UV Irradiation: An Age Old Emerging Technology for Water Treatment

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Introduction

Ultraviolet (UV) irradiation is considered an emerging technology for public health protection while at the same time an ageless process that was instrumental in bringing about life on earth and was harnessed into a "technology" for human use in treating water in the late 1800's (Downes and Blunt, 1877). This paper will review why there is now such an emerging interest in UV, the basics of UV technology, why UV works, the use of UV for disinfection and oxidation of pollutants in water, and the frontiers of UV technologies.

Traditional Use of UV Technologies in Water Treatment

Since the 1970's, there has been a growing understanding that chlorine application for disinfection of water has adverse effects in both natural waters and drinking water. In wastewater, chlorine was used to disinfect the sewage before it was discharged into natural water bodies. In drinking water, chlorine has been used for over 100 years to disinfect water for potable uses. In North America, UV first found wide application for treatment of wastewater. Because chlorine residual is toxic to aquatic life, the discharge of wastewater into waterways had to cease by either dechlorinating the water or changing the disinfectant. UV was a natural application because it was effective and does not leave any residual. Not until recently, UV was not acceptable for disinfection of drinking water for the very reason it was accepted for wastewater – no residual. However, since the 1970's, a growing concern over chlorinated disinfection byproducts with associated more stringent regulations (USEPA, 1996), coupled with the ineffectiveness of chlorine against hardy protozoan pathogens, a search for disinfection alternatives has been on-going. In 1998 and soon thereafter, it was discovered that UV was in fact very effective against many chlorine resistant pathogens, including *Cryptosporidium* (Clancy et al. 1998) and *Giardia* (Linden et al., 2002), which propelled UV into the forefront of disinfection alternatives and allowed the EPA to establish more stringent regulations for the control of *Cryptosporidium* and *Giardia* in drinking water. Now UV is a fast growing disinfection process being incorporated all over the world and is encouraged as an effective water disinfection process in the most recent EPA drinking water regulations (USEPA, 2006).

How Does UV Work for Disinfection and Oxidation?

UV is a physical process, harnessing the power and energy of photons to effect destruction of pathogenic microorganisms and break apart chemical bonds of pollutants. In order for UV to be effective, the photons both have to be absorbed by the target pathogen (First Law of Photochemistry) or chemical and pack enough energy to cause a lasting photochemical effect.

In disinfection applications, the photon target is the DNA of a microorganism. The absorbance spectrum of the target is one determinant of the wavelengths that will be most effective. UV radiation covers the electromagnetic spectrum from 200 to 400 nm (100-200 nm is the vacuum UV range) where the most important for disinfection is between 240 to 280 nm, the peak wavelengths of DNA absorbance (See Figure 1). In chemical destruction applications, the target wavelengths depend upon the absorbance features of the target pollutant. Two examples of target pollutants are presented in Figure 1.

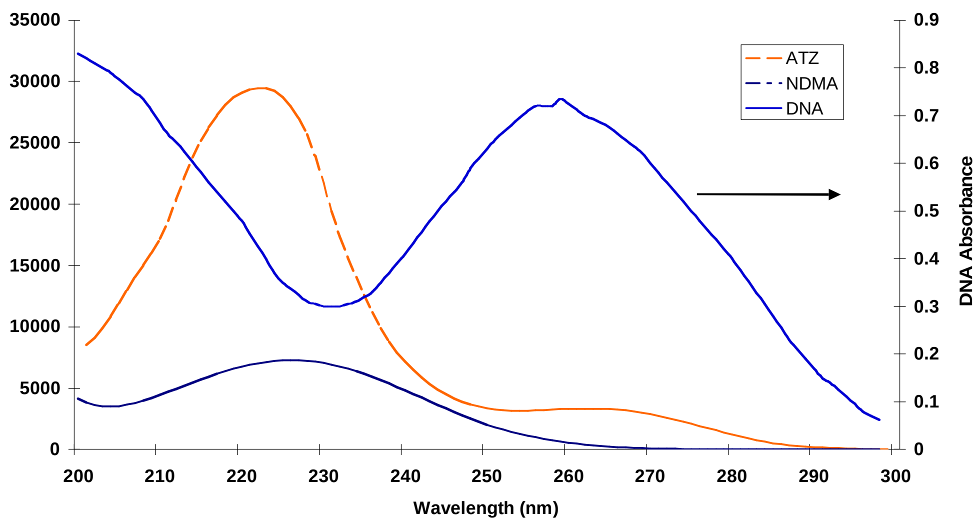

Figure 1. Absorbance spectra of chemical pollutants atrazine (ATZ) and N-nitrosodimethylamine (NDMA), compared to the absorbance features of DNA.

