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A Report on Two Water Recycle and Air Revitalization Projects

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MINIMIZING EQUIVALENT SYSTEM MASS FOR A REGENERATIVE LIFE-SUPPORT SYSTEM BY OPTIMIZING KINETICS AND ENERGETICS OF MAJOR BIO-TRANSFORMATIONS – Development of a System for Disinfection of Potable Water Based on the Combined Application of UV Radiation and Iodine

A numerical model for simulation of liquid-phase (water) disinfection was refined. The boundary conditions were refined to more precisely represent the actual geometry of the physical prototype we received from Ushio, Inc.

1. Modification of geometry

The numerical representation of the reactor was modified to include the inlet baffle plate and entrance port, as produced in the actual reactor. This updated reactor geometry provides a more accurate representation of reactor geometry in its as-built form than was included in previous simulations.

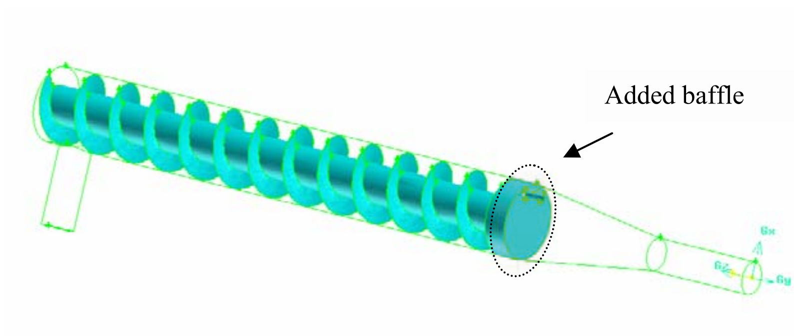

Figure 1. Reactor geometry.

2. Reactor simulation

Experiments with the actual reactor were conducted at four different flow rates: 0.31, 1.05, 1.68, and 3.9 gpm. During the experiments, lamp output was measured through a collimator using a radiometer; in turn the measurements of intensity were used as input in an inverse intensity field model to estimate lamp output power. Lamp output power at the wavelength of interest (λ = 282 nm) was estimated as 4.46 W based on these measurements.

Based on these operating conditions, numerical simulations of reactor behavior were conducted at each of those flow rates. For each flow rate, a commercially-available CFD package (FLUENT) was used to simulate the flow field. A particle-tracking algorithm within FLUENT was used to simulate individual particle trajectories through the reactor for each operating condition (see Figure 2). The particle size in selected for these particle trajectory simulations was 1 μm, which is consistent with the size of many relevant waterborne microbes, including the *B. subtilis* spores that were used in reactor challenge experiments. For each operating condition, roughly 1000 particle trajectories were simulated and UV dose delivered to each particle was calculated.

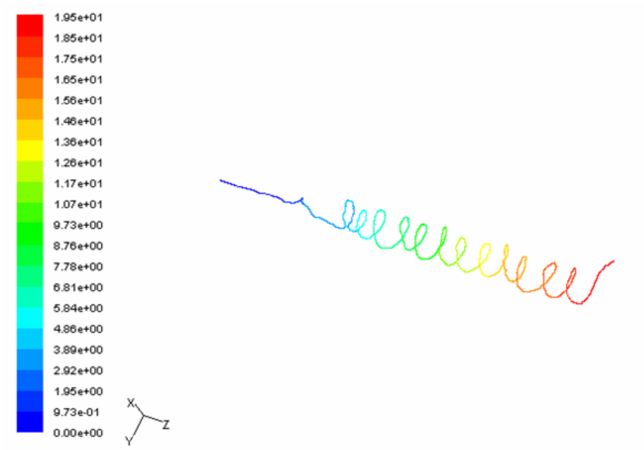

Figure 2. Particle trajectory in the reactor (velocity = 0.1638 m/s (0.31gal/min)).

