ANNUAL SIMULATION OF IN-DUCT ULTRAVIOLET GERMICIDAL IRRADIATION SYSTEM PERFORMANCE

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ABSTRACT

In-duct ultraviolet germicidal irradiation (UVGI) systems treat moving air streams in heating, ventilation, and air-conditioning (HVAC) systems to inactivate airborne microorganisms. UVGI system performance depends on air temperature, velocity, cumulative operating time, variations in exposure time and other factors. Annual simulations of UVGI efficiency and space concentration that accounted for these effects were performed for a hypothetical building served by a VAV system. The UVGI device was assumed to be located in the supply air stream and exposed to a near constant temperature, but variable flow. UVGI performance was compared with enhanced ventilation and infiltration. Large seasonal variations in UVC dose due mainly to the effect of airflow variation on residence time were observed. UVGI air treatment resulted in much lower predicted space concentrations of *Staphylococcus aureus* than ventilation according to ASHRAE Standard 62.1 and levels comparable to those achieved by high efficiency, but sub-HEPA, particulate filtration. Transient variations in space concentration due to lamp output variation were small, but adjustment of lamp output to the design operating condition was very important for modeling accuracy.

KEYWORDS

Ultraviolet germicidal irradiation, UVGI, UVC lamp performance, Airborne contaminant control, Indoor air quality.

INTRODUCTION

Transmission of respiratory diseases by airborne pathogens is a major problem of indoor air quality (IAQ). Droplet residues generated by talking, coughing and sneezing can be suspended in the air for hours, entrained into HVAC ductwork, and distributed throughout a building (Sehulster et al., 2004). In-duct UVGI systems treat air streams as they pass through HVAC ductwork.

UVGI systems use electromagnetic energy in the UVC spectrum to damage and prevent replication of microbial DNA and RNA (Noakes et al., 2004). Low-pressure mercury vapor lamps used in UVGI systems produce most of their output at 254 nm, which has ~85% of the effect produced by the optimal 265 nm wavelength (Philips, 2006).

To a first approximation, the survival of a population of microorganisms exposed to UVC is

$$S = \frac{N_t}{N_o} = e^{-k(It)} \tag{1}$$

The surviving fraction *S*, defined as the ratio of the surviving population, N_t to the initial population, N_0, is a decreasing exponential function of the UVC fluence, *I*; the exposure time, *t*; and a microorganism-specific rate constant, *k*. The product "*It*" is the dose received by the microbial population. For example, using the rate constant value of 0.0035 cm^2/μJ for *Staphylococcus aureus* measured by Sharp (1940), Equation 1 predicts that a dose of 542 μJ/cm^2, is required to achieve 85% inactivation. This dose may result from any combination of fluence and exposure duration.

The UVC output of a UV lamp is rated in still air at a temperature approximating typical room conditions after a burn-in of 100 hours (IESNA 1999). Output in application may be very different because of the effects of operating conditions and aging. In-duct UVGI design methods are not standardized and account for these effects in a variety of ways, generally through a combination of lamp selection and sizing based on perceived worst-case conditions. This paper describes the investigation, via hourly annual simulation, of the performance of a typical in-duct UVGI system for a range of scenarios and operating conditions.

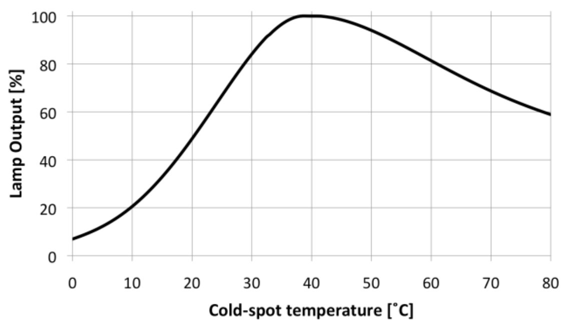

Figure 1. Lamp UVC output as a function of cold-spot temperature (Philips, 2006)

UVC Lamp Characteristics

With small but important differences, low-pressure mercury vapor germicidal lamps are essentially identical to fluorescent lamps used for illumination.

Lamp UVC output is a function of the mercury vapor pressure, which varies with the temperature of the coolest location on the lamp surface. Depending upon the lamp type, maximum output occurs when cold-spot temperature is between 39˚C and 50˚C (103˚F and 122˚F) (ASHRAE, 2008). Figure 1 shows a typical performance curve with peak UVC output at 40˚C (104˚F).

