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Ultraviolet Germicidal Irradiation for Heating, Ventilation, and Air Conditioning: Literature Review

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ABSTRACT

Ultraviolet germicidal irradiation (UVGI) remains the only ASHRAE-recognized technology for the effective disinfection of air and surfaces, yet the technology still faces barriers to adoption. Even so, there is a growing body of literature on the subject, somewhat due the possibilities that a technology that can disinfect from a distance presents but also because the technology has been known for some time. Recent interest in the technology has been driven by the COVID-19 pandemic, increasing the rate of growth of the literature. This document attempts to provide an overview of the technology and map out the various important parts of the literature, including potential sources of literature.

1. INTRODUCTION

The disinfecting powers of sunlight have been known about since at least the 19th century, some years before any understanding of the nature of light and electromagnetic radiation. The discovery of the wavelengths that comprise the ultraviolet (UV) range of the electromagnetic spectrum would come somewhat later, and the use of ultraviolet light in engineered systems is a relatively recent development. Ultraviolet germicidal irradiation (UVGI) or germicidal ultraviolet (GUV) systems are now used in a number of different and distinct applications within buildings. The primary application types are (in no particular order):

- In-duct air and surface disinfection
- Upper-room air disinfection
- Full-room air and surface disinfection

While the physics and mechanisms of UVGI are relatively well understood, barriers remain before these systems could be considered standard equipment in buildings. The COVID-19 pandemic has demonstrated that there is a need for cleaning and disinfection systems more generally within buildings, even if only on a temporary basis, and UVGI systems are potentially a solution to this need. Early in the pandemic, there was some skepticism as to whether there was much, if any, airborne transmission of the SARS-CoV-2 virus and the disease that it causes (ASHRAE, 2021). As time went on, it became clear that while airborne transmission did not take place at the grand scales believed to be present in the Asian SARS outbreak of 2002-2004 (Yu et al. 2004), at smaller scales and shorter distances the main vehicle of transmission may be airborne. However, evidence that supports the degree to which the virus can spread indoors, including the difficulty of determining if the virus was viable when it arrived at the location where it was connect (Moreno et al. 2021) continues to mount. Preparation for the next pandemic must therefore include the possibility that airborne transmission may include longer distances. The overall need for air cleaning has driven additional interest in UVGI, and this interest has resulted in an outpouring of publications and information on the subject, including a very informative "Frequently Asked Questions" document from the Illuminating Engineering Society (IES Photobiology Committee, 2020).

It is useful to consider categorization of the publications related to UVGI. As is often the case, publications and research in this area can be categorized broadly on a spectrum from basic research to applied research, but here it is useful to slightly modify the two ends of the spectrum as "basics" and "applications". As a relatively mature technology, a number of standards are available that describe the safe application of UV. While this could be considered as a subset of the application-oriented category, here it will be treated as a third broad category.

2. BASIC OPERATION OF THE TECHNOLOGY

A complete description and explanation of the mechanisms by which ultraviolet light inactivates microorganisms is beyond the scope of this document, but it is important to understand the basic mechanism. For a more complete description, see Kowalski's monograph on the subject (Kowalski, 2009). Ultraviolet light occupies the space between visible light and x-rays on the electromagnetic spectrum, as shown in Figure 1. The wavelengths between 200 nm and 280 nm (termed UV-C) and the 280 nm and 320 nm (termed UV-B). While both UV-C and UV-B have demonstrated effectiveness, the wavelengths in the UV-C range are in general more effective than the wavelengths in the UV-B range and the larger UV-B wavelengths are somewhat more dangerous to humans and are thus less attractive for the buildings applications discussed later. More recently, there has been interest in so-called "far UV-C" radiation around 222 nm because of potential safety benefits, but there is no scientific consensus yet on whether far UV-C is actually safer (Buonanno, 2017 and Woods et al. 2015).

