Introduction

Ultraviolet germicidal irradiation (UVGI) has been used for the disinfection of air almost as long as it has been used for the disinfection of water and surfaces. Unlike water-based UV disinfection, where performance has become routinely predictable, UVGI air disinfection applications have experienced a mixture of successes and failures. Until recently there has been no accurate means of predicting the effectiveness of any system design short of performing a bench test. This article reviews the fundamentals of UVGI systems for air and the newest modeling and design methods.

Various types of UVGI systems are currently available for air applications. Moving air can be treated in a Heating, Ventilating, and Air Conditioning (HVAC) system by installing UV fixtures within a duct. Stand-alone recirculation units and portable air cleaners are available for use inside rooms. One method involves mounting UV lamps in the upper portion of a room and depends upon room air convection – these are known as upper air UVGI systems. One of the fastest growing markets today is the use of UVGI to control microbial growth on cooling coils and other surfaces such as filters and drain pans inside air handling units.

Upper-air UVGI systems have uncontrolled airflow and their performance depends on local air currents. The performance of upper air-systems does not lend itself to prediction by any but empirical methods, and limited data is available at present. Upper-air systems can be an economic alternative, but care must be taken to avoid exceeding UV exposure levels to personnel.

In-duct UVGI and recirculation systems depend on forced air. These systems have a controlled flow rate and their performance can be predicted theoretically. Until recently, most such systems were sized by rules of thumb, catalog guides, or by adapting previous designs. Some systems were sized by laboratory testing. The development of new computer models now allows the prediction of disinfection rates for UVGI systems and laboratory testing can be used for validation.

A typical UVGI system for airstream or surface disinfection consists of one or more UVGI lamps located inside a duct, as shown in Figure 1. Typically the lamp axis is oriented perpendicular to the airstream. Highly reflective internal surfaces are often used to enhance the intensity field.

Figure 1. Typical UVGI System in a rectangular duct.

Axial arrangements, in which the lamp axis parallels the flow direction, are not as commonly used in air disinfection as they are in the water industry. This is primarily because the attenuation of UV rays in water is high and it is necessary to keep the flow within a few centimeters of the lamp surface. Air has negligible attenuation of UV rays, regardless of humidity, and larger volumes of air are typically disinfected.
Mathematical Modeling

Microorganisms exposed to UVGI experience a normal exponential decrease in population. The classic single stage exponential decay equation for microbes exposed to UV irradiation is as follows:

\[ S = e^{-klt} \]  \hspace{1cm} (1)

where
- \( S \) = surviving fraction of initial microbial population
- \( k \) = UVGI rate constant, cm\(^2\)/\( \mu\)W-s
- \( I \) = Intensity of UVGI irradiation, \( \mu\)W/cm\(^2\)
- \( t \) = time of exposure, seconds

The rate constant defines the sensitivity of a microorganism to UVGI intensity and is unique to each microbial species. Most published rate constants are single-stage rate constants for microbes exposed on petri dishes or in fluids. Few airborne rate constants are known with certainty, mainly due to the difficulties with establishing the absorbed dose.

In water-based systems, *Escherichia coli* is considered a valid test microorganism, and it has been used traditionally for testing of air systems. However, it is not an airborne pathogen and therefore not the best choice for testing air systems. *S. marcescens* is a true airborne pathogen, albeit a mostly innocuous one, and therefore is a superior choice for aerosolization tests. Use of computer modeling to evaluate the intensity field in laboratory tests has enabled determination of the rate constants for a representative species, *Serratia marcescens*.

Based on a series of tests by an independent laboratory, the airborne rate constant for *S. marcescens* has been found to be approximately 0.002909 cm\(^2\)/\( \mu\)W-s. The plate-based rate constant for *S. marcescens* has been found to be approximately 0.000718 cm\(^2\)/\( \mu\)W-s.

Equation (1) represents a simplification of the actual survival curve but it proves adequate in most cases. However, if the exposure time is very short or very long, two effects may come into play – the shoulder and the second stage. Figure 2 illustrates a generic survival curve when both effects are present.

The shoulder represents a delay in the response of a microbial population and is primarily dependent on the intensity (or dose). The second stage represents the response of the resistant fraction of the population. Typically, any population consists of a large fraction of susceptible microbes and a small fraction of resistant ones with different rate constants. The resistant fraction typically varies from 0.1% to 10%, although it may sometimes be much greater.

