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BALKANS REGIONAL YOUNG WATER PROFESSIONALS CONFERENCE

29-30 April 2010
Belgrade Serbia

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Prof. Dr Milan A. Dimkic

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DESIGN AND PERFORMANCE TESTING OF A NON-MERCURY ULTRAVIOLET DISINFECTION REACTOR

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Abstract

A non-mercury, excimer UV disinfection reactor was designed by integration of the results of numerical simulations based on computational fluid dynamics and an irradiance field model for cylindrical excimer lamps. The irradiance field model was developed based on the principle that excimer lamps emit radiation from a large number of point sources; the model incorporates calculations for absorption, dissipation, reflection, and refraction within the reactor system. A prototype reactor was constructed with a xenon-bromide excimer lamp and a quartz internal spiral baffle. Experiments were conducted on the reactor to test its effectiveness for disinfection of drinking water in situations where the use of mercury-based UV sources is restricted or undesirable; a similar design approach could be used to develop an excimer UV reactor for disinfection of other fluid media, including wastewater and air.

Keywords

irradiance field modeling, excimer lamp, XeBr*, ultraviolet (UV) disinfection

INTRODUCTION

Disinfection reactors that employ ultraviolet (UV) irradiation inactivate pathogenic microorganisms by altering their genetic material and hindering their replication. The efficiency with which UV disinfection reactors are able to inactivate microorganisms is dependent on the hydraulic characteristics of the reactor, the radiation intensity field within the reactor, and microbial inactivation kinetics or the degree of microbial resistance to UV radiation. A numerical modeling tool was developed to incorporate information on these three components that influence process performance of UV systems. This tool was used to investigate various reactor geometries and develop a numerical prototype of a reactor system based on non-mercury containing excimer lamps.

DEVELOPMENT OF NUMERICAL METHODS AND INTENSITY FIELD MODELING

Reactors employing excimer lamp technology represent a suitable choice in situations where lamp mercury content is restricted, or otherwise undesirable. As illustrated in Figure 1, cylindrical excimer lamps typically consist of two co-axial tubes that are made of a dielectric material, usually quartz, and contain a rare gas or a mixture of rare gases/halogens at close to atmospheric pressure (Kogelschatz, 1990). The imposition of an electrical potential across the two dielectric barriers leads to the formation of an excited molecular complex, which has no stable ground state under normal conditions. This molecular complex is called an excimer and it decomposes within nanoseconds, giving up its excitation (binding) energy in the form of photons at a characteristic wavelength. The wavelength of radiation is dependent upon the gas mixture present within the dielectric barrier. Baseline experiments conducted with a xenon-bromide (XeBr) excimer lamp demonstrated its germicidal UV output at 282 nm to be highly effective for inactivation of *Bacillus subtilis* spores, similar to UV254 (Pennell *et al.*, 2005).

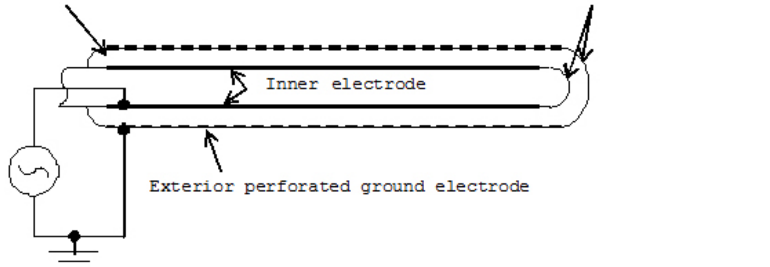

Figure 1. Cylindrical dielectric barrier discharge excimer lamp configuration with an annular discharge gap (adapted from Kogelschatz, 1990, with permission).

