Advances in UV technology, more efficient lamps, and more reliable equipment are increasing the popularity of UV disinfection. These advances have resulted in commercial application of UV for water treatment in pharmaceutical, food, and electronic industries and for municipal water and wastewater disinfection.

Determining the efficiency of UV technologies requires recognition that it is a combination of UV system (lamp technology and output spectra, lamp age, reactor hydraulics), water quality parameters, and microorganism's action spectra/repair capabilities and their state of aggregation (free or particle associated) that determines the efficiency of the UV systems and DBP formation. Today, there is not a single model that can reliably predict how the interaction of these parameters impacts the UV dose and performance of UV systems. Therefore, the need exists for a simple standardized technology validation approach that integrates the complex variables of UV disinfection into a simple output that can be measured readily to assess the performance of UV systems. To achieve this objective and assess the performance and reliability of UV systems, the following major issues need to be addressed:

- Protocol for establishing UV dose and validating UV systems performance and scale-up.
- Target pathogens and surrogate microorganisms.
- Microorganism response spectra and repair mechanisms.
- UV by-products and associated disinfection by-products.
- Performance monitoring requirements and instruments.

The following presents these significant UV disinfection issues in greater detail.

**Protocol for Establishing UV Dose and Validating UV Systems Performance and Scale-Up**

In addition to the low-pressure low-intensity systems, which are widely used, other technologies such as low-pressure high-intensity, medium-pressure high-intensity, pulsed UV, and excimer systems are being proposed for use in water and wastewater disinfection. There are significant differences in power input, intensity output, lamp arc length, power supply, and reactor configuration among these technologies. In addition, UV manufacturers use different methods for estimating effective germicidal intensity for polychromatic lamps and for calculating UV dose within the reactor, which further complicates establishing the performance of these systems.

The measurement of UV dose in a non-idealized, continuous-flow UV reactor is complicated by the complex flow patterns, contact time distribution within the reactor, and variations in chemical and physical water quality parameters (Severin et al., 1983a,b; Qualls et al., 1985). For measurement of UV dose in bench-scale and pilot-scale systems, two approaches have been used: (1) to use actinometric methods, either chemical or biological actinometers (Linden and Darbey, 1997; and Qualls et al., 1989), or (2) to measure UV intensity and retention time distribution with results substantiated by actinometry (Soroushian et al., 1999). Although these methods may be satisfactory for bench-scale dose verification, neither of these approaches alone would be completely satisfactory for dose measurement in a continuous-flow reactor. Therefore, the process modeling of a continuous-flow reactor based on a combination of mathematical modeling, biological or chemical actinometry, and laboratory measurements using collimated beam is the most valuable tool for characterizing the UV disinfection efficiency for the commercially available UV systems. Because currently there is not a single protocol for determination of the applied UV dose in a non-ideal reactor with polychromatic lamps, a standardized protocol for measurement of UV dose and validation of reactor performance is necessary.

**Target Pathogens and Surrogate Microorganisms**

The UV inactivation of bacterial pathogens indicates that 3-log inactivation can be achieved with doses of less than 10 mWs/cm² (Roessler and Severin, 1996). The pathogenic viruses that can cause waterborne outbreaks are more resistant. For example, the required dose for 3-log inactivation of viruses would range from 23 to 50 mWs/cm² for poliovirus, reovirus, Coxsackie virus, echovirus, and *Bacillus subtilis* spores to 55 to...
65 mWs/cm² for coliphage MS2. The adenovirus is most resistant requiring a dose of 80 to 90 mWs/cm² (Roessler and Severin, 1996). Recent studies indicate that UV is more effective than chemical disinfectants for the inactivation of protozoa. Three-logs inactivation of Cryptosporidium required a UV dose of less than 10 mWs/cm².

Kallenbach et al. (1989) made an interesting observation concerning the relative resistance of viruses. They noted that viruses with high molecular weight, double-stranded DNA or RNA, were easier to inactivate than those with low molecular weight, double-stranded genomes. This was similarly true for single-stranded viruses. However, viruses with double-stranded genomes are less susceptible than those with single-stranded genomes.

Pathogens of concern and emerging pathogens were summarized at recent EPA-sponsored workshops. Vibrio cholerae, Salmonella typhi, Shigella, Mycobacteria, and Campylobacter were listed as pathogenic bacteria. Poliovirus, Coxsackie virus, Norwalk virus, echovirus, rotavirus, and Hepatitis A virus were listed as pathogenic viruses. Cryptosporidium and Giardia were listed as pathogenic protozoa. Mycobacterium avium is an emerging pathogen of high priority and heliobacter, Norwalk, calcivirus, Cyclospora, Microsporidium, and toxin-producing algae are emerging medium-priority pathogens. However, little is known about the effectiveness of UV light against many of the emerging waterborne pathogens. These include Helicobacter pylori, Mycobacterium avium, astrovirus, calciviruses, Norwalk virus, picobirnavirus, and picotrinnavirus.