Engineered UV systems were first developed at the turn of the 20th century with the mercury arc lamp. Current conventional UV lamps include mercury vapor lamps of the low pressure (LP) and medium pressure (MP) variety, indicating the internal mercury vapor pressure, which dictates the emission spectrum illustrated in Figure 2. LP lamps are low in power, high in UV efficiency, and generate near monochromatic emission at 253.7 nm, near the peak DNA absorbance. MP lamps are higher in power, lower in UV efficiency, and generate a broadband polychromatic emission with characteristic peaks between 200 and 400 nm. These differences translate into engineering decisions and opportunities for each lamp, specific to the application considered. On the frontiers of UV lamp technology are non-mercury based sources including high-energy pulsed-UV based lamps, often with xenon gas, and UV-based light-emitting diodes (LEDs) currently under development. An example of the types of spectra emitted from these pulsed UV sources is presented in Figure 2. These new UV sources may soon radically change the engineering design of UV systems, offering more flexibility in UV reactor configuration.

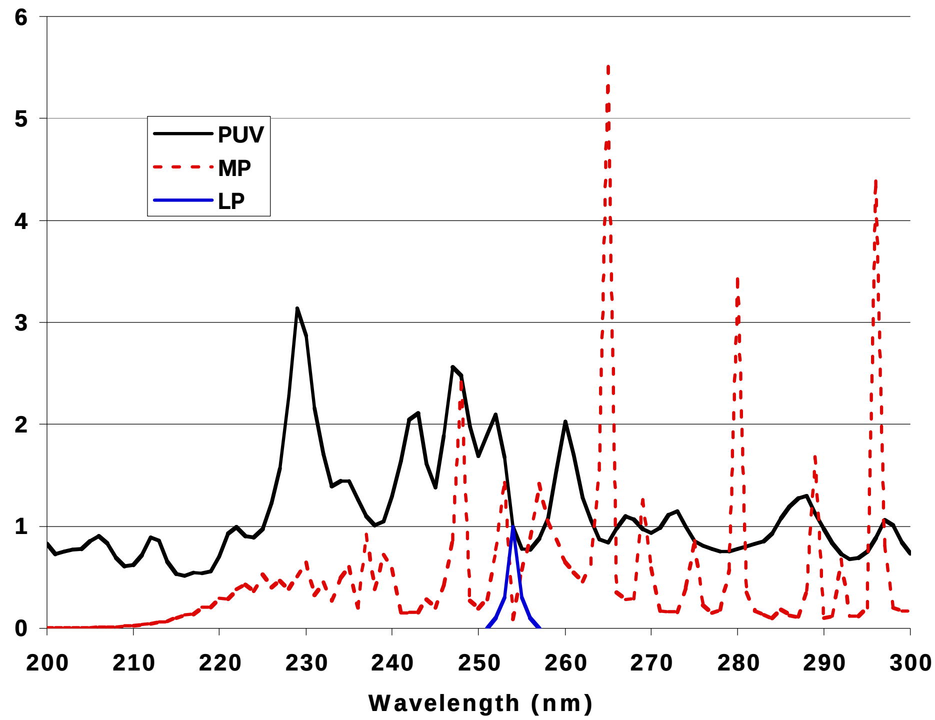

Figure 2. Emission spectra of conventional low pressure (LP) and medium pressure (MP) mercury vapor lamps, compared with a new surface discharge pulsed UV source.

UV for Disinfection of Pathogens in Water

Interestingly, the efficacy of UV against pathogens varies greatly. UV doses are measured in units of milliJoules per centimeter squared (mJ/cm^2) or energy per unit area. The UV dose required for 99.99% inactivation of various pathogens is displayed in Figure 3. UV disiinfection systems are commonly designed around a UV dose of 40 mJ/cm^2. Clearly, both bacterial and protozoan pathogens are very easy to inactivate compared to viruses and adenoviruses in particular. However, recent research shows that MP UV is much more effective than LP UV, specifically for some hard to disinfection viruses (Linden et al., 2005). The thoughts here are that MP can cause a diversity of damage to the pathogen and due to the complexity of the infection process for this virus, multiple types of damage are required for inactivation. These details will be discussed further during the presentation.