The efficiency of various reactor designs for a closed-loop water reuse system application during long-term space missions was investigated using a Lagrangian modeling scheme. The modeling approach involved simulation of fluid mechanics and particle trajectories using commercially available computational fluid dynamics software (FLUENT). Accurate simulations of the radiation intensity field within the reactor required development of a new intensity field model. This new model, called the surface power apportionment for cylindrical excimer lamps (SPACE) radiation intensity model, was developed specifically for this purpose. The SPACE model accounts for the geometry and emission characteristics of the XeBr excimer lamp, which are fundamentally different from those of conventional mercury lamps; the model also provides a detailed accounting of the effects of absorption, dissipation, reflection, and refraction within the reactor system. The lamp was represented as a collection of point sources, and radiation may be received at a receptor site from every hypothetical point source through as many as three different radiation pathways: a direct radiation pathway from the point source to the receptor site, reflection off internal high-voltage electrode, and reflection off the reactor housing. An illustration of these three radiation pathways is presented in Figure 2.

The three-dimensional SPACE model uses an iterative procedure to calculate the radiation pathway from a point source to a receptor site through different media. The procedure begins by identifying all point sources that contribute radiation to a specified receptor site. As the exact points of reflection and reflection of radiation between a point source and a receptor site are not known *a priori*, it is not possible to calculate the length of radiation pathways through each medium (excimer gas, quartz lamp walls, the surrounding fluid – water, wastewater or air). Radiation absorbance and dissipation are a function of the length of the radiation pathway through a medium, and therefore, in order to accurately represent the irradiance at a receptor site, it is necessary to determine the lengths of radiation pathways.

Trigonometry and Snell's law, which governs the refractive and reflective behavior of radiation transmitting through different interfaces, were used to establish relationships between the different segments of each radiation pathway and the associated angles of reflection and refractions. For each radiation pathway, an initial guess was made for an angle of refraction of reflection, or the length of a segment of the pathway. The initial guess value was incorporated into the established relationships and the values for each pathway segment were obtained. These new pathway values were then used to back-calculate and update the initial guess value that was used in subsequent iterations. Iterative calculations for each pathway were repeated until the initial guess values differed by no more than 10^{-6} radians for angles of reflection and refraction, and 10^{-3} cm for the length of pathway segments.

The SPACE numerical model was compiled into a FORTRAN numerical code that was able to generate representations of the irradiance field around any size cylindrical excimer lamp. Measurements of the radiation intensity field by local actinometry demonstrated the validity of the SPACE model, both in qualitative and quantitative terms (Naunovic *et al*., 2008).

