Emerging Disinfection Technologies

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The removal or inactivation of pathogenic organisms is an increasingly difficult challenge for the drinking water industry to meet. The historical, conventional approach to disinfection may not always be adequate as regulations tighten, new pathogens emerge, and previously unknown disinfection by-products are identified.

For decades, processes such as coagulation/sedimentation, granular media filtration, and chlorination have been used to reduce pathogens in water and wastewater treatment. More recently, membrane filtration, ozonation, and UV irradiation have also been established as effective methods for achieving microbial inactivation; however, a review of the literature indicates that there are a new generation of technologies being developed that may vastly improve utilities' ability to cost-effectively meet existing and future regulations associated with the microbiological quality of water.

Pulsed Arc Electrohydraulic Discharge

Electrohydraulic discharges are produced during the rapid release of stored electrical charge across electrodes submerged below the water surface. The resulting formation of an electrical arc across the spark gap produces a localized plasma region (i.e., ionized gas) that emits UV radiation and generates pressure and thermal shocks (Ching et al., 2001). These phenomena can also produce radical species and ionic reactions (Lee et al., 2004). Thus, electrohydraulic discharge processes use multiple mechanisms to achieve microbial inactivation.

A review of the literature done by Emelko et al. (2003) indicated that pulsed arc electrohydraulic discharge (PAED) can effectively treat microorganisms, algae, volatile organics, nitrogenous compounds, and some inorganics. Their research also showed a 2.6-, 3.3-, and 3.6-log E. coli inactivation after the application of 6, 18, and 30 electrohydraulic discharges, respectively.

Ultrasound

Microbial inactivation. Cell inactivation using ultrasound occurs via acoustic cavitation – the creation, growth, and implosive collapse of gas bubbles in response to an applied ultrasonic field. Ultrasonic compression (positive pressure) and rarefaction (negative pressure) waves generate local regions of high and low pressure, respectively, which can disrupt the attractive forces between molecules.

When water molecules are torn apart with sufficient force during a rarefaction cycle, micro-cavities are formed in regions where aqueous pressure falls below the vapor pressure of the liquid. This drives gas out of solution and into the cavity to form micro-bubbles (Shah et al., 1999).

This phenomenon often occurs at "weak spots"–places where gases are either dissolved in a liquid or are trapped on particulates (Maynard, 2000). The ultrasonic field then causes these micro-bubbles to grow and oscillate simultaneously.

When a bubble reaches a critical size, it can no longer resonate in frequency with the sound waves, and the next compression cycle causes the bubble to implode. This implosion, which occurs within 10^{-11} seconds, can generate local temperatures near 5,000°C and local pressures of thousands of atmospheres (Casadonte, 2000; Suslick et al., 1999). Because the bubbles are small relative to the volume of the surrounding liquid, this heat and pressure dissipate rapidly, leaving ambient conditions unaffected (Shah et al., 1999).

If bubble collapse is asymmetric, which can occur if the bubble implodes within a few radii of a particle or other solid surface, micro-water jets form that can travel up to 6,600 m/s (Maynard, 2000). While bactericidal mechanisms have not been fully proven, it is widely believed that these elevated temperatures, elevated pressures, and high-velocity water "darts" are responsible for microbial inactivation.

Although the use of ultrasound to inactivate microorganisms has been examined since the 1950s, the application of ultrasonic technology to water treatment is relatively new. In full-scale treatment, microbial disinfection/removal goals are typically accomplished through the addition of chemical oxidants such as chlorine or ozone, by the application of UV, and/or by membrane filtration. Though each of these processes can achieve a high degree of microbial log-reduction, each possesses unique limitations.

Chemical oxidation is limited by the formation of disinfection byproducts, which are regulated by the Stage 1 and Stage 2 Disinfection Byproduct (DBP) Rules. The effectiveness of UV disinfection drops significantly as water transmittance decreases and/or when pathogens are enmeshed in flocs. Membrane fouling in low-quality waters can necessitate frequent backwashing and chemical cleaning procedures. In addition, membrane technologies require monitoring to confirm membrane integrity and significant maintenance to maintain integrity.

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Water Treatment System Component	Potential Benefits Of CFD Application
Water Intake Facilities	• Improved water quality from stratified reservoirs
Pump Station	• Reduced vortexing in wet-well • Prolonged pump life
Flow Distribution	• Optimized designs for flow-splitting
Coagulation/Flocculation	• Improved Mixing • Improved Floc Formation
Sedimentation	• Reduced flow short-circuiting and velocity gradients • Improved solids capture
Chemical Disinfection	• Improved t_{10}/t ratios • Reduced DBP formation
UV Disinfection	• Optimized dosing strategy • Reduced power usage
Water Storage	• Improved t_{10}/t ratios • Reduced DBP formation

TABLE 1: Water Treatment Applications of CFD Modeling

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Alternatively, ultrasonic disinfection does not produce regulated DBPs, is not impacted by UV transmittance or pathogen enmeshment in flocs, or fouling and integrity issues. Ultrasound, therefore, appears to have a role in treating waters not suited for traditional microbial inactivation processes.

Numerous researchers have investigated bench-scale ultrasonic inactivation of microorganisms in water. Using an ultrasonic frequency, average intensity, and exposure duration of 26 kHz, 0.3 W/cm^2, and eight minutes, respectively, Scherba et al. (1991) observed between 9 and 99 percent kills of *Pseudomonas aeruginosa*, *Bacillus subtilis*, and *Staphylococcus aureous*.

