Sensor-Based Control - The Way for Safe, Energy-Efficient UV System Operation

Author: *Mike Newberry, Xylem Water Solutions*[1]

ABSTRACT

Ultraviolet disinfection systems for wastewater have been widely implemented and accepted over the last two decades. They are proven to provide reliable reduction of pathogens in the effluent if sized and operated correctly.

In recent years, discussions in the UV industry were often dealing with the subject of the most appropriate sizing model. For water reuse applications the NWRI/AwwaRF 2003 Guidelines for Drinking Water and Water Reuse describe a design method utilizing biological verification (bioassay). Calculated (mathematical only) ultraviolet sizing models, such as point source summation, have been largely used for secondary discharge installations.

Top priority for the successful operation of a UV system is to stay in compliance under all design conditions. Therefore sizing is usually based on conservative estimations for peak flow conditions, water quality, and design UV dose. As a result underperformance is seen very rarely. However, in the light of recent discussions about reliability and sustainability, the challenge is to operate the UV equipment with the highest level of energy efficiency. The goal is the smallest carbon footprint possible without putting the safety of the disinfection process at risk.

In order to accomplish safe disinfection at minimum cost, sophisticated disinfection units are calculating the operational UV dose based on real time sensor readings. This sensor-based control methodology allows observing better or worse conditions during operation and thereby reducing the number of lamps and/or the UV lamp output with better water quality or less fouling than expected, and saving energy without compromising safety.

Keywords: UV Intensity measurement, Optimized operation, Energy Efficiency.

INTRODUCTION

The sizing of a UV disinfection system is typically based on a specification produced by the user, usually in conjunction with a suitably qualified and experienced engineering consultant. The specification consists of two parts, the required disinfection levels and the expected process values.

The required permit level is set by local and/or state regulations that are in force for the location of the facility. These are typically expressed as a number of viable units per unit volume, e.g. 100 *E. coli*/100ml.

The process values at which this disinfection level must be achieved are a combination of the plant design and the characteristics of the UV system. These values typically include:

[1] Xylem Water Solutions, Private Rd No1, Colwick, Nottingham, NG2 3AN

- Flow Rate
- UVT
- TSS
- Lamp Aging Factor
- Quartz Sleeve Fouling Factor

Taking each of these values in turn, there are guidelines and best engineering practice to assist in selecting a suitable value.

Flow Rate: The UV system must be designed to deliver the required disinfection level at the maximum expected flow. Waste water facilities can experience significant fluctuations in flow during the day and even greater variations when storm flows are expected. We have seen average flows that are 20% to 30% of the peak flow.

UV Transmittance: The UV transmittance is one of the more important parameters for system design, and the UV system needs to be designed for the lowest expected UVT. The UVT can vary on a daily or seasonal basis, in some cases industrial discharge can depress the UVT on a regular basis. For existing plants the historical record of UVT measurements can be examined to determine the lowest expected UVT, for new plant, the engineer should make an informed estimate based on the upstream process.

Total Suspended Solids: This is a function of the upstream processes and affects the ultimate level of disinfection that can be attained. Typical values that are required are 20 mg/l or less.

Lamp Aging Factor: The dominant technology in wastewater UV disinfection is the low pressure high output amalgam lamp. A characteristic of this type of lamp is that the UV output will gradually reduce as the lamp ages, typically by a factor of 0.8 to 0.9. To ensure that the UV system will still deliver the design dose with aged lamps, a design factor, known as Lamp Aging Factor is included in the system design. The lamp aging factor is provided by the manufacturer, after extended operation and measuring of the lamp output in controlled conditions.

Lamp Fouling Factor: The constituents of waste water are many and varied, in most cases this causes a deposition on the quartz sleeves that will reduce the ability of the sleeve to transmit the UV light. Manufactures have addressed this issue by incorporating wiping systems that will remove the build up from surface of the quartz sleeve. The effectiveness of the wiper systems is evaluated typically under the NWRI/AWAARF guidelines; the resulting fouling factor is included in the system design.

EFFECTS OF DESIGN CONDITIONS

The UV system must be designed to deliver the required disinfection, as defined by the delivered dose, at the worst case conditions, however this may result in the system overdosing during condition that are not "worst case".

The effect of changing flows, although not linear, is close to being linear as shown below.

