Analysis of Efficacy of UVGI Inactivation of Airborne Organisms Using Eulerian and Lagrangian Approaches

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ABSTRACT

Ultraviolet germicidal irradiation (UVGI) is increasingly used in health care facilities to kill airborne bacteria and control the spread of airborne infection among occupants. The most widely used form of UVGI is the passive upper-room lamps that generate a horizontal layer irradiance field above the occupied zone. In this study, the efficacy of killing airborne bacteria by upper-room UVGI in a test room is investigated by using computational fluid dynamics (CFD). The killing of airborne bacteria is dependant on the dose the bacteria receive and their susceptibility. In order to calculate the dose, the trajectory of each of the bacteria needs to be predicted. The common practice in CFD is that the flow field is solved using an Eulerian reference system and the particle trajectory is calculated using a Lagrangian reference system from which the particle dose is derived. This approach gives very accurate and detailed information on the history and behavior of each organism. However, in typical experimental procedures, the samples are usually collected when the numbers of the bacteria killed, ventilated, or remaining viable in the room reach steady state and the bacteria killing mechanism is considered as a group activity. This makes comparison of the CFD prediction with experimental data difficult—the Lagrangian reference system is not suitable when the steady-state information regarding the overall behavior of the bacteria in a room at any moment is of interest. In this study, a new approach is proposed to estimate the bacteria inactivation rate in the Eulerian system. For each room condition, both the Lagrangian and Eulerian approaches are utilized to evaluate the UVGI efficacy. The predicted results with the Eulerian approach are compared with available experimental measurements.

INTRODUCTION

Ultraviolet germicidal irradiation (UVGI) is increasingly used in hospital laboratories and health care facilities to inactivate the airborne bacteria and so control the spread of airborne infection among occupants. The most widely used application of UVGI is in the form of passive upper-room fixtures containing UVGI lamps that provide a horizontal layer of UV energy field above the occupied zone. They are designed to inactivate bacteria that enter the upper irradiated zone, and their efficacy is highly reliant on, among other factors, the flow field conditions in the room. The survival probability of bacteria exposed to UV irradiance depends on the susceptibility of the bacteria in question and the dose in a general form (Federal Register 1993),

$$\% \text{ Survival} = 100 \times e^{-z(dose)}, \qquad (1)$$

where

dose = the UV irradiance multiplied by the exposure time ($S \cdot \mu W/cm^2$) and

z = the microbe susceptibility factor, ($cm^2/\mu W \cdot S$).

In order to determine the UVGI efficacy, the dose received by the bacteria needs to be evaluated. Dose calculation involves knowledge of the irradiance distribution, the flow field conditions, and the trajectory paths (history) of the bacteria in the room. Previous research on UVGI effectiveness has been mostly focused on empirical methods (Chang et al. 1985; Macher et al. 1992; Mortimer and Hughes 1995; Xu et al. 2002), which are time consuming and are limited by the cost of modifying physical installations of the ventilation systems. Beggs and Sleigh (2002) employed a theoretical model to evaluate the UVGI effectiveness with the assumption of

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complete air mixing. Alani et al. (2001) and Memarzadeh and Jiang (2000) applied numerical simulation to investigate the UVGI efficiency. Using computational fluid dynamics (CFD) for the airflow calculation and the Lagrangian system model for dose prediction, based on the system derived in Alani et al. (1998), Memarzadeh and Jiang studied 40 different cases of room configuration with different combinations of lamp location and irradiance.

The motion of a fluid is usually described by one of two different frames of reference. In the Eulerian reference system (hereafter shortened to the Eulerian system), attention is focused on particular locations in the space filled with fluid. The results of the fluid pressure, velocity, turbulence parameters, and other variables are presented as a function of location and, in the case of unsteady state, time. Assuming that the relative velocity between bacteria and air is negligibly small, the airborne particles' distribution in the Eulerian system is usually treated as a species concentration and solved in a space coordinate together with the airflow. In the Lagrangian reference system (hereafter shortened to the Lagrangian system), each fluid particle is labeled and accounted for individually. Then the path or trajectory, velocity, and other characteristics of each individual fluid particle are tracked as a function of time.

