate) and irradiation time, Dose = Intensity × Time. Ideal UV reactor behaviour is characterized by a uniform dose distribution. In a batch reactor, such as a collimated beam apparatus, close to ideal reactor behaviour can be achieved if the fluid within the reactor is thoroughly mixed. Ideal flow-through reactors are modeled with the assumption of plug flow. The ideal, or average, dose \( D_{\text{avg}} \) delivered by a plug flow reactor is calculated by multiplying the average UV intensity \( I_{\text{avg}} \) within the volume of the reactor by the average residence time \( t_{\text{avg}} \),

\[
D_{\text{avg}} = I_{\text{avg}} \times t_{\text{avg}}
\]  

(1)

The average intensity can be determined by integrating the UV intensity \( I \) distribution within the volume of the reactor and dividing by the reactor volume \( V \),

\[
I_{\text{avg}} = \frac{1}{V} \int \int \int I \ dV
\]  

(2)

The average residence time is given simply by dividing the reactor volume \( V \) by the flow rate \( Q \), \( t_{\text{avg}} = V/Q \). While the ideal reactor model appears simple, models for the spatial distribution of UV intensity \( I \) can be quite complex.

In a real flow-through reactor, no two microbe, or particle, trajectories are the same and thus each microbe flowing through the reactor will receive a unique dose. For this reason, the plug flow assumption is invalid. Several authors have pointed out that hydraulic profiles and intensity gradients within UV reactors give rise to a distribution of delivered
doses as opposed to a fixed value (Qualls et al., 1989; Scheible, 1985; Chiu et al., 1997). A dose histogram of a real UV reactor achieved by Computational Fluid Dynamics (CFD) modelling is depicted in Figure 2. The key to modeling real UV reactor performance is in the ability to accurately quantify the dose distribution for the reactor at each UV transmittance (UVT), flow rate and lamp power condition.

Bioassay determined dose versus average (ideal) dose for a UV reactor system under varying flow rates, UVTs and lamp power settings is plotted in Figure 3a (Petri and Olson, 2001). Poor correlation exists between the model and actual data, and using ideal dose calculations to size UV reactor systems is, therefore, inappropriate, for several reasons: (a) the spatial distribution of UV intensity is very difficult to model, especially since the absolute UV lamp output is difficult to quantify, and (b) hydraulic effects generally account for 20% to 50% of reactor inefficiency, meaning the ideal model could lead to under sizing by a factor of 2 or more. A simple example illustrates the fallacy of using ideal dose for sizing. Consider a reactor delivering a dose of 100 mJ/cm² for 99% of the flow and 0 mJ/cm² for 1% of the flow. Ideal dose calculations would average out the dose to give dose delivered by the reactor as 99 mJ/cm². Clearly, only 2 log inactivation can be achieved by such a reactor. However, the ideal dose of 99 mJ/cm² leads one to believe that if the reactor were challenged with MS2 Phage, where a dose of approximately 20 mJ/cm² is required for one log inactivation, nearly 5 log inactivation would be achieved. The preferred method to size UV reactor systems is through bioassays, or bioassay validated computational tools.

**Bioassay protocol**

The non-ideal behavior of real UV reactors and the complexity of their designs prohibits reliance solely on theoretical calculations to reliably predict the UV dose delivered by the reactor, and requires that the dose delivered by the reactor be validated using an empirical testing protocol. The bioassay protocol is the standard approach provided by all current regulatory guidance, and is currently the globally accepted approach for validation of the dose delivery performance of a UV disinfection reactor. The bioassay protocol is divided into three parts: firstly the development of a UV dose-response curve with an ideal laboratory reactor for a culture of challenge organism; secondly the passing of the challenge microbes from the same culture through the reactor being validated while it operates under specified conditions of flow rate, lamp power level and water quality; and thirdly, a comparison of the inactivation of the culture following passage through the reactor with the

**Figure 2** CFD generated histogram of dose delivered to microbes in a UV reactor
laboratory dose-response curve to determine which dose delivered by the ideal reactor gives the same microbe inactivation. For those conditions of operation, the reactor is thereby validated to deliver the Bioassay Equivalent Dose read from the dose-response curve.