Because of the problems associated with handling of pathogens and the difficulties in their production and assay, surrogates are used for pilot-scale testing. The surrogates, as discussed previously, include coliphage MS2, Bacillus subtilis, and Giardia muris. Coliphage MS2 is the most commonly used surrogate microorganism. Bacillus subtilis also is used as a virus indicator in UV disinfection studies. Giardia muris is a surrogate for protozoa.

Recent unpublished work has suggested that the age of MS-2 coliphage after production may affect its resistance to inactivation by UV light (Gerba, unpublished). Although the growth state of bacteria is known to affect UV light resistance (bacteria are more susceptible to UV light in the log phase of growth), no studies have been done to assess impact of holding conditions on virus susceptibility (temperature, in the presence of organic matter, pH). Such information is critical to accurately assess virus inactivation.

Microorganisms Response Spectra and Repair Mechanisms

Currently, the basic knowledge regarding UV wavelength-specific inactivation and repair of pathogens is deficient. Meulemans (1986) defined an effective UV dose obtained by summing the dose contribution of each wavelength weighted by the germicidal action spectra of the irradiated microbe. However, the wavelength-specific information regarding microbial responses to UV irradiation is limited. Therefore, it is not currently possible to apply more fundamental (wavelength-specific) approach for dose calculation.

DNA/RNA damage caused by UV disinfection can be reversed by microbial repair mechanisms. Exposure of microorganisms to visible light shortly after UV irradiation activates enzymes that reverse pyrimidine dimers created by UV (photoreactivation). Even in the absence of light, enzyme systems excise and rebuild sections of damaged nucleic acid (dark repair). Some, but not all, bacteria are capable of photorepair and dark repair mechanisms. The ability to undertake repair is also a function of the UV dose, with less repair observed with greater UV doses. The photorepair ability of a microorganism also is reduced if, after UV radiation, the sample is kept in the dark for a period of time prior to exposure to visible light (Groocock, 1984). Although viruses cannot repair themselves, they may utilize the enzymes within host cells to undertake repair.

UV By-Products and Associated Disinfection By-Products

Compared to chemical disinfectants, UV is considered to form minimal disinfection by-products. Malley et al. (1995) did not find any significant DBPs in groundwaters or coagulated and filtered surface waters exposed to UV doses of 60 to 200 mWs/cm². Low levels of formaldehyde were produced in highly colored waters, and BDOC levels were increased in untreated surface waters.

The combination of UV and chlorine did not significantly change THM production and HAA concentrations (Zheng et al., 1997) even at doses as high as 4,000 mWs/cm². Von Sonntag (1992) demonstrated that UV can result in the formation of nitrite ion. Pulsed UV was reported to result in very little change in THM and HAA formation and small production of formaldehyde, nitrite, and AOC next to the lamp (Mofidi, 1998). Study of by-product formation for medium-pressure, high-intensity lamps in secondary and tertiary-treated wastewater confirmed that there were no appreciable differences in concentrations of volatile and semivolatile organic compounds and THMs between untreated and UV irradiated waters, but there were small increases in aldehydes (Soroushian et al., 1997). Small increases in formaldehyde, acetaldehyde,
and glyoxal and a 2-log reduction in 8 to 16 carbon hydrocarbons with UV doses of up to 150 mW/cm² with a low-pressure UV system were reported by Awad et al., (1993).

References


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Thermodynamics of Hell Questioned on University Examination

E verett W. Hobart of Spencerport, N.Y., couldn't believe his eyes upon finding in the National Catholic Reporter of Jan. 28 an intriguing bonus question from the midterm chemistry exam at the University of Washington:

Is hell exothermic or endothermic?

The only student who got an A on the question responded as follows (in paraphrased form):

First, you must know the rate of change of the mass of hell -- the rate at which souls are moving into and out of it. You can safely assume that nobody is leaving. Members of most of the many religions contend that members of all others end up in hell, so you can project that all souls go there. Given current birth and death rates, the number of souls in hell -- its mass -- can be expected to expand exponentially.

For temperature and pressure in hell to stay the same, the volume must expand as souls are added. The student wrote, "This offers two possibilities:

If hell is expanding at a slower rate than the rate at which souls enter, then the temperature and pressure will increase until all hell breaks loose.

If hell is expanding at a rate faster than the increase of souls there, then the temperature and pressure will drop until hell freezes over."

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