Cold spot temperature is a function of the energy balance relating input power, useful UVC emission, thermal radiation, and convection. Because the main determinants of cold spot temperature are ambient air temperature and velocity, the variation of capacity with environmental conditions is commonly called "wind chill". Figure 2 illustrates the importance of the wind chill effect by comparing two geometrically similar lamps operating in a 21˚C (70˚F) air stream. One lamp is a "standard output" model with 36W of input power while the other is a "high output" lamp with an input power of 60W. The high output lamp must dissipate more energy through the same surface area, therefore, it runs hotter. Consequently, the maximum output of the high output lamp occurs at a higher velocity than the standard output lamp.

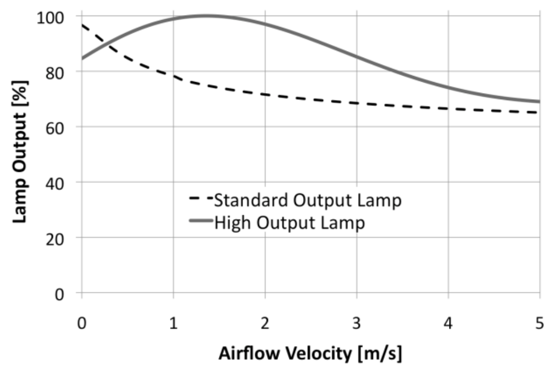

Figure 2. Wind chill effect on two germicidal lamp types a 21˚C air stream (Philips, 2006)

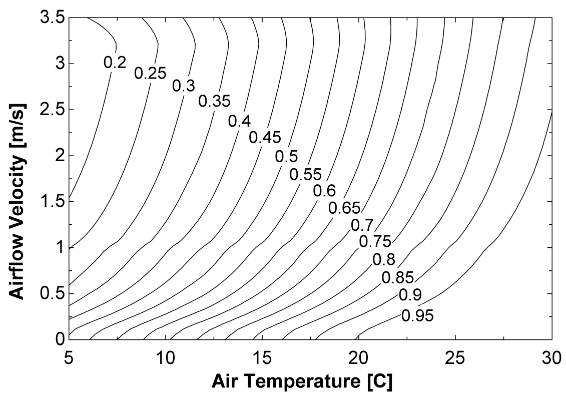

Figure 3. Study lamp ambient condition response characteristics (Lau, et al. 2009)

The lamp considered in this study is a widely used single-ended twin-tube high-output hot cathode lamp (Philips TUV PL-L 60W HO) for which a validated polynomial cross-flow performance model was developed by Lau, et al (2009). Figure 3 shows contours of predicted relative output (actual UVC as a fraction of maximum UVC) as a function of air temperature and velocity.

UVC output also diminishes (depreciates) over the life of a lamp in a manner that can be easily modeled. Figure 4 presents the depreciation of a typical lamp, in which output falls by 15-20% during the first 2000 hours of operation and then levels off.

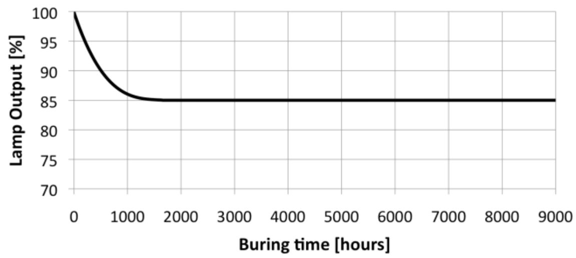

Figure 4. Typical mercury vapor lamp depreciation. (Philips, 2006)

UVGI Device Characteristics

For in-duct application, one or more lamps are installed in an air distribution duct, in an air-handling unit, or in a factory-fabricated assembly. Several properties of these assemblies have a strong effect on the dose delivered, including enclosure geometry, lamp configuration, and reflectivity. Design airflow rates may vary from 5 m/s (1000 fpm) or more in air-distribution ducts to less than 2 m/s (400 fpm) in air-handling units (AHU). Much lower velocities may occur during part-load operation of variable air volume (VAV) systems.

The combined effects of lamp output, device geometry and surface reflectivity determine the irradiance distribution while the combined effects of geometry and airflow determine the single-pass exposure time for air passing through a device. On average, exposure time is the air change rate of the device, i.e., the irradiated volume divided by the volume flow rate.