The simulated particle trajectories for each operating condition were integrated with a simulation of the radiation intensity field are incorporated with the simulated intensity field to allow estimation of the UV dose distribution delivered by the reactor at each operating condition (see Figure 3). In turn, the dose distribution estimates were integrated with measured dose-response behavior for the challenge organism used in these tests (*B. subtilis* spores) to allow an estimation of challenge organism inactivation for each operating condition.

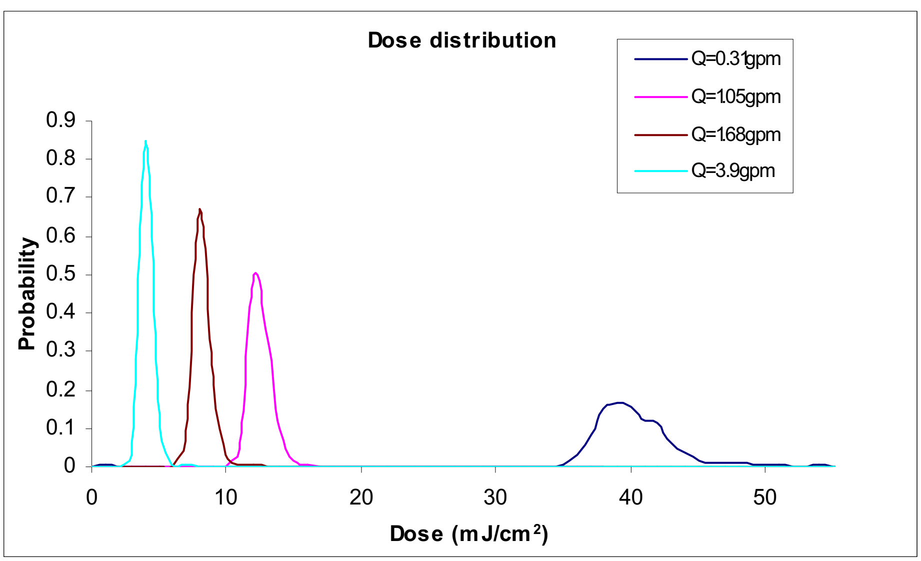

Figure 3. UV dose distribution estimates for operating conditions that correspond with physical tests of the prototype reactor.

As expected, UV dose distributions indicated relatively low UV exposures at high flow rates, and greater UV exposures at low flow rates. At each of the operating conditions, the UV dose distribution was narrow, as compared with the UV dose distributions delivered by other UV disinfection systems of similar size. Therefore, we expect this reactor to be efficient, relative to other similarly-sized UV reactors.

Development of test methods for a gas-phase (air) disinfection system. The goal of these experiments is to translate the liquid-phase measurements/tests into tests that can be conducted on gas-phase systems.

The goal of this phase of the research is to develop a UV disinfection system for cabin air. The approach to be used in this design is to define the fundamental kinetics of the (disinfection) reactions of interest, and to apply a conceptually similar modeling approach as was used with the liquid-phase reactor (see above). In particular, a numerical model will be developed to described fluid (air) transport through the system using CFD. The UV intensity field will be simulated using a separate numerical code. These simulations will be integrated using the same approach as was used for the liquid-phase reactor to allow simulation of reactor performance.

Dose-response experiments were performed using *B. subtilis* spores as a challenge organism. *Bacillus* spores are known to be resistant to UV radiation, and they are believed to be representative of microbial pathogens that could limit the performance of a gas-phase UV disinfection system.

As is the case with many microorganisms, the kinetics of *B. subtilis* spore inactivation in the gas phase are believed to be influenced by relative humidity. Therefore, experiments were conducted to allow quantification of gas-phase UV dose-response behavior as a function of relative humidity. The results of these experiments are summarized in Figure 4. In general, we observed that high humidity conditions appear to provide protection for spores in the limit of low UV dose (*i.e.*, dose < 30 mJ/cm^2), whereas low humidity appears to provide protection to spores at higher UV dose (> 40mJ/cm^2). The influence of humidity on inactivation kinetics represents an important aspect of UV disinfection of air. Therefore, these experiments will be repeated to further evaluate this behavior.

