

An Air Cleaner Effectiveness Approach to the Analysis of In-Duct UVGI Systems

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SUMMARY

Air cleaner effectiveness (ϵ) is the fractional change in concentration of an air contaminant resulting from the addition of an air cleaner to a system. Unlike component single-pass efficiency, it takes into account the aggregate effect of all contaminant removal mechanisms as well as the effects of air cleaner placement in the system. The usefulness of ϵ in the analysis and application of air cleaners, as well as its shortcomings, is illustrated by the modeling of in-duct ultraviolet germicidal irradiation (UVGI) in a hypothetical two-zone building served by a constant volume system. The impact of design parameters such as the location of UVGI units, particulate filter efficiency, and the nature of contaminant release are investigated, with calculated ϵ values ranging from 5% to 90% depending on the nature of these parameters.

IMPLICATIONS

This study expands on prior work on the use of effectiveness, examining the range of values associated with a single air cleaner type due to system effects and demonstrating transient behavior of effectiveness.

KEYWORDS

Models, Contaminants

INTRODUCTION

In-duct ultraviolet germicidal irradiation (UVGI) is a method of inactivating biological contaminants in the air in a building that involves placement of UVC sources inside an air distribution system, often inside an air-handling unit. (ASHRAE 2008). Like other air cleaning technologies, UVGI installations can be evaluated in terms of single pass efficiency, i.e. the percentage of viable organisms that remain in the air stream after passing through a UVGI bank. However, single pass efficiency may not adequately describe an air cleaning technology installation when it is interacting with other removal mechanisms (Howard-Reed, et al 2008). Nazaroff (2000) proposed evaluation of air cleaners using the measure termed effectiveness:

$$\epsilon = \frac{C_{uncontrolled} - C_{controlled}}{C_{uncontrolled}} \quad (1)$$

where $C_{uncontrolled}$ is a concentration-related measure of interest without a given control device, and $C_{controlled}$ is the same concentration measure with the control device in place. This enables an evaluation of the incremental benefit of an air cleaning technology specific to a given system, typically through modelling the system and contaminant of interest (Howard-Reed, et

al 2008). Air cleaner effectiveness is frequently modelled with the well mixed assumption applied to conditioned spaces, and is therefore different than other measures with similar names that are concerned with the distribution of contaminant within a space (Novoselac and Srebric 2003). The concentration measure may have a variety of definitions as appropriate for the application, such as the steady state concentration of ozone with and without various air cleaner configurations (Nazaroff and Weschler 2009), or the steady state concentration of a biological contaminant (Lee 2009). Other concentration measures (e.g. cumulative concentration over a time period of interest) can be used as well. In this study, occupant inhaled dose over a specified time period was used to calculate ϵ :

$$Dose = \sum_{i=1}^n C_i \cdot Q_{occupant} \cdot \Delta t \quad (2)$$

where $Dose$ is dimensionless (dose has units of mass, but the contaminant mass units are dimensionless in this study, as the purpose is to examine relative trends rather than the results of a specific contaminant release amount), n is the total number of time steps of length Δt (min), C_i ($1/m^3$) is the concentration at the time step indicated by i , and $Q_{occupant}$ (m^3/min) is the occupant breathing rate. $Dose$, by this definition, is the amount of contaminant inhaled by an occupant during a period of time, not the actual uptake.

This paper examines the use of air cleaner effectiveness as a performance metric for a number of UVGI applications.

METHODS

The study was conducted using a two-zone, well mixed model of the system shown in Figure 1, which shows the locations considered for a UVGI device and the location of the contaminant source. The effectiveness of adding UVGI at either of these locations was calculated based on concentrations in both the release room (zone A) and the non-release room (zone B). Each zone has a floor area of $92.9 m^2$ and floor-to floor height of $3.05 m$ tall, giving a volume of $283.2 m^3$. Supply air volume was set at a nominal $0.31 m^3/min\cdot m^2$, or $28.32 m^3/min$ for each room. The fraction of outdoor air was set at 20%, a rough value for an office-type building. The model was constructed using numerical integration of the contaminant mass balance differential equations in implicit equation solving software (Klein, 2010).