A single-pass inactivation efficiency can be derived from Equation 1:

$$\eta_{UVGI} = 1 - S = 1 - e^{-k(It)} \quad (2)$$

A design UV dose for a particular value of *S* can be obtained by rearranging Equation 1:

$$(It)_{design} = \frac{\ln(S_{design})}{-k} \quad (3)$$

By combining Equations 2 and 3, the expression for device efficiency at off-design condition becomes:

$$\eta_{UVGI} = 1 - e^{\ln(S_{design})\frac{It}{(It)_{design}}} \quad (4)$$

Taking into account both the effects of temperature and velocity on lamp output and of geometry and flow rate on residence time, the dose for an off-design condition in Equation 4 can be expressed as a fraction of design dose as follows:

$$\frac{It}{(It)_{design}} = \left(\frac{LampOutput}{LampOutput_{design}}\right)\left(\frac{V_{design}}{V}\right) \quad (5)$$

METHODOLOGY

Parametric simulations were performed for a hypothetical four-storey office building located in New York, NY. Each floor of 2380 m^2 (25,600 ft^2) was served by an independent AHU capable of delivering a supply air flow rate of 8 m^3/s (17,000 cfm) and constant ventilation air flow of 1.8 m^3/s (3837 cfm), i.e., 22.5% of design supply air flow. Figure 5 shows the general arrangement of a typical system. For the purposes of this study, only one system from a middle floor was studied in detail.

A UVGI device was located in the supply air of each AHU downstream of the cooling coil and assumed to operate only during business hours (9 a m. – 5 p m., Monday through Friday, a total of 2008 hours per year). It should be noted that the selected UVGI location is only one of several typical locations. It is also common to install UVGI upstream of the cooling coil in an AHU.

The microorganism treated by the system was assumed to be *S. aureus* with the *k* value measured by Sharp (1940). It was chosen somewhat arbitrarily because it is a well-characterized reference. In a typical design process intended to provide protection against a range of infectious agents, the lowest *k* value of concern (i.e., the most UVC-resistant) would be chosen.

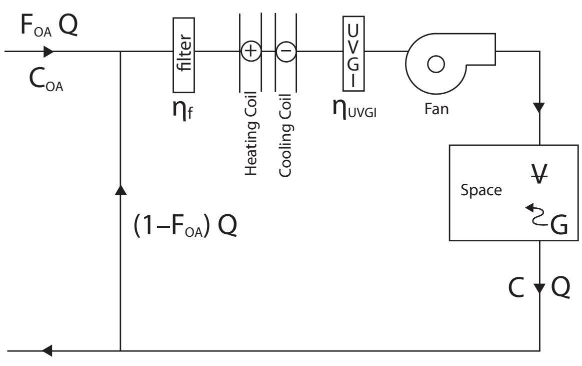

Figure 5 Typical HVAC system schematic

Varied parameters included particulate filtration (MERV 6, 12, and 13) and UVGI sizing strategy, as discussed below. In all cases, the design single-pass efficiency of the UVGI device was assumed to be 85%. For simulating removal of *S. aureus* by filtration, a 1 μm, diameter particle size was assumed, for which the efficiencies of typical MERV 6, 12, and 13 filters, respectively, are approximately 15%, 82%, and 90% (Kowalski and Bahnfleth 2002).

Simulation

The modeling methodology had three components: 1) whole building energy simulation to determine energy use air flow rates, and air temperatures, 2) UVGI device modeling to determine annual distribution of single pass efficiency using air flows and temperatures passed from the whole-building simulation, and 3) modeling of airborne contaminant concentration using a well-mixed space model incorporating UVGI device efficiency results.

The governing equation for concentration of a contaminant in a single well-mixed zone of volume $\forall$ with dilution ventilation and with UVGI and filtration of specified efficiencies in the supply air stream is:

$$\forall \frac{dC}{dt} = G - \left\{1 - (1-\eta_{UVGI})(1-\eta_f)(1-F_{OA})\right\} QC \quad (6)$$

Where *G* is the source strength of the contaminant and F_{OA} is the fraction of outside air in the supply air. Equation 6 expresses that the rate of accumulation of the contaminant in the space is equal to the rate of generation less the rate of removal by all three mechanisms noted.