![Figure 2. The Complete Survival Curve with Shoulder and Second Stage.](image)

Equation (2) represents a mathematical model that incorporates both the shoulder and second stage (Kowalski, 2001). Use of this equation requires knowledge of the constants associated with the shoulder and the second stage, although few of these are currently known with any certainty.

\[ S(t) = (1 - f)S_0e^{-k_flt'} + fe^{-k_sl't'} \]  \hspace{1cm} (2)

where
- \( I \) = Intensity, \( \mu\)W/ cm\(^2\)
- \( t \) = exposure time, sec
- \( k_f \) = rate constant for fast decay population, cm\(^2\)/\( \mu\)W-s
- \( k_s \) = rate constant for slow decay population, cm\(^2\)/\( \mu\)W-s
- \( t_c \) = threshold of shoulder, sec
- \( f \) = resistant fraction of population

When the threshold is short (\( t_c \) approaches zero) and the fraction is negligible (\( f \) approaches zero), Equation (2) reverts to
Equation (1). The threshold $t_c$ will decrease as the intensity increases for constant exposure. Equation (3) is one method of determining the threshold (Kowalski, 2001). The constants $A$ and $B$ can be found by performing lab tests under two different intensities and solving the resulting equations.

$$t_c = Ae^{-BI}$$

where

$A = \text{a constant defining the intercept at } I=0$

$B = \text{a constant defining the slope of the plotted line of } \ln(t_c) \text{ vs. } I$

In forced air systems, where the velocity may be as high as 2.5 m/s and the average intensity lower than in water-based systems, insufficient exposure time (or absorbed dose) may place the average survival in the shoulder region. The use of Equation (1) will overpredict kill rates in the shoulder region. Since the response of most microbes in this region is unknown, it is prudent to maintain the kill rate well within the first stage region.

Although little is known about shoulder constants and second stage rate constants, a review of available data suggests that the second stage rate constant may be approximately $1/10^6$ the first stage rate constant, and shoulder constants may have values in the range of $A = 5-12$ and $B = 0.001-0.01$ (Kowalski, 2001). These values should provide conservative approximations when the shoulder or the second stage become significant factors.

### Modeling the UVGI Intensity Field

Mathematical modeling of UVGI air disinfection systems has recently been developed through the use of a computer model that evaluates the three-dimensional (3D) intensity field inside rectangular UVGI systems (Kowalski, 2001). In this model a 3D matrix is used to define the UV intensity field that consists of three major components: 1) an intensity field model of the UV lamp, 2) an intensity field model of the first reflection, and 3) an intensity field model of the inter-reflections, or reflections between the reflective surfaces. These components are based on radiation view factors and details of the model are available in the literature (Kowalski and Bahnfleth, 2000).

The absorbed dose can be calculated for two limiting conditions – complete air mixing and completely unmixed air. Figure 3 illustrates these conditions in a model air handling unit.

The mixed air condition represents the upper limit of the kill rate, while the unmixed air (or integrated) condition represents a conservative lower limit. Real-world conditions tend to approach complete mixing (Severin et al., 1984). Together, these limits provide a range within which actual performance can be predicted.

![Figure 3. Bounding Conditions — Mixed and Unmixed Air.](image)

In complete mixing, every microbe is subject to the same average intensity and the survival fraction is computed using Equation (1). In unmixed air, the survival fraction must be computed at each and every point in the 3D intensity field, and then summed to obtain the integrated survival rate.

The overall intensity field produced by the computer models a summation of the direct field of the lamp, and the reflected and inter-reflected fields produced by the surfaces. One such intensity field is shown in Figure 4, which represents a horizontal plane at mid-height of a rectangular UVGI system. In this system a half-width lamp is located towards the front and left side of the rectangular duct.

![Figure 4. The intensity field inside a duct with reflective internal surfaces.](image)
The unmixed condition can be used to produce diagrams of kill zones such as in Figure 4, which represents the same system as in the previous figure. There are no kill zones for the mixed air condition since there is only one average kill rate for the entire system.

In Figure 4, the intensity field is unevenly distributed — if air mixing is poor, then microbes passing through one corner may receive an insufficient dose. If, however, multiple lamps (with the same total UV wattage) were positioned appropriately inside the reflective enclosure, the intensity field would become more evenly distributed. This approach raises the lower limit kill rate for the unmixed air condition, prudently ensuring a higher average kill rate. The same effect could be obtained by turbulating the airstream, but this would consume energy.

For surface disinfection applications, it is only necessary to determine the intensity contour for a particular surface such as the face of a cooling coil. The same methods described above for computing the entire intensity field can be used for surface disinfection, but the rate constants used can be from plate-based studies.

![UVGI Kill Zones - Unmixed Air Streamlines](image)

**Figure 5.** Kill zones in unmixed air, for a single lamp configuration in a reflective enclosure.

The computer model can account for many other factors as well, including multiple lamps, non-orthogonal lamp orientations, and lamp performance under varying airflow or air temperature conditions.

**Conclusions**

This article has provided an overview of the design and analysis of UVGI systems for air and surface disinfection applications using a computer model of the UV intensity field. The mathematics of UVGI disinfection in air have been summarized for both a single stage survival curve and for the complete survival curve. Computer modeling allows for rapid evaluation of a UVGI system and prediction of disinfection performance, and provides a means of achieving optimization of design parameters including lamp selection, lamp location, and the lamp air cooling effects.

Laboratory-verified rate constants have been provided for *Serratia marcescens*, for use with the single stage decay curve equation. For the complete decay curve, some general ranges for shoulder and second stage parameters have been provided.

The advances in engineering analysis of UVGI systems have progressed beyond the currently available microbiological data on airborne pathogens. There is a pressing need today to develop complete survival curves for the scores of pathogens of concern. Use of computer modeling will facilitate research and design, and so enable the development of more effective UVGI systems for disease control applications.

**References**