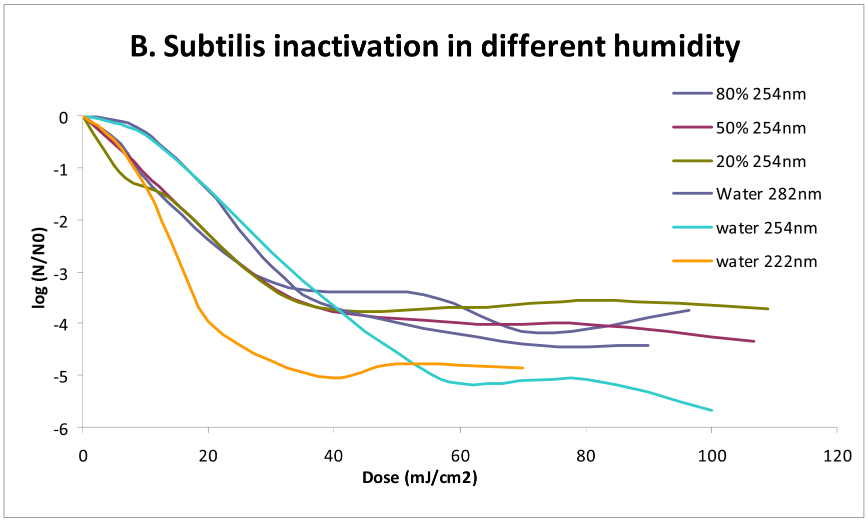

Figure 4. UV dose-response behavior for *B. subtilis* spores in gas-phase as a function of relative humidity.

The dose-response behavior of *B. subtilis* spores was characterized by a shoulder at low dose, log linear inactivation at mid-range doses, and tailing behavior at high dose. The shoulder can be explained due to spore repair during spore germination or the requirement for multiple photochemical events to accomplish inactivation. On the other hand, tailing behavior is not explained by most conventional models of microbial inactivation. Under some circumstances, tailing is ascribed to aggregation of microorganisms, or incorporation into particles. However, microscopic images of the spores used in these experiments indicate that the spores were well-dispersed, and that aggregation was unlikely to contribute to tailing behavior (see Figure 5).