In UVGI performance simulations, the depreciation and ambient condition response of lamps were modeled and compared with predictions of performance when these effects are neglected. In space concentration calculations, a distributed source of *S. aureus* was assumed. Results of these calculations are presented in normalized form (ratio of concentration to a maximum reference concentration), so that the specific value of source strength is not significant.

The eQUEST implementation of DOE2 (Hirsch 2009) was used for whole building energy modeling and other calculations were programmed in a general purpose computing environment, MATLAB (MathWorks 2009). From these simulations, it is possible to compare different scenarios on the basis of energy use, UVGI device efficiency, and exposure in occupied spaces.

UVGI sizing strategies

Two sizing strategies were considered: "average condition" sizing and "worst case" sizing. Average condition sizing is defined to refer to selection of a system for a desired single-pass efficiency at mean values of temperature and air flow at the installation location. Based on analysis of simulation results the "average" conditions for the study building were a temperature of 10.1˚C (50.2˚F) and velocity of 1.7 m/s (380 fpm). The output of the study lamp under these conditions was 31.7% of maximum.

It was noted previously that the dose required for 85% inactivation of *S. aureus* is 542 μJ/cm^2. With an assumed "average condition" exposure time of 0.39 s, and 31.7% lamp output, the nominal average spherical irradiance (fluence rate) required for this system would be 4,384 μW/cm^2.

The "worst case" sizing strategy is based on an extreme condition for which the combination of air flow and air temperature yields the lowest inactivation efficiency (or some statistically extreme value). For the study building, the worst case combination identified by simulation was 10.8˚C (51.4˚F) temperature and 2.7 m/s (540 fpm) velocity, which yielded a lamp output of 29.5% of the maximum. The spherical irradiance required to achieve the target single pass efficiency was 6,695 μW/cm^2 — 50% more than that for the average condition approach.

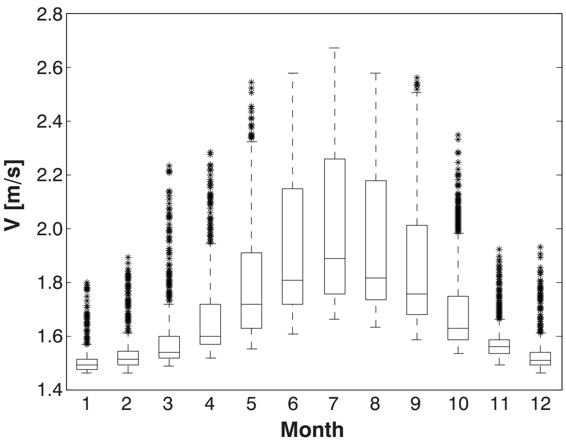

Figure 6. Air velocity at UVGI device location

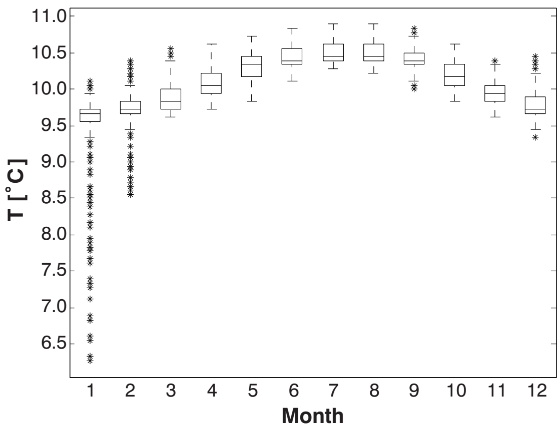

Figure 7. Air temperature at UVGI device location

RESULTS

Lamp environment

Figure 6 shows the air velocity distribution at the UVGI device location obtained from energy simulation. Figure 7 is a similar plot of air temperature results.

Results are presented in a monthly box and whisker format. For each month of data, the line inside the box denotes the median of all data. The ends of the box bound the quartiles above and below the median. The ends of the whiskers attached to each end of the box show the high and low values. Asterisks and circles indicate data outliers, i.e., unique conditions outside the range in which large numbers of data points are distributed.

Air velocity varies over a wide range as the VAV system adjusts air flow to meet the space cooling load. Air temperature, on the other hand, fluctuates within a small range, since this temperature is under control continuously during operating hours.