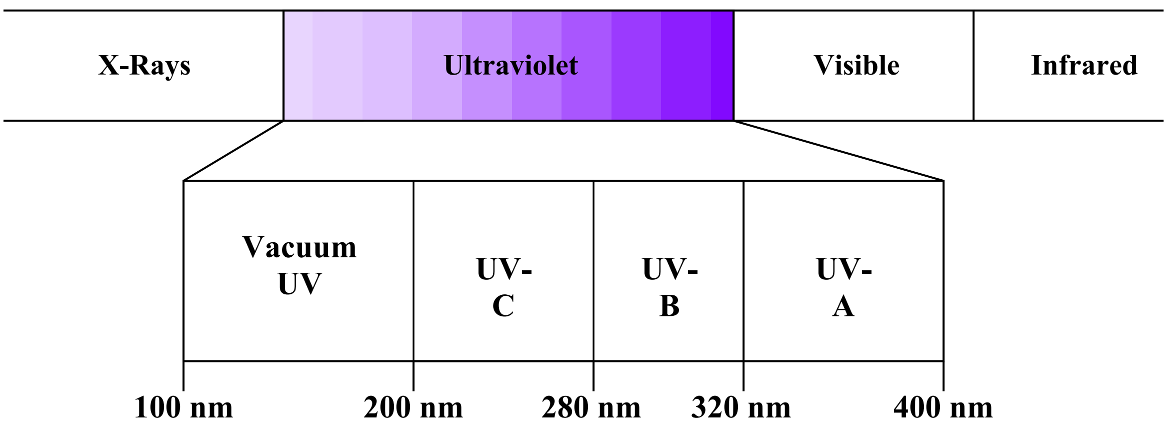

Figure 1: Ultraviolet radiation occupies wavelengths between 200 and 280 nm on the electromagnetic spectrum.

The main operating principle of UVGI is that the radiation is absorbed by the proteins that make up RNA and DNA and irreparably damages this genetic material, rendering the microorganism unable to reproduce. In some cases, this may lead to cell death, but in many cases (including in the case of viruses, for which the labels "alive" and "dead" are not particularly meaningful) the correct term is "inactivation" but the term "kill" is often used interchangeably. It should be noted that the wavelength that does maximum damage to an organism depends on the organism itself, so it is necessary to demonstrate that UV is indeed effective against new organisms. This vulnerability (or lack thereof) to UV is termed the susceptibility to UV and the determination and reporting of the susceptibility of organisms is an important part of the literature.

The susceptibility of a particular microorganism is often expressed as the dose required to inactivate a specified percentage of microorganisms exposed to that dose. Using Kowalski's notation, the dose is

$$D = E_t I_R, \quad (1)$$

where D is the dose, E_t is the exposure time, and I_R is the irradiance. The dose required to inactivate 90% of the microorganisms that encounter the dose is denoted by D_{90}. In the design of an engineered system, there are two ways to meet a required dose: lengthen the exposure time or increase the irradiance.
UV radiation for germicidal applications is typically produced by mercury vapor or xenon arc lamps, though there is increasing work being done on LEDs, which have some potential for this application.

Many lamps are superficially similar in appearance to regular fluorescent lamps. The lamps are placed in proximity to the material or volume to be disinfected, typically designed with a target dose. The placement of the lamps and the power of the lamps are subjects for engineering design.

3. RELEVANT ORGANIZATIONS

Because UV is relatively new as an engineered system and the possibility that improper application of the technology could present very immediate hazards to building occupants, educational and practical materials are still very important in the development of UV applications. There are a number of organizations that are relevant to buildings application of UV.

3.1 AMERICAN SOCIETY OF HEATING, REFRIGERATION, AND AIR-CONDITIONING ENGINEERS (ASHRAE)

ASHRAE publishes several standards and guidance documents related to air and surface disinfection. ASHRAE's Technical Committee 2.9 (Ultraviolet Air and Surface Disinfection) is the cognizant committee for these documents. The ASHRAE interest in UVGI is more typically at the system integration and application level than the basic science of UV. ASHRAE is a standards developing organization (SDO). Two of ASHRAE's standards (90.1 and 62.1) are crucial standards within HVAC practice.

3.2 ILLUMINATING ENGINEERING SOCIETY (IES)

IES publishes a recommended practice related to UV safety. IES's Photobiology Committee is the cognizant committee for the UV-related output. IES interest in UVGI is geared more toward the basic science of UV. IES is also an SDO and is notably a co-developer of ASHRAE Standard 90.1.

3.3 INTERNATIONAL ULTRAVIOLET ASSOCIATION (IUVA)

IUVA is a general organization that promotes UV technologies with related documents, webinars, and educational activities.

4. STANDARDS AND GUIDELINES

As a potential part of an engineered system, it is natural that standards and guidelines be developed to assist engineers in the application of the technology. This is particularly import with UV, as most of the wavelengths used in this application are potentially hazardous to humans.