In most CFD software packages, the flow, temperature, and other scalar fields are computed in the Eulerian system. However, in order to evaluate UV dose, the time that the particles spend in the UV zone is required, which is not a straightforward calculation in the Eulerian system. The advantage of the Lagrangian system in this application is quite clear since the trajectory of each particle is monitored and calculated, and the time a particle spends in the UV zone when traveling in the room can be determined quite precisely. Therefore, the most obvious numerical analysis practice is that the flow field is solved in the Eulerian system, and the dose is calculated in the Lagrangian system (Alani et al. 2001; Memarzadeh and Jiang 2000).

As an example of a suitable application of these two calculation systems, the bacteria generation from a cough by a hospital facility occupant is not of steady-state nature. In calculating the cough using the Lagrangian system, the results show, at any given moment within the tracking period, how many particles are vented out, how many remain in the room, and how many are still viable. However, as the particle-tracking procedure in the Lagrangian system is in time-dependant form, it is not therefore strictly suitable in applications where steady-state conditions are prevalent. An example of this would be in experimental scenarios in which the particle generation, the rate of extraction of the particles from the room, and the deactivation of the particles from UVGI can all be considered constant. It is therefore useful to consider a model based on the Eulerian system that is more applicable to steady-state scenarios. The scope of this study is to utilize airflow modeling for the following:

1. Propose and validate an analytical model for evaluating the UV dose in steady-state situations using the Eulerian system.
2. Use the proposed model to assess the effects of the ventilation flow rates and types of UV fixtures on inactivation of airborne bacteria in a test chamber room.
3. Compare the Eulerian and Lagrangian system models and discuss their typical applications.

DOSE CALCULATION MODEL USING THE EULERIAN SYSTEM

With the known airflow field and UV irradiance energy distribution, the time a particle spends in the UV zone is the most crucial piece of information in the dose calculation since dose is defined as UV irradiance multiplied by the exposure time. In the Eulerian system, however, the history of the particle trajectories is not recorded; no detailed information regarding individual particle is available. Therefore, the concepts of "scale" and "average" must be used to derive overall information on a group basis. In the Eulerian system, particles in the room are usually simulated aspecies concentration distribution. These particles travel in and out of the UV zone several times before being removed from the room by the ventilation system. In order to estimate the dose of the particles, we need to estimate (1) the average resident time in the UV zone, t_{r-UV}, and (2) the average number of passes, N_{pass}, of the particles through the UV zone before being vented out. The total dose received by particles before being vented out can then be estimated as

$$\text{Total dose} = (t_{r-UV} * \text{average UV\_irradiance} * N_{pass})\,. \quad (2)$$

Let us consider a typical room equipped with an upper-room fixture of UVGI. The thickness of the UV zone is considered to be identical to the thickness of the fixture. There is a particle source located in the lower part of the room with the generation rate of M, as illustrated in Figure 1. As the particle concentration in the UV zone is a direct output of CFD simu-

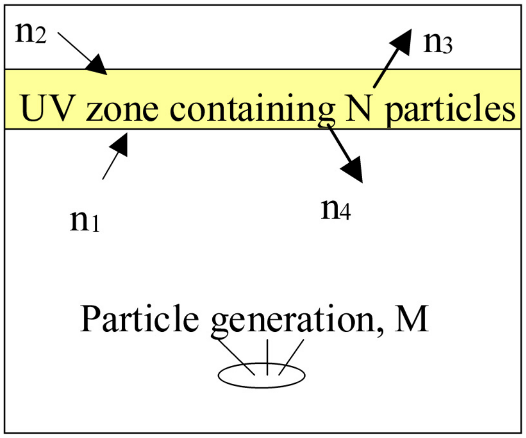

Figure 1 *Schematic drawing of the particles in and out of the UV zone.*

Table 1. Comparison of the Results from Proposed Model and from Xu et al. (2002)

	Z-Value $cm^2/W \cdot S$	Average UV Irradiance $\mu W/cm^{-2}$	Inactivated by UVGI
CFD simulation with the proposed dose calculation model	0.0012	42	85%
Xu et al. (2002) Experiment 1	0.0012	42	82%
Experiment 2	0.0012	42	93%

lation, the total number of particles in the UV zone, denoted by N, can be calculated if the particles size and density are given. The rate of the particle entering the UV zone, n (number of particles per second), is

$$n = n_1 + n_2 , \tag{3}$$

where

n_1 and n_2 = the numbers of particles entering the UV zone per second from below and above, respectively.