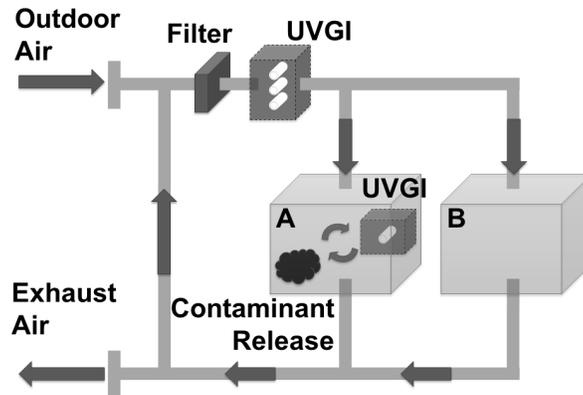


Figure 1. System Schematic

Four scenarios were examined (Table 1), each a dimensionless release (e.g. adding material at a constant rate of $1/\text{min}$, or having an initial concentration of $1/\text{m}^3$). The single pass inactivation efficiency of the UVGI systems was set at 85% based on manufacturer's typical practice as reported in previous work by Bahnfleth, et al (2009). Filtration was varied based on single pass removal efficiencies of MERV 6 and MERV 12 filters for $1 \mu\text{m}$ particles (Kowalski and Bahnfleth 2002). This approximate microbe size was based on species that are typically transmitted through the air, e.g. anthrax (Kowalski 2003). The recirculating cleaner operated at $1/3$ of the room supply air rate, or $9.44 \text{ m}^3/\text{min}$, the approximate flow rate of a commercially available recirculating UVGI air purifier with a maximum coverage area of 140 m^2 (Air and Water, Inc. 2010). Again, an 85% single-pass inactivation efficiency was used. Effectiveness was calculated using total inhaled occupant dose over a 4 hour release period. Occupant breathing rate was assumed to be $0.5 \text{ m}^3/\text{h}$ (EPA 1997).

Table 1. Examined Scenarios

Scenario	Filter Efficiency	UVGI Location	Release Type
Base	15%	Central	Constant $1/\text{min}$
Filter	82%	Central	Constant $1/\text{min}$
Recirc	15%	In room recirculating cleaner $9.44 \text{ m}^3/\text{min}$	Constant $1/\text{min}$
Burst	15%	Central	Initial Concentration $1/\text{m}^3$

RESULTS

The results of the base release (Figure 2) show that the addition of a centrally located, 85% efficient UVGI device has an effectiveness of approximately 50% in the release room, and approximately 90% effectiveness in the non-release room, i.e., 50% and 90% reductions in inhaled dose, respectively. Note that these values are time dependent. In the release room, the effectiveness starts out near zero, as the source is in the space and occupants are initially exposed mainly to air that has not passed through the air cleaner. As time passes and contaminated air flows through the UVGI device (and as the room concentration approaches steady state), the effectiveness increases toward an asymptotic maximum. In the non-release room, ϵ is near its final value almost from the start, as the room is initially uncontaminated and receives only cleaned air. Consequently, the non-release room experiences a significantly higher effectiveness than the release room.