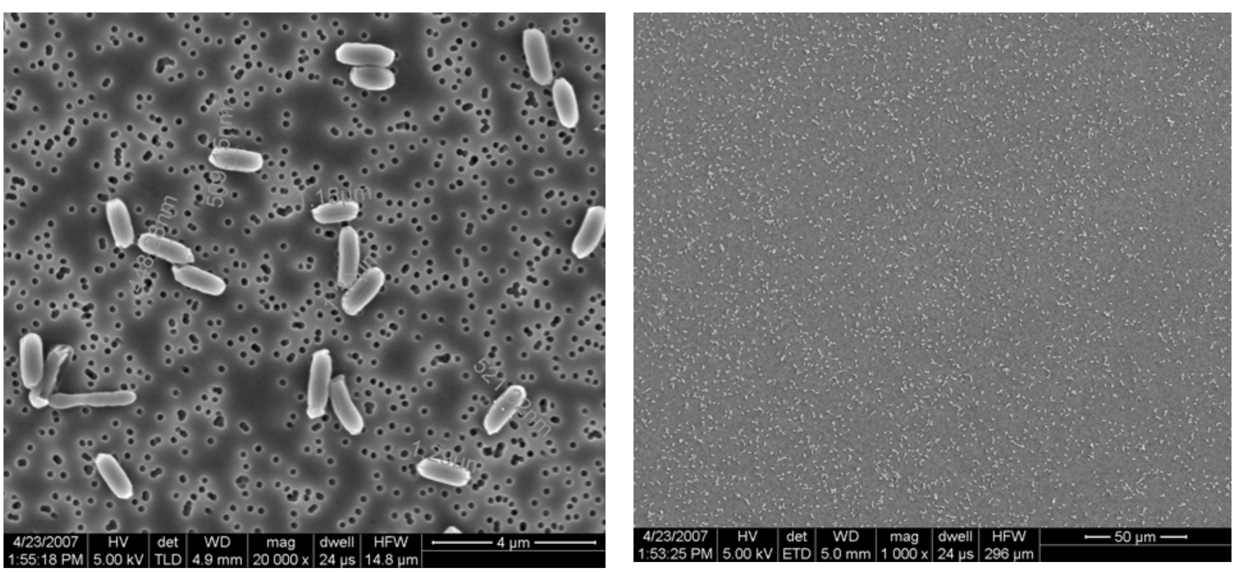

Figure 5. Electron Microscope image of *Bacillus subtilis* on isopore membrane filter

Pennell *et al.* (2007) provided an alternative explanation for tailing behavior. Specifically, they hypothesized that phenotypic heterogeneity within a microbial population could account for tailing behavior. In other words, it is hypothesized that natural (phenotypic) variability within a microbial population will yield some organisms that are inherently more resistant to disinfectant exposure than others within the same population. Pennell's model provided a good fit to the data presented in Figure 4.

REFERENCES

K.G. Pennell, A.I. Aronson and E.R. Blatchley III (2007) "Phenotypic persistence and external shielding ultraviolet radiation inactivation kinetic model," accepted for publication in *Journal of Applied Microbiology*.

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GAS-PHASE REVITALIZATION USING BIOFILTERS IN ADVANCED LIFE SUPPORT **(BREATHE II)**

To enable efficient removal of a broad spectrum of gaseous trace contaminants from the cabin air, the design and operation of ALS BREATHe II (Bio-Regenerative Environmental Treatment for Health) system will need to be optimized based on results from bench-scale reactors. Thus, it is necessary to generate ersatz cabin air and evaluate bench-scale reactor performance operated with different reactor configurations, packing material, gas-residence time, liquid-recirculation rates, contaminant-loading rates, etc.

Biofiltration Experiment #1

Ten laboratory-scale biofilters and biotrickling filters were operated for removal of ersatz multi-component gaseous streams representative of spacecraft atmospheric contaminants released during long-term space travel. The model waste-gas stream contained a five-component mixture of acetone, *n*-butanol, methane, ethylene, and ammonia. The waste-gas stream was diverted uniformly to six biofilters and four biotrickling filters identical in dimensions for biological treatment, each operated under an empty-bed residence time (EBRT) of 30 s. The biofilters were packed with either perlite, polyurethane foam, or a mixture of compost, wood chips, and straw. The biotrickling filters were packed with either perlite or polyurethane foam.

Overall Performance. Both the biofilters and biotrickling filters packed with different media were able to achieve complete removal of acetone, *n*-butanol, and ammonia, all of which are water-soluble compounds, within a short startup period. No methane was removed by any of the bioreactors. The perlite biofilters exhibited the highest performance of ethylene removal followed by the perlite biotrickling filters, the foam biotrickling filters, the foam biofilters, and the compost biofilters.

Biofiltration Experiment #2

As a follow-up to experiment #1, 20 laboratory-scale biofilters and biotrickling filters (duplicate reactors run for each operating strategy) were operated in parallel to study the removal of binary mixtures of ammonia and ethylene, in effort to study the interactions between ammonia and ethylene removal.

Overall Performance. Greater than 95% ammonia removal has been achieved in all 20 bioreactors with different operating strategies 40 days after startup of the bioreactors. Ethylene removal remained low in all bioreactors during the first 60 days. Starting from day 65, its removal increased rapidly.

Recent Air-Revitalization Progress:

Doctoral candidate Mr. Sang-hun Lee finalized statistical analysis for pair-wise comparisons of ammonia and ethylene-removal efficiencies from multiple BREATHe II reactors with different operating strategies. Construction of a process model was completed to simulate experimental biofiltration, and a dissertation on this topic is in review.