Lamp output, UVC dose, and inactivation efficiency

Figure 8 shows the impact of air temperature and velocity on lamp output. These data reflect only lamp ambient condition response and not depreciation. The monthly median varies around 32% with most of the data between 29% and 33%.

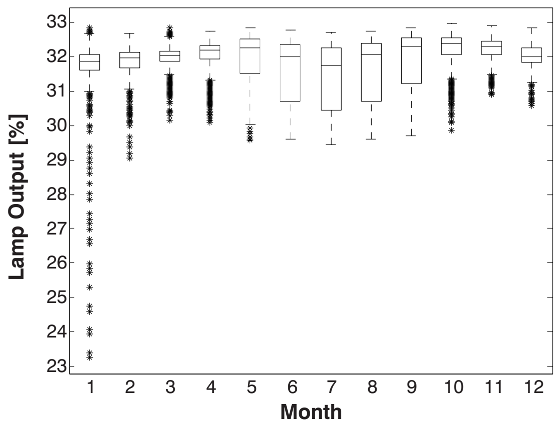

Figure 8. Monthly variation in lamp output, excluding depreciation

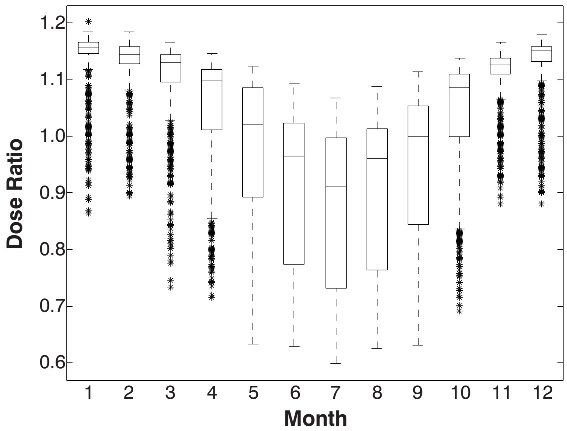

Figure 9. Dose ratio for average condition sizing, excluding depreciation

Although lamp output is relatively stable, the UVC dose and microbial inactivation efficiency will vary because of the effect of air flow on residence time. The variation of dose for the average condition sizing strategy is shown in Figure 9 in the form of a dose ratio, R_{Dose}, defined as the ratio of the actual dose to the design dose. The median value is below 1 for three months during summer, while median values higher than 1 occur during colder months and shoulder months on either side. The effect of air flow is quite significant. In July (month 7), dose ratio falls below 0.75 for more than 25% of the operating hours.

Figure 10 shows the implications of dose variation for inactivation of *S. aureus*. Recalling that the design target was 85%, it is clear that the system generally meets the requirement during the winter but fails to do so during the summer. However, the low monthly median is still above 80%.

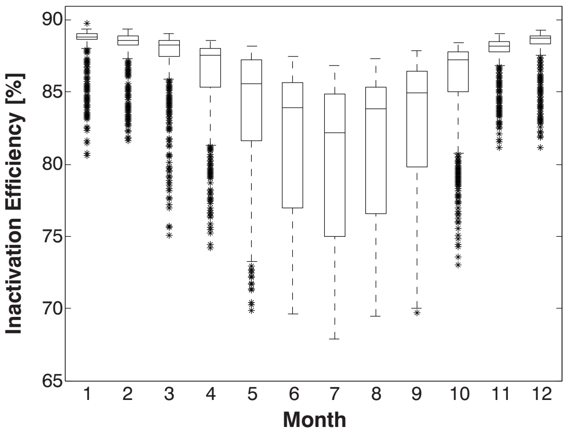

Figure 10 Inactivation efficiency for average condition sizing, excluding depreciation

Depreciation progressively reduces lamp output over time. When the depreciation effects shown in Figure 4 are included in the simulation, the outcome in terms of inactivation efficiency is worse, with the median for some months now less than 80%.