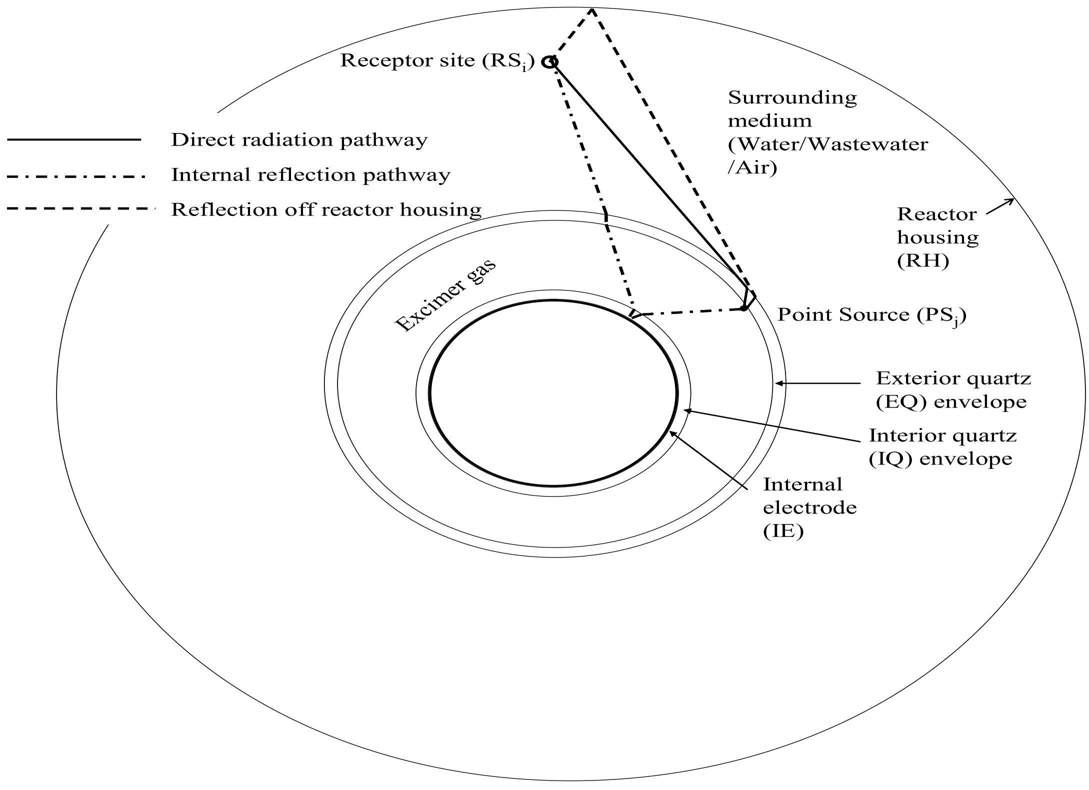

Figure 2. Illustration of three different radiation pathways from a point source to a receptor site (2D representation).

RESULT OF NUMERICAL MODELING EFFORTS - CHOSEN REACTOR GEOMETRY

The SPACE intensity field model was used along with microbial particle trajectory simulations and experimentally measured inactivation kinetics of *Bacillus subtilis* spores to evaluate disinfection efficacy of various reactor geometries and process variables. The final design of the reactor was produced by an iterative procedure using the modeling tools, thereby allowing for optimization of reactor characteristics. The reactor design had to ensure microbial inactivation efficacy, as well as minimize volume, mass, power and man-hours for maintenance tasks. The reactor was designed to treat 46.5 gallons per day, which is equal to the daily rate of water use and wastewater generation by six astronauts.

The investigated reactor variations included a 90-degree inlet elbow and a straight inlet, three different reactor diameters, and internal baffle structures. From these simulations, it was determined that a reactor with a straight conical inlet and a spiral baffle would satisfy all requirements for a water disinfection reactor to be used during long-term space missions. The inclusion of the spiral baffle provides the benefit of enhanced inactivation at lower transmittance values. An illustration of a reactor design with spiral baffles and a diagram of four representative microbial trajectories through the system are presented in Figure 3. A digital image of the physical prototype is presented as Figure 4. The total length of the constructed prototype reactor was 1.05 m. The total length included a straight inlet section and a conical inlet section that were 14.8 cm and 20.0 cm long, respectively. The interior diameter of the reactor was 9.55 cm. The length of the excimer lamp was 71.1 cm and the exterior diameter was 5 cm.

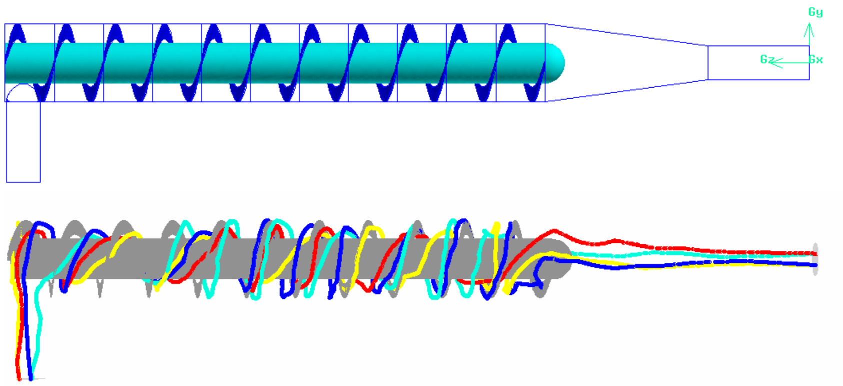

Figure 3. Illustration of reactor design with spiral baffles and four particle trajectories through the reactor.