Ordoñez et al. (1984) used 20 kHz ultrasound at 160 W to examine the inactivation of *Streptococcus faecium* suspensions. They found that D-values (time required to reach one log inactivation) decreased with increasing suspension temperature. At 5, 20 and 45°C, they observed D-values of 30, 29.2, and 12.4 minutes, respectively. Blume et al. (2002) observed 2.9-log reduction of E. coli when aqueous solutions were irradiated with 20 kHz ultrasound for 60 minutes at 400 W/L.

Ultrasound technologies have also been developed for full-scale drinking water treatment applications. A 30-mgd surface water plant serving the city and region of Bonn, Germany, premiered the use of ultrasound for drinking water treatment in 2002. In this case, ultrasound is used to inactivate highly motile zooplankton that can destroy flocs and release microorganisms capable of reaching the filtrate.

Pilot-scale experimentation showed > 95 percent inactivation with an intensity of 1.2 W/cm^2, a residence time of 20 seconds, and a frequency of 20 kHz (Hoyer, 2002). Full-scale performance data are not yet available.

Combined Oxidants/ Technologies—Synergy

Historically, disinfection technologies and chemicals have been applied independently; however, recent research has demonstrated that there may be substantial benefit to applying multiple disinfection processes simultaneously or sequentially. The following discussion

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describes some of the results of this research.

UV and Chlorine

A study presented at the 2nd International Congress on UV Technologies by Loterierzo et al. (2003) examined the impact of using low-dose UV, followed by either chlorine dioxide or free chlorine addition. The results indicated that a UV dose of only 7 mJ/cm^2 resulted in a measurable increase (~one log better reduction) in both chlorine dioxide and free chlorine *E. coli* disinfection ability.

Ultrasound and Chlorine

Testing by Plummer et al. (2002) examined the impact of using ultrasound (sonication) and chlorine (free) for disinfection of *E. coli*. Testing was performed to document the stand-alone disinfection ability of both ultrasound and chlorine at target doses. The two disinfection methods were then tested in series and as a combined batch reactor (simultaneous disinfection).

Sequential application of sonication followed by chlorination did not show synergy. In fact, the resulting disinfection was less than additive, but simultaneous application of sonication and chlorination did show measurable synergy, with 4 to 5 log reduction of *E. coli* with the simultaneous disinfection, compared to 2-log reduction based on additive performance of the two stand-alone disinfection processes.

Ultrasound and UV

UV has emerged as a viable alternative to chlorination for reclaimed water disinfection. One of the main concerns with this disinfection approach is the presence of large particles (>7 microns) in reclaimed water streams, which can severely limit the effectiveness of UV disinfection. Large particles shield organisms (both unassociated organisms in the water and organisms embedded in the wastewater particle) from UV light, making it difficult or impossible to achieve the desired level of microbial inactivation.

To address this issue, a filtration step can be installed upstream of the UV system to remove large particles. Alternatively, ultrasound can be placed upstream of UV and can achieve two treatment objectives: 1) facilitate the degradation of larger particles into smaller particles to improve the effectiveness of subsequent UV irradiation, and 2) provide direct inactivation of microorganisms.

Testing by Blume et al. (2002) indicated that five seconds of exposure to ultrasound followed by five seconds of exposure to UV light resulted in greater inactivation levels than 30 seconds of exposure to UV light alone.

Ozone and UV

The synergistic benefits of using ozone followed by UV were demonstrated by Cushing et al. (2002). During disinfection pilot testing of the challenging waters of Lake Okeechobee (Florida), it was found that the use of low-dose ozonation prior to UV disinfection resulted in a rise in ultraviolet light transmittance (UVT), leading to a dramatic reduction in the required UV system size. A cost analysis showed that to achieve the same level of disinfection, the use of ozone + UV was less expensive than UV alone.

Sequential Chemical Oxidants

A substantial amount of research has also been performed to examine the synergistic effects of applying various chemical disinfectants in series. Ozone/free chlorine, ozone combined chlorine, chlorine dioxide/free chlorine, and chlorine dioxide/combined chlorine pairs have all been tested sequentially.

It was found that while chlorine dioxide + free or combined chlorine show minimal to moderate disinfection synergy, ozone + free or combined chlorine increased *Cryptosporidium* inactivation kinetics 15- to 50-fold (Corona-Vasquez et al., 2002a; Corona-Vasquez et al., 2002b; Rennecker et al., 2001a; Rennecker et al., 2001b).

Bank Filtration

Drilled near rivers and lakes, bank filtration (BF) wells draw surface water through soil and aquifer material, subjecting it to filtration, dilution, sorption, and biodegradation processes. Bank filtration has been used for over 100 years in Europe and is now gaining interest and application in the United States. BF can improve disinfection in two ways: first, BF by providing several log removal of pathogenic bacteria and protozoa through natural filtration, and second, by decreasing the level of disinfection byproduct precursors through sorptive and biodegradation processes (Gollnitz et al., 2003; Weiss et al., 2003a; Weiss et al. 2003b Ray et al., 2002).

Computational Fluid Dynamics

While not a disinfection process itself, computational fluid dynamics (CFD) is a powerful tool that is increasingly being considered to optimize numerous water treatment processes, including disinfection. CFD is a modeling technique by which flow patterns within a hydraulic process can be simulated numerically. CFD models are built on a highly accurate and advanced modeling technique known as the finite element method.

Until recently, CFD was used primarily by the aerospace, defense, and biomedical industries; however, the technique is quickly becoming one of the most powerful tools available for optimizing water treatment plant performance. Table 1 lists specific CFD applications related to water treatment.

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