4.1 ANSI/IES RP-27.1-15

Recommended Practice For Photobiological Safety For Lamps And Lamp Systems - General Requirements. This document provides recommended practices for the evaluation and control of the hazards that are presented by many of the lamps that are used in GUV devices. The document is not specific to these lamps alone, however, and other exposure guidelines are available that may be more appropriate depending upon the application.

4.2 ANSI/ASHRAE STANDARD 185.1-2020

Method of Testing UV-C Lights for Use in Air-Handling Units or Air Ducts to Inactivate Airborne Microorganisms. This standard establishes a method of test for the evaluation of the inactivation capabilities of UV-C lights against airborne microorganisms in air handlers and ducts. As a method of test, it does not establish criteria for acceptance of a lamp or system.

4.3 ANSI/ASHRAE STANDARD 185.2-2020

Method of Testing Ultraviolet Lamps for Use in HVAC&R Units or Air Ducts to Inactivate Microorganisms on Irradiated Surfaces. This standard establishes a method of test for the evaluation of the inactivation capabilities of UV lamps for on-surface pathogens. As a method of test, it does not establish criteria for acceptance of a lamp or system.

5. BASICS

Publications in this category are typically examinations of the mechanisms by which UV deactivates and/or damages organisms, determination of the susceptibility of particular organisms, and methods for determining the effectiveness of particular system configurations. There is some overlap between this category and the applications category, especially when considering the effectiveness of a particular application of the technology against a particular pathogen. The following subcategories are considered: theory, susceptibility, modeling, and lamp performance.

5.1 THEORY

Kowalski's Ultraviolet Germicidal Irradiation Handbook (Kowalski, 2009) devotes several chapters to the theory of UV disinfection, the determination of susceptibility, and modeling. The publisher claims that this book is the only monograph on the subject, a claim that of this date appears to be true. This book provides a suitable starting point for most investigations into the theory of buildings-related applications of UV, with the notable exception of far UV and LED lamps. These deficiencies are a function of the book's age, and the main issue with the book today is that it is now somewhat old.

5.2 SUSCEPTIBILITY

Kowalski (2009) gives the susceptibility parameters of 600 bacteria, viruses, and fungi, and the literature contains other efforts to determine the susceptibility of organisms and to develop reliable means to evaluate susceptibility. Additional examples of dosage data are available in the literature, often focusing on a particular pathogen. McDevitt et al. (2012), for example, focuses on the H1N1 influenza virus, while Heilingloh et al. (2020) and Simmons et al. (2021) focus on SARS-CoV-2. There are many more examples in the literature, and unfortunately this is often the case. The dose response depends upon many factors, and it is known that the dose required for inactivation varies depending upon whether the microorganism is in water or air and whether it is on a surface or not. Efforts have been made to develop methods that better represent the required dose, and one example is Martin's (2014) Ph. D. dissertation. The reactor designed in this research is intended to allow the determination of inactivation doses in a more device independent manner.

5.3 IMPACT ON MATERIALS

Just as UV-C radiation can damage and inactivate pathogens, the damaging effects of UV upon other materials is well documented – hence the need for UV-resistant materials in situations where the material is expected to be exposed to sunlight for extended periods. While much is known about general UV degradation, little was known about the specific impacts of UV-C on the materials that are commonly used in HVAC systems. ASHRAE funded two studies into these impacts (Kauffman, 2011 and Kauffman et al. 2017) that addressed by higher intensity and lower intensity UV-C systems.

5.4 IRRADIANCE FIELD MODELING

Modeling of the field of irradiance that results from a particular lamp configuration has played a somewhat important role in the development of UVGI systems, with a number of vendors relying heavily upon modeling tools to design systems. While water applications have been around for many years (at least since the early 1900s), UV radiation is rapidly attenuated in water and there is little need to consider reflections. Beggs and coworkers (Beggs et al., 2000) have proposed an inverse square law approach that does not account for reflections, but as UV is not significantly attenuated in the air application, this method (and similar approaches) are less preferred. Kowalski (Kowalski, 2003) developed a radiosity-based approach to the calculation of UV irradiation that takes into account reflections. This approach, which is somewhat similar to radiation heat transfer analysis, has been the method that vendors have historically relied upon. Ray tracing is the preferred approach to visible light modeling has also been used. Lau et al. (Lau et al., 2012) used a commercial package to determine the irradiance field in the in-duct application, and more recently Hou and coworkers (Hou et al., 2021) have used a similar approach in the upper-room application. This second work is notable because it uses the DOE-funded ray tracing engine Radiance (Ward, 1994). While Radiance is no longer cutting edge in the sense that there are much faster ray tracing engines available, it has been more thoroughly validated than any other engine and remains the de facto state-of-the-art in lighting simulation.

