Disinfection of Drinking Water

Innovation, Development & Opportunities

Conventional drinking water treatment technologies include the use of chlorine or other oxidants for final disinfection. In the case of surface waters, pre-treatment such as coagulation, sedimentation and filtration is generally used to prepare the water before final disinfection. The disinfection of drinking water using chemicals has successfully protected public health against waterborne disease for many years.

There are a number of drawbacks to chemical disinfection, however, such as potentially toxic by-products and problems with taste and odour. The emergence of water-borne pathogens such as *Cryptosporidium*, which are resistant to chemical disinfection, has led to a reappraisal of traditional disinfection practices. Water companies and regulators need to consider how they can respond to such concerns without compromising safety and public health and whilst maintaining scientific credibility.

The development of UV disinfection technology over the last decade has been a perfect example of an industry investing to meet this demand need for an effective, low cost, non-hazardous and environmentally friendly water disinfection technology. The acceptance of UV disinfection at water plants treating in excess of three billion litres daily worldwide is proof that UV is no longer an 'emerging' technology, but rather an accepted technology to be used routinely by engineers to safeguard human health.

The UV industry continues to change, grow and invent new products and applications.

Growing Maturity of the UV Industry.

Multi-product, financially mature industrial groups such as ITT, GE, Halma, Siemens and Suez have now acquired virtually all of the leading UV companies. This has induced market stability and, whilst this will ensure highly professional product offerings, it also means that many of these newly acquired companies must either become or remain profitable to justify the investment made in them. The regulatory acceptance of UV for treating drinking water and regulatory standards for validating new UV reactor designs all signal a major shift in the acceptance of the technology into the mainstream. The UV industry has experienced double-digit sales growth over the last 20 years, and combined annual sales of UV products worldwide will soon be in excess of US$600 million.

Massive Potential for Growth

Probably the greatest potential market for UV disinfection is drinking water. UV is now accepted as a suitable technology to deactivate *Cryptosporidium* and *Giardia* in surface water and other vulnerable sources. From 1997 to the present growth in this market has been generally slow due to several factors, including the uncertainty of sensitivity of *Cryptosporidium* and *Giardia* to UV, the lack of a regulatory framework for UV disinfection, the widespread lack of guidance manuals, the lack of case histories and engineering knowledge in the application of UV in drinking water plants, the general conservatism of the water industry and, finally, the uncertainty of the outcome of several court cases considering a royalty on the use of UV for *Cryptosporidium* and *Giardia* destruction. All of these issues have now either been resolved or resolutions are imminent, paving the way for rapid growth in this market.

UV Disinfection – the basics

UV is the part of the electromagnetic spectrum between visible light and X-rays. The specific portion of the UV spectrum between 185-400nm has a strong germicidal effect. There are two main types of UV technology, based on the type of UV lamps used: low pressure and medium pressure. Low-pressure lamps have a *monochromatic* UV output (limited to a single wavelength at 254nm), whereas medium pressure lamps have a *polychromatic* UV output (between 185-400nm).

DNA has its maximum absorption at both 200nm and 265nm (Von Sonntag, 1986). Maximum absorption does not occur at 254nm, the wavelength produced by low-pressure lamps and often wrongly assumed to be optimum wavelength for killing microorganisms. At 200nm most absorption occurs in the 'backbone' DNA molecules of deoxyribose and phosphate. At 265nm, UV absorption mainly occurs in the nucleotide bases: adenine, guanine, cytosine and thymine (and uracil in the case of RNA). The most common products resulting from damage by UV radiation are thymine dimers, which are formed when two adjacent thymine molecules become fused. The formation of these dimers and other photoproducts prevents the DNA from being able to replicate, effectively killing the cell.

In some cases UV is effective above 265nm. It has been shown, for example, that the optimum wavelength for destroying *Cryptosporidium parvum* oocysts is 271nm (15% more effective than 254nm) (Linden, 2001), while the optimum wavelength for *Bacillus subtillis* is 270nm (40% more effective than 254nm) (Waites, 1988).