**Modeling real UV reactor performance**

Although the empirical bioassay is the standard method for validating UV dose delivery, there are several reasons to pursue a more exacting method to calculate UV dose using sophisticated models. With such models, reactor design and optimization could be accelerated. Such models, once validated could be an important part of monitoring UV dose online, and again, once validated such models could be an important part of UV technology control packages designed to deliver dose on demand rather than in gross excess. The consequence is more efficient reactors being designed to meet specific dose requirements, and being operated under conditions that provide dose-on-demand rather than dose in excess when operating parameters such as water quality change.

Such sophisticated models of dose delivery combine the elements of fluid behavior, optics and microbe inactivation kinetics (Wright and Lawryshyn, 2000). Fluid behavior is necessary to track the path of microbes through the reactor. The fluid tracking is necessary to understand how a microbe interacts with the optics (light intensity profile) within the reactor and accumulates UV dose as it passes through zones of high and low intensity and spends different amounts of time in each zone. If the reactor has been poorly designed, some tracks could be predominantly through regions of lower light intensity, and the result is a short circuit that restricts the efficiency of the reactor by always allowing some microbes to take a low dose path. The key to UV reactor optimization is to reduce short circuiting paths as much as possible. However, a very narrow dose distribution, and thus high hydraulic efficiency, can be achieved by designing a reactor with a very small water layer (i.e. short distance between lamps and the wall). Unfortunately, such a reactor would be very inefficient due to loss of UV radiation energy absorbed by the walls of the reactor. Effective reactor design requires a delicate balance between maximizing hydraulic mixing and minimizing absorption of UV irradiance at the walls.

CFD for determining fluid behavior is a potent tool for conceptual as well as quantitative determination. To utilize CFD models effectively, the models must be validated with bioassays. The bioassay dose versus CFD modeled dose for the same UV reactor is plotted in Figure 3b as in Figure 3a, again under varying flow rates, UVTs and lamp settings. The CFD model has linearized the highly nonlinear behavior associated with hydraulics and disinfection. Validated CFD based models can be used for UV system design and for sophisticated on-line reactor control, such as the Trojan UVDosimeter™.

**Online control strategies**

Today, two on-line monitoring strategies exist which can account for non-ideal reactor behavior; the sensor set-point strategy and the CFD based UVDosimeter strategy. The following subsections will present both methods.

**Sensor set-point method**

Variations of the sensor set-point method are used by both the German DVGW and Austrian ONORM standards. As mentioned above, in a hydraulically well mixed reactor, the bioassay equivalent dose will approach the plug flow model ideal average dose. Thus, under these conditions, the bioassay equivalent dose will closely vary directly with the average intensity times the average residence time: \(D_{\text{avg}} \propto I_{\text{avg}} \times T_{\text{avg}}\). Since the average residence time equals the volume of the reactor divided by the average volume flow rate through the reactor, and since the volume of the reactor will remain constant, the Equation
can be rewritten as: \( D_{\text{avg}} \propto \frac{I_{\text{avg}}}{Q} \). This Equation suggests that monitoring intensity might be a surrogate for monitoring dose if certain requirements are met. If the sensor is located in such a way that it responds “equally” to intensity changes from lamp output or UVT, then a linear Equation can be used to determine the dose.

For a well designed UV reactor, a plot of sensor readings versus bioassay equivalent dose for a number of CFD simulations for varying lamp power, UVT and flow rates is shown in Figure 4a. Using the same data, however, and dividing the sensor reading by the flow rate leads to the plots shown in Figures 4b–e. The sensor is positioned ideally for the particular UV reactor configuration being studied, as presented in Figure 4b. It can be seen that the data points align almost linearly. The set-point for this numerically generated theoretical reactor (sensor reading divided by flow rate) can be 0.4 to achieve a dose of 40 mJ/cm². The controls strategy can calculate sensor reading divided by flow rate, and correlate these values to the dose. The same theoretical data as in Figure 4b are plotted in Figures 4c and 4d, but at different sensor water layers (defined as the distance from the sensor to the lamp being monitored). Clearly, wrong sensor positioning can lead to significant error. The optimal sensor location for a poorly performing reactor with poor hydraulic mixing is plotted in Figure 4e. In this case, no linearization can be achieved.