5.5 PATHOGEN MODELING

Once an irradiance field has been computed, it remains to determine the outcome for a pathogen exposed to that irradiance is to determine what the irradiance field does to the pathogen. Generally, this process is broken into two parts: dose and inactivation calculation.

In order to calculate dose, Equation 1 indicates that it is necessary to determine a residence time. There are two general approaches here: the Lagrangian approach and the Eulerian approach. The Lagrangian approach follows individual particles and tracks these particles through space and time. Here, particle could mean:

a) an individual virus,
b) an individual bacterium,
c) a particle carrying multiple viruses and/or bacteria, or
d) a droplet carrying multiple viruses and/or bacteria.

Kowalski's approach (Kowalski, 2001) is essentially a Lagrangian approach, and a more recent example of the Lagrangian approach is given in Yang et al. (2021). An expression of Newton's second law is integrated through time for each simulated particle and having previously determined the irradiance field, the dose can be calculated. Given an inactivation dose, it is a simple matter to check the dose experienced by the particle and the inactivation dose. This approach has the advantage that it faithfully determines the trajectory of individual particles, but the further disadvantage that many particles may need to be simulated in order to determine the average values that are most likely of interest. The Eulerian approach treats the pathogen as if it were a continuum variable, or in the terminology of computational fluid dynamics (CFD), a scalar variable. The use of this approach is almost exclusively associated with CFD. The movement and inactivation of the pathogen can be tracked using similar governing equations to those used for the underlying fluid flow. A good example of this approach is given in Gilkeson and Noakes (2013), in which the Fluent CFD code is used to determine outcomes for an upper-air application. The biggest advantage of this approach is that it is generally easy to compute efficiently and adds little to the computational expense of the CFD. The disadvantage of the approach is that it is difficult to represent some external forces (e.g. gravity) that will be significant for some particles in some situations.

One factor that further complicates these calculations is that most engineering flows of interest are turbulent or at least transitional. The impact of this upon these two approaches is potentially profound. CFD calculations of these flows are generally pursued via the Reynolds-averaged Navier-Stokes approach (RANS) in which only the largest scales of motion are computed or large-eddy simulation (LES) in which some smaller scales of motion are represented. Both of these approaches implement some form of a turbulence model that represents the smaller scales. If the Lagrangian approach is used with CFD, then it is important to note that the underlying turbulence model may not interact with the Lagrangian equations of motion sufficiently to represent the true motion of a particle. Some CFD codes (e.g. Ansys Fluent) include an option to compute a perturbing force from the turbulent kinetic energy that is computed by some turbulence models. This can make the movements of the particle more realistic, but there remains the possibility that a flow computed using direct numerical simulation (in which there is no turbulence model and all scales of motion are present) might give different outcomes for a particle. Similarly, the Eulerian approach can be formulated to include additional mixing terms, typically involving some sort of diffusion coefficient, that will account for turbulence driven movements of the pathogen. The diffusion coefficient can be computed via a Reynolds analogy (as is done for the heat transfer problem), but there is little to recommend this practice other than it usually works well enough.

5.6 LAMP PERFORMANCE

Most current UVGI systems use mercury vapor lamps or similar technologies. As usual, Kowalski (2009) provides background information on these lamps. One aspect of the usage of these types of lamps in the HVAC context is that the power output of these lamps depends upon the temperature of the lamp, and generally colder temperatures lead to lower output from the lamp. Lau (2009) investigated the so-called “wind chill” effect and developed several models for lamp performance. Before this investigation, the importance of the temperatures that the lamp was operating at was not fully understood. LED lamps offer some potential improvements over the traditional lamps but are an active area of research. A recent example of research in this area is the work of Nunayon et al. (2020) that focuses on the upper-room application.

5.7 APPLICATIONS

Application-oriented publications include reports on the effectiveness of a particular system or approach, field studies, and energy-efficiency studies. There are three primary application areas related to HVAC:

1) Surface disinfection
2) Air disinfection
3) Water disinfection

Water disinfection is included here for completeness due to its historical importance in UV research, but it will not be covered in any detail. Focusing on the applications that are concerned with surface and/or air disinfection, it is possible to categorize the systems that fulfill applications into three types: in-duct, upper-room, and in-room systems. Before looking at these three types, it is useful to note that it is possible (and somewhat likely) that many basic research publications will be associated with one or more of these system types. For example, the publication of Gilkeson and Noakes (2013) cited above describes the use of CFD in the context of upper-room disinfection.