In addition to DNA and RNA, UV also causes photochemical reactions in proteins, enzymes and other molecules within the cell. Absorption in proteins peaks around 280nm, and there is some absorption in the peptide bond (-CONH-) within proteins at wavelengths below 240nm. Other biological molecules with unsaturated bonds may also be susceptible to destruction by UV – examples include coenzymes, hormones and electron carriers. The ability of UV to affect molecules other than DNA and RNA is particularly interesting in the case of larger microorganisms such as fungi, protozoa and algae. In these microorganisms, although UV may be unable to penetrate as far as the DNA, it could still have a lethal effect by damaging other molecules.

Recovery from UV Damage

The need to recover from or repair UV damage is common to virtually all microorganisms that are regularly exposed to UV light in nature. Known as reactivation, the process can take place in both light and dark conditions and is called, respectively, photoreactivation and dark repair. The ability to reactivate varies significantly depending on the type of UV damage inflicted and by the level of biological organization of the microorganism. The repair mechanism is not universal and there are no clearly defined characteristics determining which species can repair themselves and those, which cannot.

The part of cells most vulnerable to UV damage is the DNA and RNA. This is due partly to its unique function as the repository of the cell's genetic code, and also because of its highly complex structure and large size. It is hardly surprising therefore that all known molecular repair mechanisms have evolved to act upon the macromolecular nucleic acids, particularly DNA. In photoreactivation, repair is carried out by an enzyme called photolyase, which reverses the UV-induced damage, while in the case of dark repair it is carried out, by a complex combination of more than a dozen enzymes. To begin reactivation (both light and dark), these enzymes must first be activated by an energy source – in photoreactivation this energy is supplied by visible light (300-500nm), and in dark repair it is provided by nutrients within the cell. In both cases, reactivation is achieved by the enzymes repairing the damaged DNA, allowing replication to take place again.
Common strains of *E. coli* contain about 20 photolyase enzymes, each of which can repair up to five thymine dimers per minute – this means that, in a single cell, up to 100 such dimers can be repaired per minute. 1mJ/cm^2 of UV produces approximately 3000-4000 dimers (Oguma, 2002) so, theoretically, damage induced by 1mJ/cm^2 of UV can be repaired in just 30 minutes.

Repair After Exposure to Low and Medium Pressure UV

Low-pressure UV lamps have traditionally been used in water treatment plants because their UV output at 254nm closely matches the absorption peak of DNA bases at 265nm. A number of studies, however, have shown that microbial DNA is capable of photoreactivation after exposure to low pressure UV (e.g. Sommer et al, 2000).

Because of these findings, and because of the increased use of medium pressure UV lamps in water and effluent treatment, recent research has begun to look at whether medium pressure UV can permanently inactivate the DNA of microorganisms. It has been suggested that, because the broader wavelengths emitted by medium pressure lamps not only damage DNA but also cause damage to other molecules, it is therefore much more difficult for cells to repair their DNA.

The recent research compared the effects of low pressure and medium pressure UV on the ability of microorganisms to repair their DNA. In their tests they compared the ability of *E. coli* to recover in photoreactivating light after being exposed to different amounts of low and medium pressure UV. *E.coli* was used in the study as it is a useful 'biological indicator' of disinfection efficiency in water systems. The results of these studies showed a significant difference in photoreactivation following low and medium pressure radiation. While high levels of photorepair were observed after low-pressure irradiation, with maximum repair occurring after 2–3 hours, there was virtually no photorepair after medium pressure treatment. This was particularly the case at higher log reductions (log 3 and above) (Oguma et al (2002), Zimmer et al (2002) and Hu et al (2005).

Zimmer et al proposed a number of reasons why medium pressure UV causes irreparable damage, while low pressure UV does not. One hypothesis is that there is a synergistic effect between the various wavelengths emitted by medium pressure lamps that cause irreparable damage to the DNA. Another possible explanation is that the repair enzymes themselves are damaged. According to Zimmer et al, while absorption of UV by proteins is considered of little importance to cells, any damage to repair enzymes would be critical due to that fact that there are so few of them present in the cell.

All these studies concluded that polychromatic medium pressure UV radiation was more effective than monochromatic low pressure UV at causing permanent, irreparable damage to the DNA of *E. coli*.