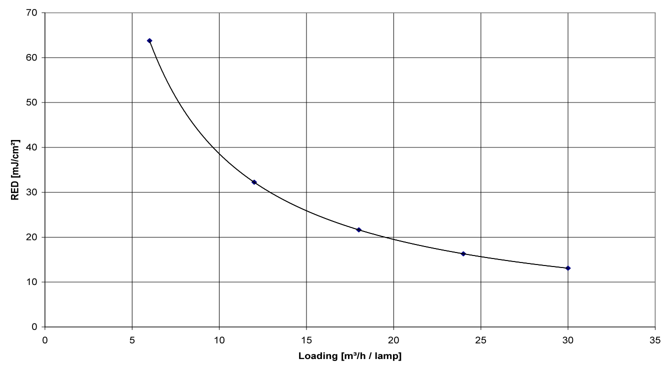

Figure 1 – Typical dose/flow curve.

Here we can see that a system that was sized for a maximum flow of 30 m^3/hour (per lamp) will be delivering nearly double the required dose at half flow and 3.5 times the required dose at ¼ of maximum flow.

The effect of UVT on delivered dose is decidedly nonlinear. The graph below shows the flow rate that can be achieved for a fixed dose as the UVT is varied.

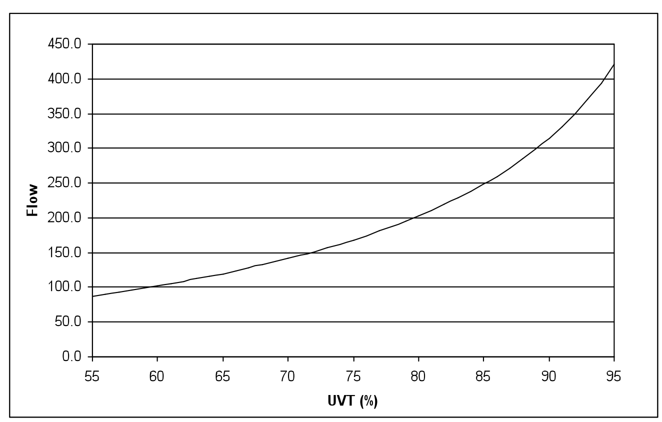

Figure 2 – Typical Dose/UVT curve.

At lower UVT's the effect is less pronounced, increasing as the UVT increases.

Change in UVT (%)	Change of Flow	Percentage increase
55 to 60	87 to 102	17.2
70 to 75	141 to 168	19.1
85 to 90	249 to 314	26.1

It can be clearly seen that a system that is operating at a UVT of only 5% greater than the design UVT could easily be overdoing by over 20%

Lamp aging is typically non-linear, as shown below.

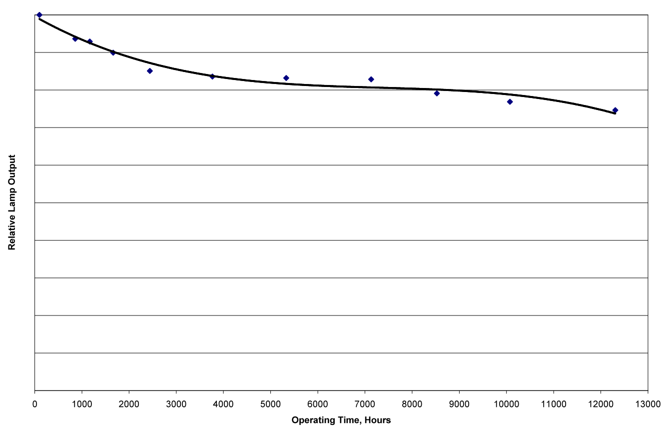

Figure 3 – Typical lamp aging curve.

The lamp aging curve is developed under ideal conditions. The use of the lamp aging curve to predict the lamp output at any point during the life of the lamp assumes that the lamps are behaving exactly the same as during the lamp aging tests; this may not always be the case. Lamps may suffer from premature aging caused by site conditions such as different cycling patterns, water temperature and no flow conditions.

To summarize, the UV system was designed using a set of worst case parameters, in actual operation we have:

- The flow is almost always less then the design flow, which requires less UV energy i.e. fewer lamps operating or lamps at lower power.
- The UVT is usually higher than the design value, again requiring less UV energy.
- The lamp age is known, but the real time UV output of the lamps is unknown
- The state of the quartz sleeves is unknown. The specified fouling factor is only relevant for a working wiping system, just after the wipe has completed.

The advantages of being able to turn down the UV system by powering off individual banks of lamps or reducing lamp power are clear

- Reducing the number of lamps running will directly reduce the number of lamps that will need to be changed, lower consumable costs, lower labor costs and fewer lamps needing to be disposed
- Reducing the lamp power will result in lower energy costs and a reduction of the carbon footprint of the facility.