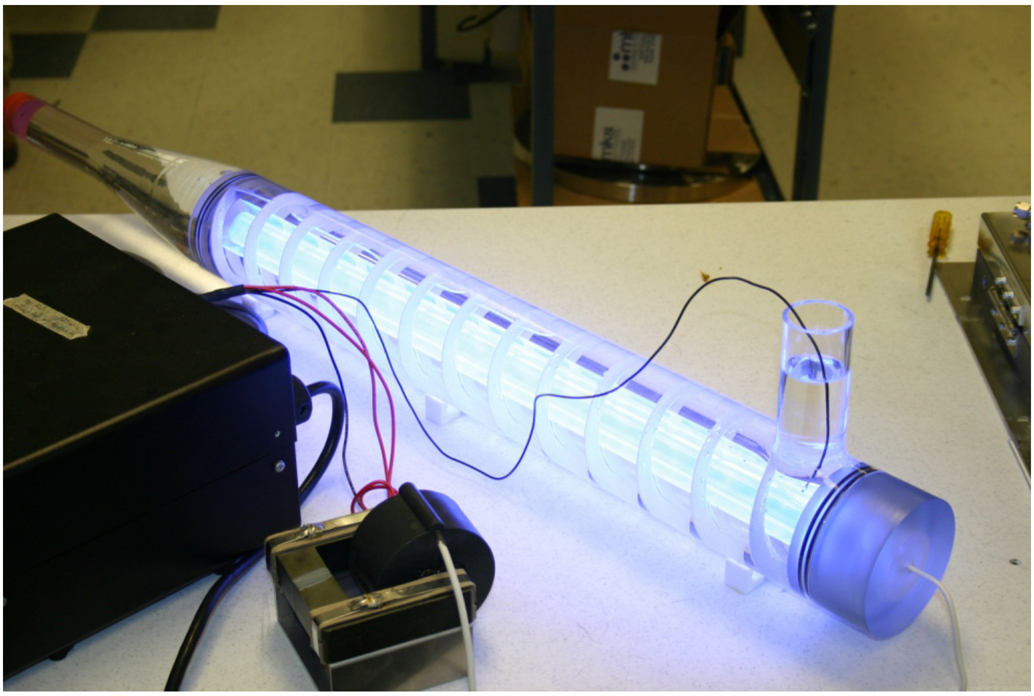

Figure 4. Digital image of the reactor with a XeBr excimer lamp as the UV radiation source.

TESTING OF REACTOR PROTOTYPE

The testing of the reactor prototype included measurements of microbial inactivation of *Bacillus subtilis* spores. *Bacillus subtilis* spores were chosen as the challenge organism because they are relatively easy to culture and assay, they are essentially non-pathogenic to humans, and they exhibit relatively high resistance to UV radiation, which allows for quantification of their UV dose-response behavior over a wide range of doses (Sommer and Cabaj, 1993; Nicholson *et al*., 2000). They are commonly used in biodosimetry-based testing of UV reactors, including those designed to treat drinking water (US EPA, 2003). *Bacillus subtilis* spores have also been identified as a microorganism of concern for planetary contamination due to their high resistance to UV radiation (Nicholson *et al*., 2005).

A schematic of the experimental set-up is presented in Figure 5. A continuous flow-through experiment was conducted with tap water that had been subjected to pretreatment through a reverse osmosis system as a basic aqueous matrix. Microbial inactivation achieved by the reactor was measured at four flow rates.

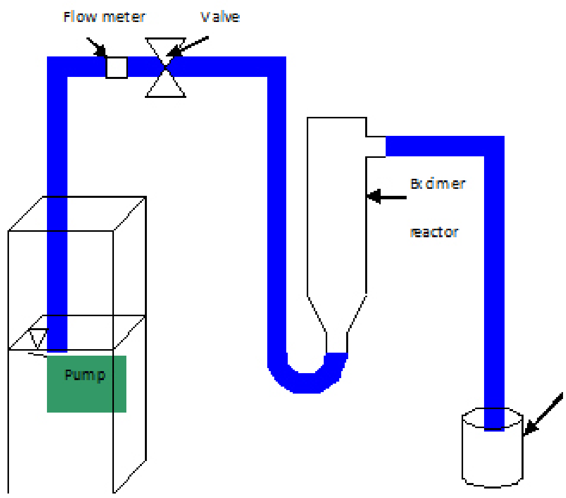

Figure 5. Experimental set-up.