5.7.1 In-Duct Systems

In-duct systems are succinctly described as UV systems that operate inside an HVAC system (typically in a duct) to disinfect the surfaces inside the system or the air that passes through the system. For the surface cleaning application, the approach is usually to use lower output lamps and rely long run times to provide sufficient dose to disinfect. This reduces the risk that the UV system will unintentionally damage vulnerable materials (filters, gaskets, etc.), but also means that these systems have little-to-no capability to disinfect the air. Systems that target the air are generally higher-output systems and are associated with mission-critical capabilities where the energy use is far outweighed by the potential damage that an airborne pathogen could do. As noted above, Kowalski's (2009) book contains basic information on these systems.

Surface cleaning systems typically target the cooling coils in systems, as this is the location within systems where moisture is most likely to collect and provide a positive environment for growth of bacteria and mold, fouling (or biofouling) the coil. This biofouling could potentially impact air quality in the spaces served and reduce the operational efficiency of the coil. Firrantello (2016) studied the potential impacts of UV on coil performance. Several air handling units (in the field) with dirty coils were instrumented to measure pressure drop across the coil and other key parameters. Data was collected before and after the installation of coil-cleaning UV systems. A similar study was undertaken by Luongo (2016), in which an experimental apparatus with parallel coils was used. Unfortunately, neither study showed an especially significant impact on fan power or heat transfer. While both studies had limitations, the general consensus is that this application is still a good one in high humidity climates where it otherwise might be difficult to keep coils clean without regular mechanical cleanings. These cleanings would likely require that the system be shut down, but a UV system will keep the coil clean continuously.

Air cleaning systems, as noted above, are typically expected to require more power to operate, as the residence time (see Equation 1) in this application is necessarily quite small due to the air speeds involved. The effectiveness of these systems has been tested on several occasions (see, for example, the EPA studies done by Foarde et al. 2006 and Franke et al. 2006) and a number of modeling studies have been done (see the earlier cited work by Yang, 2021), so the effectiveness of these systems is not generally in much doubt. However, the energy use is a matter of some doubt. The two EPA studies were done as a part of an effort to assess the suitability of these devices to reduce risks of criminal attacks, and as noted above these devices are currently more likely to be deployed in environments where the need balances the cost.

5.7.2 Upper-Room Systems

Upper-room systems target the air (and surfaces to a lesser degree) in the upper part of a room to disinfect the air in the entire room as the air is mixed (either by natural or mechanical means). This approach implicitly designates at least two subvolumes: an occupied volume and an irradiated volume. For a properly designed system, these two volumes should be disjoint. The upper air is targeted as irradiated volume because this air is generally above the occupants' heads, making the occupied and irradiated volumes separate, but also because the occupants' thermal plumes will tend to take potentially infectious aerosols into that region of the room even if there are no mechanical mixing means available. These systems typically use luminaires that direct the UV toward the ceiling and should only be used in spaces with high ceilings for added safety. Reflective materials in or bordering the irradiated volume are strongly discouraged, as any reflections of the UV effectively increases the size of the irradiated volume.

This application was one the first applied in the field, with early efforts in schools and similar locations (Wells, 1943). Modern applications of this technique rely heavily upon CFD to predict flow fields, but the calculation of the irradiance field would not necessarily need to include reflections. Hou et al. (2021) use ray tracing for this application, and while this is perhaps somewhat unusual, this approach acknowledges that some degree of reflection is possible and represents a change in the assumptions that one might make. Most other research into this application assumes away reflections. Gilkeson and Noakes (2013) use a Eulerian approach with an experimentally measured irradiance field, while Pichurov et al. (2015) use both

Lagrangian and Eulerian models with experimentally measured irradiance fields in an investigation of the influence of ceilings fans on the effectiveness of the upper room systems.

5.7.3 In-Room Systems

Less space is devoted in the literature to in-room systems. A number of vendors sell in-room units, some intended for use when the space is occupied (i.e., an air cleaner based on UV) or when the space is unoccupied. As usual, Kowalski (2009) presents some information on these devices. Many of the small air-purifier-type devices are reputed to be too low-power to have much disinfecting capability, but there are publications in the literature on unoccupied space systems. Jelden et al. (2016) study a particular system intended for healthcare uses.

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