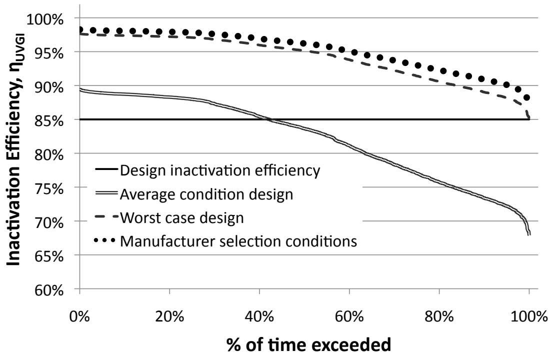

Figure 11 Duration curves of inactivation efficiency for various operating scenarios

Figures 8-11 are not replicated for the worst case sizing strategy as the results would be similar in trend to those for the average condition approach. Instead, the more conservative worst case strategy is compared with the average condition strategy in Figures 11 and 12 using "duration curve" format. A duration curve shows the distribution of a quantity of interest plotted against the fraction of time that a given value is exceeded. The value at 0% is never exceeded and the value at 100% is always exceeded.

Figure 11 shows duration curves of inactivation efficiency for four cases:

- Design inactivation efficiency (reference);
- Average condition design, excluding depreciation effects;
- Worst case design;
- Manufacturer selection. 50°F, 2.5 m/s (500 fpm)

The "manufacturer" selection scenario reflects the conditions that a manufacturer lacking more detailed data, such as the results of an energy simulation, might reasonably use to select lamps.

From Figure 10 it is clear that average condition design results in performance that is below that intended for many hours per year. Whether this matters is an important question that does not have a simple answer, and which is discussed further below. True worst case design substantially oversizes the system. Although the design target is only 85% inactivation, more than half the annual operating hours are at efficiency greater than 95%. It appears that neither approach is truly satisfactory in that one (average condition design) performs poorly a substantial fraction of the time while worst case design results in unnecessary first cost and annual cost penalties due to oversizing. In this case, the manufacturer's selection conditions are conservative and very close to the worst case in their implications for sizing.

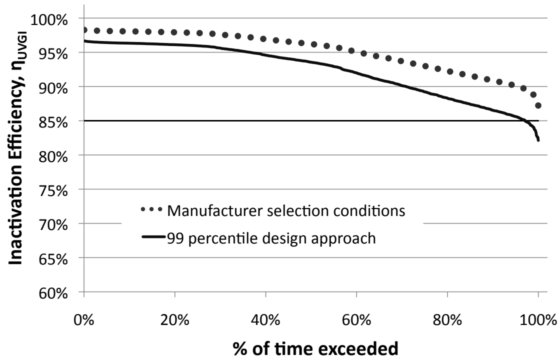

Figure 12 Duration curves of occupied hour inactivation efficiency for the "99%" design strategy

An alternative sizing approach not currently in use that could strike a suitable balance between economy and performance is, with the help of simulation, to select the system so that design lamp output is achieved for a high percentage of operating hours, say 99%. This is analogous to the approach taken in HVAC load calculations to size heating and cooling equipment.

Figure 12 illustrates the application of sizing for the study building system based on the 99% condition, which for the study building corresponded to a velocity of 2.5 m/s (500 fpm) with an air temperature of 10.7˚C (51.3˚F). To achieve 85% inactivation at this condition, an irradiance of 6,042 μW/cm^2 is required. This is about 10% less than the requirement for worst-case design. The device sized for the 99% lamp output condition meets the single pass efficiency requirement 90% of the time. For non-critical applications, a somewhat less conservative target would result in further initial cost and power reductions.

Space microorganism concentration

The preceding discussion has focused on single pass efficiency of the UVGI device. The more important issue, and one generally not addressed in design, is the effectiveness of the UVGI device within the system comprised of the building and its HVAC systems. In application, UVGI is only one of three modes of control, the others being particulate filtration and dilution. Further, the impact of a filter or UVGI device depends on where it is located in system airflow paths. Results of contaminant concentration modeling illustrate some of the characteristics of these effects.

Figure 13 depicts a typical day of normalized space concentration resulting from the distributed, business-hour release of *S. aureus* under several different operating scenarios. The base case that defines the scale factor for normalized concentration is one with no UVGI, minimum outside air flow rate as required by ASHRAE Standard 62.1, and the MERV 6 filters also required by ASHRAE Standard 62.1 (ASHRAE 2007). Other cases considered include enhanced ventilation (30% above Standard 62.1), enhanced filtration (MERV 12 and 13), UVGI (85% efficiency, manufacturer selection condition sizing) with and without depreciation, and enhanced UVGI (98% design single pass efficiency).