Whilst there are clear financial and operating advantages, the overriding directive for operation of the UV system must be to meet the disinfection Permits, which is to say that the design dose must be delivered at all times.

BENEFITS OF SENSOR-BASED CONTROL

One way to ensure that the dose is being delivered is to utilize a system that is capable of calculating the real time delivered dose. The increasing requirement for bioassay-sized and operated systems allows the possibility to calculate the real time dose and hence safe reduction of the UV system power. A modern validation is complex and sophisticated; however, the parameters required for dose calculation can be stated simply:

- Flow – defines the residence time of the effluent in the system
- UVT – Defines the water quality.
- UV Intensity – Delivered UV Energy

The above parameters are used to generate an algorithm that will calculate the real time dose which can be used to control the UV system.
The typical dose algorithm consists of two parts:

$$So = A * UVT^2 + B * UVT \quad [1]$$

Where:

So: Predicted UV intensity of a new lamp operated at 100% output with clean quartz and sensor window, mW/cm^2

UVT: Water UVT transmittance at 254 nm, %/cm

And

$$\text{Dose} = \text{RLOo} * 10\ A + B * \text{Log flow} + C * \text{Log UVT} \quad [2]$$

Where UV dose is a function of:

RLOo: Operational Relative Lamp Output (Measured Intensity/So)
Flow: Flow rate/lamp, gpm
UVT: Water UV transmittance at 254 nm

Clearly, in order to calculate a real time dose, the flow, UVT and intensity must be measured and not assumed. The measurement of flow and UVT can be achieved fairly easily and accurately using readily available equipment, however the UV intensity sensor is usually supplied as part of the UV system. The sensor(s) supplied with the UV system should be the same as those used during the validation and must be wave length selective i.e. respond to germicidal wavelengths only, and traceable to known standards.

Using Eqn1 it is possible to predict the expected intensity at the current operating conditions of UVT, and then by using the actual measured intensity, the real time instantaneous dose can be calculated.

Consider now, the various conditions where assuming the lamp output may lead to a lower or higher dose than anticipated.

Quartz sleeve Fouling

Using Fixed Fouling Factor – The calculated dose will not be dependant on the actual condition of the quartz sleeve, if the Fouling is worse than the assumption then under dosing will occur.

Using Measured Intensity – The amount of fouling will directly affect the measured intensity and hence the calculated dose. Excessive fouling will result in a lower intensity and calculated dose, the UV system will respond by increasing the lamp power (or number of banks) thereby maintaining the required dose. Conversely, if the fouling is less than expected, a higher dose will be calculated and the system is able to turn down the lamp power until the calculated dose is reduced to the required dose.

Lamp Aging

Using Fixed Lamp Aging – The calculated dose will not be dependant on the actual condition of the lamp; the lamp may not be aging as per the laboratory measured results. Excessive cycling of the lamp and less than optimal operating conditions may result in a lower output than expected, resulting in under dosing

Using Measured Intensity – The condition of the lamp will directly affect the measured intensity and hence the calculated dose. Excessive aging will result in a lower intensity and calculated dose, the UV system will respond by increasing the lamp power (or number of banks) thereby maintaining the required dose.

Water Quality – UVT

Using Worst Case UVT – When the UVT is higher than the design, as is usually the case, the delivered dose will be greater, however lamp aging and fouling may have reduced the UV output. Using an assumed value for the UVT may result in an undetermined dose.

Using Measured Intensity – The equation shown at Eqn 1 allows the UV system to compensate for changing UVT's. The equation predicts the expected intensity at the current UVT, any reduction in UV output caused by lamp aging or fouling will be reflected in the ratio of the instantaneous measured intensity to the predicted intensity. This ratio (S/So) is part of the calculated dose equation, hence the calculated dose will dependant on this ratio.

CONCLUSIONS

It is entirely reasonable and proper that the UV system should be designed for worst case conditions. However, this means that for most of the time, the UV system will be oversized, with the resultant excess use of power and consumables. The only safe and reliable way to reduce the system power is to utilize a dose equation that uses real time values of Flow, UVT and intensity and then to use the calculated dose to control the system power.

Indeed the NWRI guidelines state that "Continuous determination of the operational UV dose is technologically feasible and is constant with the current requirement for continuous chlorine residual monitoring" It would be ill advised to operate a chlorine injection system without monitoring the residual, why would you want to run a UV system without measuring the real dose?

A system thus controlled will minimize power consumption and lamp replacement, whilst assuring that the primary objective of disinfection is met.