It should be emphasized that the data presented here was generated numerically through CFD and simplified optical models. The degree of linearization depicted in Figure 4b will not be achieved in real life. Furthermore, if a broad range of flow rate, UVT and lamp power conditions are not tested through bioassay, one cannot be sure that conditions exist where the intensity reading for a given flow (i.e. the set-point) is above the specified value but design dose is not achieved, as illustrated in Figure 4e. To avoid such discrepancies, it is best to test reactors over a range of operating conditions if the sensor set-point is to be used.

**Dosimeter method**

Trojan has developed an online dose-predicting algorithm, the UV Dosimeter™, which interfaces fluid dynamics, optics and microbial kinetics to predict UV dose delivery. The algorithm has certain resident information that is unique to a given UV reactor and associated installation piping; namely, the fluid behavior of the reactor (as revealed in hundreds of tracks of microbes through the reactor). The algorithm also has microbial

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**Figure 3** Bioassay dose vs. (a) average dose, (b) CFD generated dose

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kinetics information (essentially dose-response information for the microbes of potential interest). The algorithm then accepts input information including water quality information (UV transmittance), flow rate information, and lamp intensity information. The resident information and the input information are then used to determine the output information: the Bioassay Equivalent Dose for the organism of choice. Using the dose-response curve, the dose can also be used to predict logs of inactivation of the target organism.

It is easy to see that the algorithm could then be used to control the UV system (e.g. lamp intensity) to deliver a specified dose or a specified log inactivation. By varying the intensity of the lamps or even the on-off status of lamps, dose could be modulated. The predicted dose output of the algorithm when lamps are turned off and on in different positions within the reactor is illustrated in Figure 5. Note that the algorithm predicts the sensitivity of dose to which lamp positions are turned off. Three lamps off in Figure 5c are worse than 4 lamps off in Figure 5b because of the short circuit created when the lamps are off in a cluster. Amongst other benefits, the algorithm can enable the operator to receive a minor alarm when a lamp goes out if the algorithm indicates that the design dose is still being delivered, whereas without the ability to determine the dose being delivered, the system would have to be immediately shut down and the lamp problem addressed.

The first rule of innovative technology that could impact on public health is that it must be validated. We described briefly above the use of the Bioassay to empirically validate the dose delivered by an UV reactor under various conditions of operation. To validate a monitoring or controlling algorithm, it is necessary to check that the output Dose of the algorithm matches that of the Bioassay Equivalent Dose and that the output is managed in an appropriate statistical manner (Petri and Olson, 2001). The performance of the algorithm against the Bioassay Equivalent Dose of the UVSwift™ reactor is addressed in Figure 3b. Note that these data...
were collected over several different water qualities, different flow rates, different lamps on or off, and at different power levels to the lamps. Appropriate statistical treatment of these data provide a high level of confidence in the monitored dose being delivered under a broad range of operating conditions. This is essential to addressing regulator requirements for system monitoring.

Conclusions

UV disinfection is a cost-effective way to meet new disinfection demands of water and wastewater systems, and it allows new multiple disinfectant and multiple barrier strategies to be contemplated and validated. UV disinfection reactors are non-ideal and must be validated empirically for dose delivery, and although the protocols are continuing to be refined for greater accuracy, the Bioassay protocols are already in place and being used by most UV equipment manufacturers that wish to provide assurances to those who use their equipment. UV monitoring and controlling technologies are sophisticated, but exist and like reactor performance must be empirically validated to ensure that the monitor/controller output dose is in agreement with the Bioassay validation dose of the reactor over a wide range of operating conditions.

References


Figure 5 UV Dosimeter™ online control (dose in MJ/cm²): (a) all lamps on, (b) 4 lamps on, (c) 5 lamps on, and (d) 3 lamps on