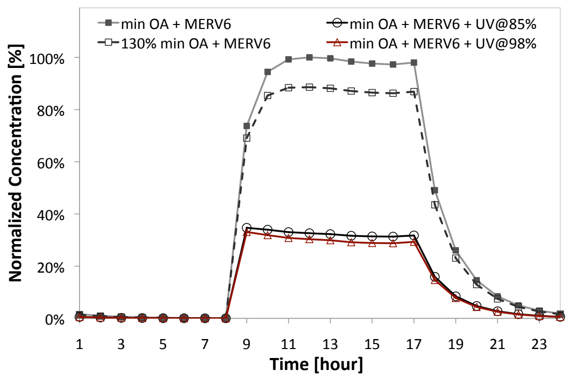

Figure 13. July 16 space concentration for various air treatment scenarios

Figure 13 shows that 85% efficient UVGI results in much lower space concentrations than MERV 6 filters with Standard 62.1 or Standard 62.1 + 30% outside air. However, increasing UVGI design efficiency from 85% to 98% has little impact on maximum concentration in this case.

Figure 14 illustrates the effect of ambient condition variation and depreciation on July 16 space concentration predictions. The "constant output" case is assumed to provide design irradiance at all times. The "new" lamp case is adjusted for wind chill but not depreciation, and the remaining case includes both depreciation and wind chill effects. The most significant effect in this comparison is the wind chill correction of the lamp. However, depreciation also reduces the effectiveness of the system, such that the space concentration increased by 5%.

Figure 15 compares the effect of other air cleaning mechanisms--such as ventilation with 30% more OA, or higher efficiency filtration (MERV 12 and MERV 13) with UVGI operation. It was seen previously that 30% additional OA is far less effective than 85% UVGI. Figure 15 shows that additional ventilation added to a system with UVGI has almost no effect. MERV 12 and 13 filters without UVGI bracket the performance of UVGI with MERV 6 filters. This suggests that it is important to perform a thorough cost analysis of the two approaches that considers all operation and maintenance cost impacts.

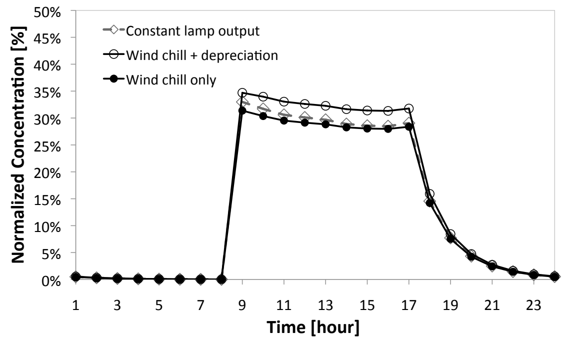

Figure 14. Effect of ambient condition response and depreciation on July 16 concentration results for min OA, MERV6, and 85% UVGI scenario.

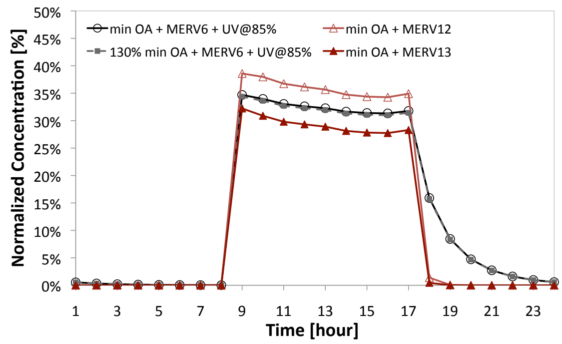

Figure 15. Comparison of enhanced ventilation and filtration effects on July 16

The preceding discussion has focused on a representative 24 hour period. The annual performance of the system from the prespective of space concentration control is also of interest.

Figure 16 shows annual duration curves of normalized space concentration during occupied hours comparing the effects of the baseline case of minimum outside air ventilation + MERV 6 filtration, baseline case + variable output UVGI with depreciation, and baseline case + constant lamp output UVGI.