One caveat with disinfection is that many microbes have the ability to repair their UV induced DNA damage through both light and dark based repair processes (Harm, 1980). Light based repair involves an enzyme – photolyase – that gets activated during exposure to near UV and visible light wavelengths (350 – 450 nm). Dark repair typically involves excision repair and does not need light activation. These repair processes attack the pyrimidine dimers formed from UV exposure that leads to inactivation. At high enough doses (2-3 times that needed for disinfection) the repair processes are not effective and under typical drinking water conditions light based repair is not a concern.

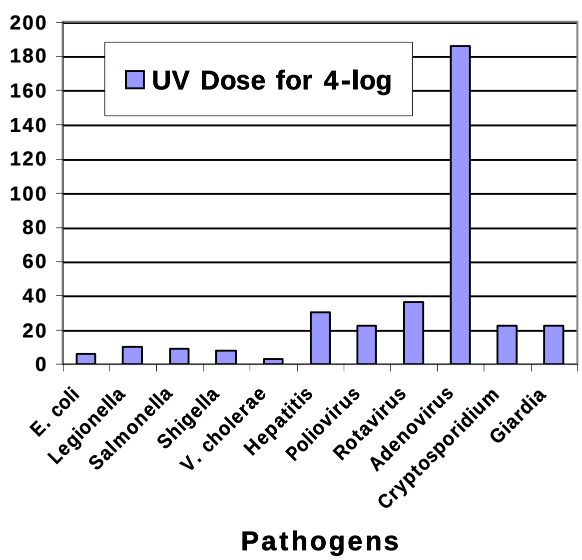

Figure 3. UV doses required for 4-log (99.99%) disinfection of various pathogens in water.

UV for Oxidation of Pollutants in Water

Another application for UV irradiation is the destruction of chemical pollutants in water (Oppenlander, 2003). This chemical destruction can take place through direct absorption of UV photons – termed photolysis – or indirectly via formation of highly reactive oxidative radicals. UV photolysis requires very high levels of UV energy, up to 100 times higher than required for disinfection. When hydrogen peroxide (H_2O_2) is added to water in the presence of UV photons in the germicidal range, the H_2O_2 is split into two hydroxyl radicals (•OH) by the photons and the radicals react rapidly (less than micro-seconds) with organic molecules in the water and thus degrade pollutants.

$$H_2O_2 + h\nu(UV_{200\text{-}300}) \Rightarrow 2\bullet OH$$

The UV- H_2O_2 process is termed an advanced oxidation process (AOP) because it accelerates the natural oxidation that occurs in the environment. It is a rapidly growing treatment technology using either LP or MP UV technologies for destroying a variety of pollutants in water including taste and odor causing compounds, endocrine disrupting compounds, pharmaceuticals and personal care products, as well as agricultural chemicals. There is currently a lot of research on-going in the area of AOPs for water treatment as the public is getting more concerned about these emerging contaminants.

Other UV Applications

Another area of growing interest is the use of UV irradiation for treatment of water in lesser-developed countries. A number of student groups working through Engineers Without Borders and other groups have installed LP UV systems in Africa, Latin America, Asia, and India. These systems can be constructed with local materials and be run using a low-power solar panel. Solar UV disinfection – using the sun's UV rays – is also an area of high interest among students where water is placed in discarded plastic bottles and exposed to sunlight over 4-6 hours to disinfect it via light and heat based processes.

The Frontiers of UV

Although UV itself is an emerging technology on the frontiers of water treatment, there are many new engineering and scientific advances that continue to push and improve the technology and help develop a better understanding of the fundamentals of how UV works, leading to improved process design. Advances in UV lamp technologies coupled with concerns over mercury in UV lamps have led to lamp development including the new pulsed UV lamps which have instant-on capabilities and generate intensities up to 10,000 times greater than LP UV sources. UV-based LEDs are also emerging as this technology is being pushed to lower wavelengths that are more germicidally effective. New technologies offer the possibility of radical changes in UV reactor design and improvements in effectiveness for water treatment, at lower energy costs, with safe materials for the environment. As UV technologies become accepted for drinking water, they are also being explored in water reuse applications – an important source of new water as our freshwater resources are rapidly being either compromised or drained. Of great interest is the

UV-AOP process in water reuse for combined disinfection and oxidation of contaminants. Advances in molecular biology and analytical chemistry have all contributed to furthering the knowledge of how UV works for improving water quality. In summary, UV technology is another example of the ways of harnessing the power of nature for use by humans in our modern society. Natural UV from the sun has been harvested, engineered, and channeled to serve water quality.

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