Bacillus subtilis spores at an initial concentration of 10^5 cfu/L were added to a 300 L reservoir of water. Sodium chloride (150 g) was also added to the reservoir to provide conductivity and allow the aqueous medium to act as a ground electrode for the excimer lamp system. This aqueous suspension in the reservoir was mixed using an impeller system, and then sampled directly from the tank and assayed to determine the exact initial *Bacillus subtilis* spore concentration. A submersible pump inside the reservoir was turned on and the suspension was drawn from the tank and passed through the UV reactor at the maximum flow rate for 20 min to reach a steady-state condition. The water passed through the reactor at the four volumetric flow rates. The flow was adjusted at each flow rate and effluent samples were collected for subsequent spore viability assays at the outlet of the reactor; a single biodosimetric test run was conducted for each flow rate.

Aliquots of influent and effluent samples were then filtered through 0.45 mm membrane filters (Millipore Corp.) to separate the spores from the aqueous matrix. The membranes with the collected spores were incubated on nutrient agar plates (DIFCO, Becton Dickinson Microbiology Systems) for 24 h at 37 ºC. For each effluent sample thatwas collected, three different sample volumes were filtered in triplicate. The degree of inactivation achieved by the reactor at each flow rate was expressed by the ratio N/N_0, where N is the concentration of viable spores in the effluent of the reactor and N_0 is the concentration of viable spores in the tank prior to UV irradiation.

The predicted *Bacillus subtilis* spore inactivation responses made using numerical methods are shown along with the biodosimetry measurements in Figure 6. The numerical simulation results are in good agreement with the biodosimetry measurements.

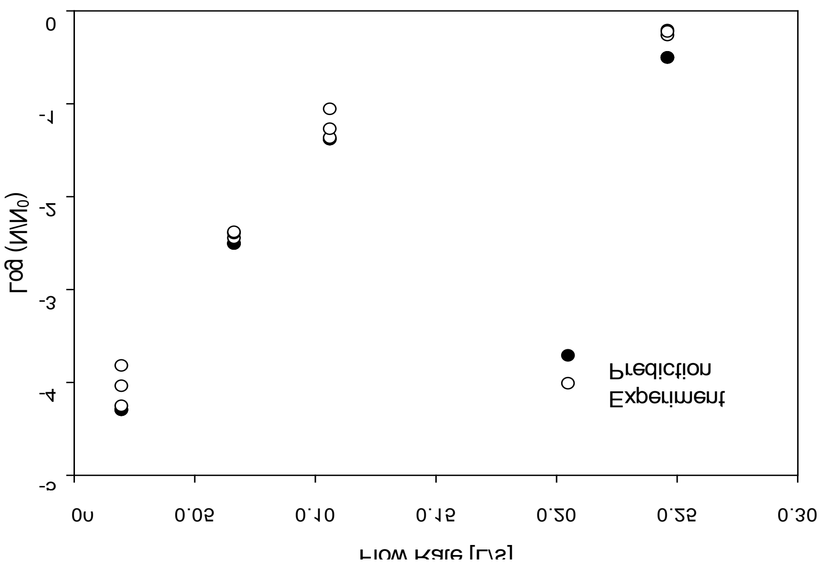

Figure 10. Comparison of measured *Bacillus subtilis* spore inactivation with numerical simulation predictions for a reactor with a spiral attached to a XeBr* excimer lamp and a water transmittance value of of 90%.

CONCLUSIONS

The numerical design approach was originally developed as an aid in the design of a UV reactor suitable for water disinfection use in long-term space missions. The modeling approach was successfully implemented for development of an efficient UV disinfection system based on a non-Hg-containing UV source (i.e., a XeBr excimer lamp).

While the intended use for the reactor that was the subject of this research was in water treatment for long-term space missions, it is clear that the application of this approach is not limited to such applications. More generally, this modeling approach could be used as a tool for designing UV reactor systems for potable water, wastewater and water re-use scenarios. The advantage of the numerical model is that alternate UV reactor designs can be assessed in the design stage prior to prototype construction. The numerical model can in this way be used to improve overall reactor performance and reduce the need for over-design, thereby reducing the size and power requirements for UV systems and consequently, capital and operating costs of UV disinfection systems. Reactor design efforts based on numerical prototyping should be accompanied by physical measurements, so as to validate the model and the performance of the actual reactor.

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