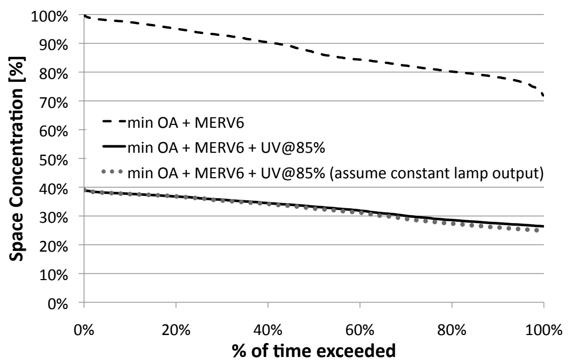

Figure 16. Duration curves of occupied hour space concentration.

Figure 16 indicates that the difference in impact on space concentration between a constant output lamp and a lamp for which adjustment is made for wind chill and depreciation is small in this application. In part, the relatively small difference is due to the incremental effect of UVGI in combination with filtration and dilution.

This result should not be over-generalized. As shown in Figure 8, the combined effect of temperature and air flow is to maintain lamp output within a quite narrow range. Under other circumstances, for example, if the UVGI device was located at a point in the system with different temperature and flow profiles, more sensitivity to wind chill might be expected. Finally, it should also be noted that both the constant output and wind chill + depreciation cases shown in Figure 16 were compensated for wind chill at the design point, so the full impact of neglect of wind chill is not indicated.

DISCUSSION

The analysis presented in this paper is illustrative of an approach that could improve the application of UVGI to in-duct systems through the use of simulation-based design. The advantage this approach offers over existing methods is the opportunity to optimize performance by understanding, for example, the consequences of locating UVGI in various points in an HVAC system or the annual distribution of performance resulting from a particular sizing decision. In particular, simulation permits the analysis of the performance of a UVGI device in a system in terms of its effect on airborne contaminant levels. This is a distinctly different approach than that frequently applied in design, which focuses on the single pass efficiency of the device.

In addition to other sources common to building simulations, uncertainty in k values adds a potentially large component of error to calculations of UVGI system performance. In some cases, k values for a particular microorganism span orders of magnitude. This is true of *S. aureus*, for which measurements have been made in many media under a variety of conditions. The value used in this study is among the lowest in the literature and, therefore, gives a conservative estimate of UVGI effectiveness.

Although conclusions may be drawn for the specific system modeled in this study, these should be viewed as definitive guidance. Only one HVAC system type, one lamp type, one microorganism, one UVGI location, etc., were modeled. Even with this very limited set of parameters, a number of important phenomena were demonstrated, but a far wider range of conditions remains to be investigated.

CONCLUSION

Based upon the results of this study, a number of conclusions can be drawn:

- Both air temperature and air velocity play important roles in determining the UV dose delivered by a UVGI device through their influence on lamp output and residence time.
- The impact of age and ambient conditions on the single-pass inactivation efficiency of in-duct UVGI systems may be large. In this study, dose ratio varied by more than 20%.
- Design for typical or "average" conditions is likely to result in a system that delivers less than its intended design dose much of the time.
- Design for worst-case conditions tends to result in a system that requires substantially more input power and exceeds design dose significantly most of the time.
- Knowledge of the full range of conditions under which a UVGI device will operate may permit informed reduction in installed lamp power while still meeting performance targets for contaminant levels.
- Until a UVGI device is evaluated in a system model that accounts for the effect of ventilation and other modes of air cleaning, its impact is uncertain. In some cases, differences in performance measured in terms of dose or single pass efficiency have a smaller than expected impact because of such interactions. Consequently, system performance calculations may lead to more economical design.
- Ventilation quantities would need to be increased drastically to equal the effect of a moderately efficient UVGI device on airborne microorganisms. High efficiency filtration can equal the performance of UVGI, but potentially at a greater cost.

NOMENCLATURE

C	concentration of microorganism in space (m^{-3})
F	fraction of a substance
G	microorganism generation rate in space (s^{-1})
I	the effective (germicidal) irradiance received by the microorganism ($\mu W/cm^2$)
k	microorganism-specific rate constant ($cm^2/\mu W\text{-}s$)
N	size of a microbial population of the microorganism
Q	volume flow rate (m^3/s)
S	N_t / N_o, survival fraction of the microorganism
R	ratio between two values
t	exposure time (s)
T	air temperature (˚C)
V	airflow velocity (m/s)
Ɏ	space volume (m^3)
η	efficiency (%)

Subscripts

design	design values
f	filter
0	initial value
OA	outdoor air
t	value at time t
UVGI	ultra-violet germicidal irradiation

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