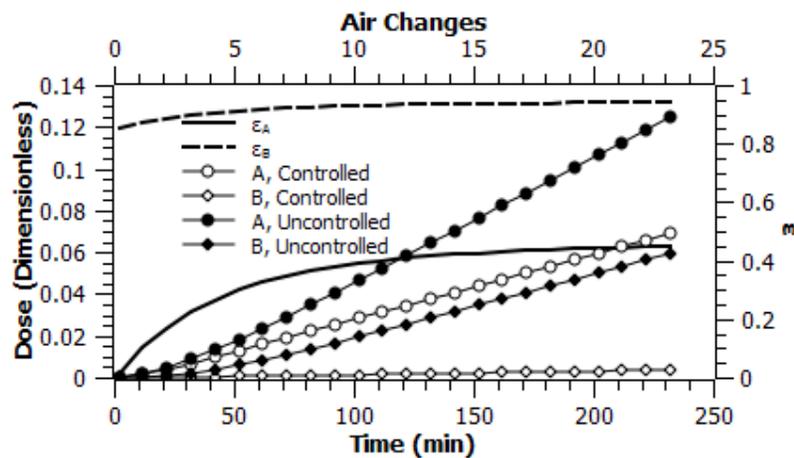


Figure 2. Base case results

The use of an 82% filter (Figure 3) greatly reduces the dose received by the occupants in both rooms. However, centrally located UVGI has much lower effectiveness in the release room, while it maintains a high (though slightly less than the previous scenario) effectiveness in the non-release room. The high effectiveness in the non-release room is somewhat misleading; as the absolute change in dose due to the addition of UVGI is very small in both cases. Though the effectiveness in the non-release room is high, the change in dose may be insignificant in application.

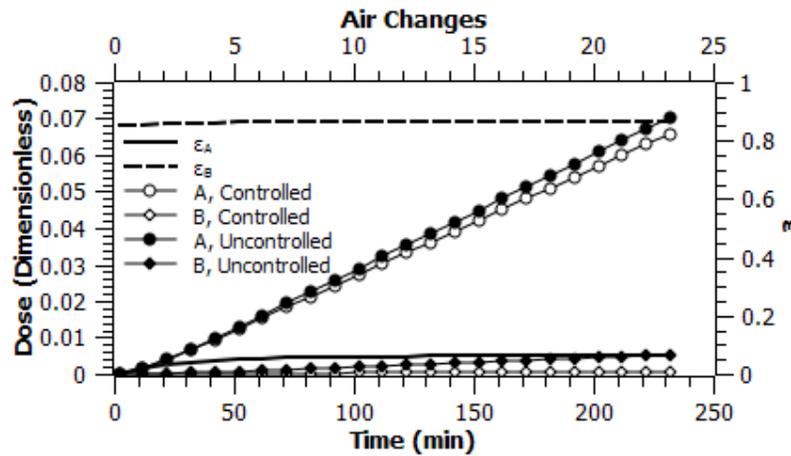


Figure 3. Filtration efficiency increased to 82%

The addition of an in-room, recirculating UVGI system produces the highest effectiveness for the release room (Figure 4), due to the ability to remove the contaminant locally. This also increases ϵ in the non-release room.

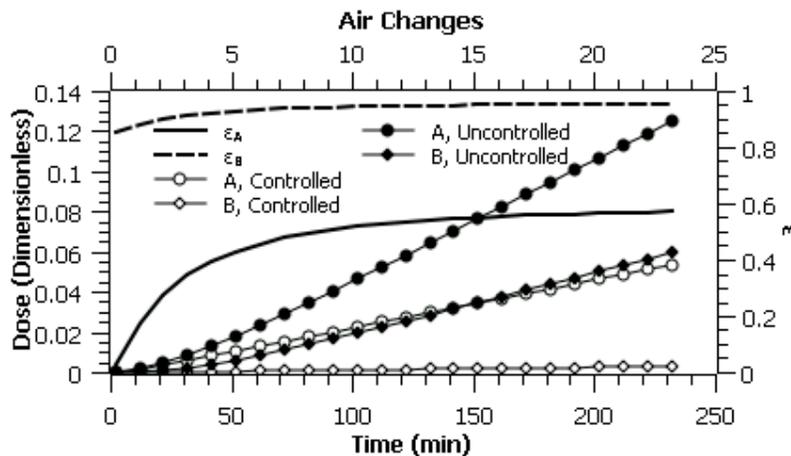


Figure 4. Local, recirculating UVGI air cleaner

Calculating ϵ using a burst release (Figure 5) produces an almost identical effectiveness as the base scenario. The main difference is the faster increase of effectiveness in the release room.