Implications of the Findings

The implications of these findings are far-reaching. For any installation where UV is used to disinfect drinking water, the operator needs to be sure that the treatment is permanent. Zimmer at al suggest that medium pressure UV could therefore provide better protection against reactivation. A much larger research effort into the area of photoreactivation is still required, especially research involving real water treatment plants, and this will most likely be forthcoming over the next 5 years.

Developing UV Technology

The use of computational fluid dynamics modelling has vastly improved UV system manufacturers' ability to predict with confidence the level of treatment required using their proprietary equipment. System sizing is no longer a black art, as the selected manufacturer can work with the design engineer to accurately predict treatment levels under varying conditions of water quality and flow. All UV equipment manufacturers will soon use this tool to optimize the dose delivery of their reactors and minimize energy costs. As manufacturers develop and improve optimized reactors, they will then validate the designs using USEPA* validation protocols.

Conventional UV lamp technology will also improve, with medium pressure lamps continuing to see gains in energy efficiency, lamp life and power density. This approach will remain favoured for compact, small footprint installations, particularly retrofit, or where automated wiping is required. Low pressure, high output lamps will also have increasing power, perhaps approaching 1kW, which will decrease the footprint and maintenance requirements for systems using this technology. Lamp disposal will emerge as a significant issue for low-pressure UV installations, which use many thousands of low-pressure lamps.

UV monitor technology has also greatly improved over the last decade, with stable, reliable and germicidally accurate sensors now available and a well regulated calibration protocol now in place. In addition, manufacturers have improved the proprietary control systems for taking information from the sensors, flow meters and other monitoring devices and using this information to optimize the performance of their equipment. They can also interface with the operator at a plant's control centre.

The D_{10} values** of more and more microorganisms is now known, with the list growing all the time. Most notably, research has confirmed the very low doses required to disinfect *Cryptosporidium* and *Giardia*, while also finding several viruses that have an unusually high D_{10}. As new applications for UV are found, new microbes will be added to existing D_{10} tables.

Case Study – Paris, France

A large-scale UV disinfection system from Dutch UV specialist Berson is treating drinking water for around 650,000 people in Paris, France. Located to the north of the city in the suburb of Méry-sur-Oise, the system is one of the largest European installations of Berson's InLine range of UV equipment. Five InLine 1500 units are installed in parallel to provide disinfected drinking water at the rate of 7500 m^3/h.

Owned by SEDIF (the Syndicat des Eaux d'Île-de-France) and operated by the Compagnie Générale des Eaux, the plant uses water from the nearby River Oise. Following pre-treatment and nanofiltration, the water is pumped through the UV units, which kill any remaining microorganisms. The treated drinking water is supplied to 37 districts in the northern suburbs of Paris, with daily production totalling 340,000 m^3.

The InLine units feature Berson's innovative MultiWave medium pressure UV lamps, which are orientated perpendicular to the water flow to achieve optimum UV exposure. An integral sensor monitors UV light intensity in each treatment chamber, while a custom-built control panel provides communication between the UV units and the plant control room. Also incorporated in each UV unit is an automatic wiping mechanism, which cleans the quartz sleeves surrounding the lamps, and keeps them free of water-borne deposits.

Conclusion

The UV industry has matured considerably over the last decade and is now highly regulated and dominated by major water companies. Conventional UV technologies have been field-tested and now have considerable track records in a wide range of applications. Uncertainties surrounding regulations, royalties, technology and engineering have decreased and acceptance of UV is expected to grow rapidly over the next 20 years.

The advantages of medium pressure UV are becoming more apparent as a way of permanently destroying microorganisms. More research in this area is required, especially in real water treatment plants.

Conventional UV designs have been greatly aided by CFD***, which will be used as a routine sizing tool for future designs. Incremental improvements in conventional lamps, monitors and controls will also continue over the next decade. The stage is now set for dramatic growth in the drinking water market, especially if new technologies can bring increased efficiencies and lower costs.

Notes

** U.S. Environmental Protection Agency*

*** The D_{10} value for a microorganism is the UV dose necessary to cause a 99% reduction in colony forming units. The relationship between UV dose and kill rate is* *logarithmic. For example, if a 99.99% kill rate of a particular microorganism is desired, the necessary dose is determined by multiplying the D10 value by four.*

**** Computational Fluid Dynamics*

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