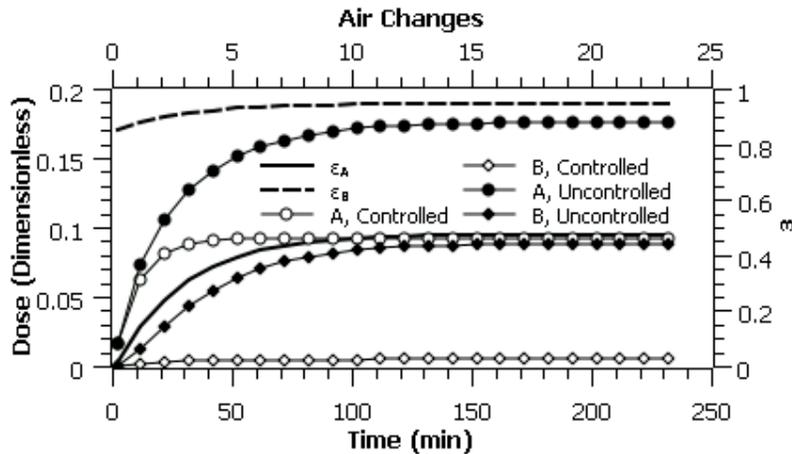


Figure 5. Burst release

DISCUSSION

There are inherent limitations in the results. Zones are assumed to be well mixed, and the only system examined is constant volume. No allowance is made for degradation of performance over time or faulty installation of air cleaning devices, nor to the effects that airflow rate and air temperature variations can have on UVGI inactivation efficiency. Occupants are treated in a static manner; i.e. occupant breathing rate does not change and the occupant remains in the room for the duration of the four hour period. Also, the dose model is simple so as to evaluate general trends with a generic contaminant, and does not include contaminant specific pathways.

Even with these limitations, a number of useful observations can be made. Effectiveness can be time dependent. If ϵ is based on dose, occupant behavior can influence it (e.g. the effectiveness would vary based on whether the person was in the room for thirty minutes from the start of the release, sixty minutes, and so forth). Though ϵ in the non-release zone is time dependent, it approaches its maximum value more rapidly and changes much less over time.

Adding UVGI (or any air cleaner) to a system that already has a high efficiency cleaning device or high ventilation rate has minimal impact on the occupant dosage, but varying impact on ϵ . In some situations, such as a non-release zone, the effectiveness can give an exaggerated impression of the benefit resulting from additional air treatment. Note that the low impact on ϵ in the release room is not a function of UVGI itself, but of the order in which air cleaners are added. If a system prior to the addition of an air cleaner with UVGI and a MERV 6 filter, and the effectiveness of adding a MERV 12 filter was evaluated, it too would be low.

Placing a local, recirculating air cleaner in the release room was the most effective method for controlling in-room sources. Note that this is dependent on the recirculation rate of the air cleaning equipment.

Effectiveness results for a burst release are similar to those using a steady state release. Though this indicates that release type may not be significant in some analyses, it also demonstrates that it will be of concern when shorter, transient periods are of interest; e.g., calculating ϵ of an air cleaner in mitigating a spill-type release where the occupant(s) would respond to the spill by moving out of the contaminated area soon after the release.

CONCLUSIONS

The analysis of the UVGI installations by the effectiveness measure demonstrates the limitations of using single pass efficiency as an evaluation metric. An air cleaning device (not necessarily UVGI) with a stated air cleaning efficiency can have a wide range of effectiveness based on installation location and the use of other removal mechanisms in the system.

Modeling the benefit of a UVGI installation (or any incremental increase in air cleaning) for the specific system and situation of interest gives designers and owners a clearer idea of the worth of a given installation than the single pass efficiency, and therefore can aid in design decisions. However, the designer must still be aware of how the use of different definitions of ϵ will alter its value, e.g. average concentration vs. cumulative concentration (in essence, what the dose measure used in this research is) vs. steady state concentration, which of these definitions is appropriate for a given design problem, and what sort of contaminant release is appropriate. The transient nature of effectiveness when considering occupant dose is important to note, as well.

While there are some demonstrated issues with this approach, e.g., a high ϵ corresponding to a possibly insignificant change in dose and ambiguity regarding how to deal fairly with multiple air treatment modalities in a system, using effectiveness to evaluate specific release scenarios and occupant behavior has clear benefits over simpler measures that do not account for system effects.

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