In a steady-state condition, the number of particles entering the UV zone is equal to that leaving the UV zone.

$$n_1 + n_2 = n_3 + n_4 \tag{4}$$

Using the concept of air change per hour (ACH), the time scale (N/n) indicates the time required for a complete replacement of particles in the UV zone. This replacement time is actually the average resident time of the particles in the UV zone, $t_{r\text{-}UV}$. In the steady-state condition, there is a constant particle flow, n, into and out of the UV zone. These particles spend an average of N/n seconds in the UV zone for a single pass. Knowing the average UV irradiance in UV zone, the average dose received by the particles when spending N/n seconds in the zone can be evaluated. Note that the particle flow rate into the UV zone, n, can be higher than the particle generation rate M, which indicates recirculation and, thus, the possibility of multi-pass to the UV zone.

The next step is to estimate how many passes to the UV zone the particles make before being vented out. To answer this question, we need to know the total residence time of the particle in the room, $t_{r\text{-}room}$, the characteristic velocity of the particles, and the characteristic length of the room. The ACH and "replacement" concepts are employed again to evaluate the total resident time of the particle in the room. In the steady-state condition, the total number of particles in the room N_r is a constant that is dependant on the source strength and the removal effectiveness of the ventilation system. For a particle generation rate M (number of particles per second), the time required to completely replace the particles in the room, $t_{r\text{-}room}$, can be evaluated as

$$t_{r\text{-}room} = N_r / M \text{ (second)} . \tag{5}$$

The variable $t_{r\text{–}room}$ is equivalent to the average resident time of the particles in the room. Based on the configuration of the room, it is reasonable to take the room height, H, as the characteristic length, and the average vertical velocity component, V_y, as the characteristic velocity. Then the time required for particles to make a single pass to the UV zone can be estimated as

$$t_{pass} = H/V_y . \tag{6}$$

The total number of pass then can be determined as

$$N_{pass} = t_{r\text{-}room} / t_{pass} . \tag{7}$$

With the average UV irradiance, the average resident time and the number of passes of the particles to the UV zone being available, the total dose the particles received before being vented out can be determined by using Equation 2. The survival probability of a given bacteria can then be evaluated using Equation 1.

VALIDATION OF THE EULERIAN SYSTEM MODEL

In order to validate the model, a comparison was made to the experimental data from Xu et al. (2002). The 87 m^3 experimental room included five upper-room lamps—one 72 W at the center of the ceiling, and the other four (36 W each) installed at each of the four corners. The average UV irradiance was around 42 μWcm^{-2} at full operating capacity. The flow rate was 6 ACH. The proposed model was employed based on the results predicted by CFD package FLOVENT (1995) using finite volume approach and the k-ε turbulence model to solve the set of conservation equations. The comparison, shown in Table 1, indicates that the proposed model works quite well in the cases with well-mixed room condition.

APPLICATION OF THE EULERIAN SYSTEM MODEL

A typical physical test chamber was considered to assess the effects of the ventilation flow rates and UVGI configurations on the inactivation of airborne bacteria. The test chamber was 4.6 m × 2.97 m × 3.05 m. It was equipped with two UVGI units, as shown in Figure 2.

1. A wall-mounted tube type unit, 12.7 cm thick, with 30 W output on the right wall, 2.02 m from the floor.
2. A cylindrical pendant 36.8 cm in diameter and 12.7 cm thick with 30 W output located in the center of the room, 2.24 m from the floor.

The thickness of the UV zone was considered to be identical to the thickness of the UVGI unit. In the physical case, the particles representing organisms were delivered via a nebu-

Table 2. Particle Flow Rate, Average Resident Time for a Single Pass to the UV Zones and the Total Number of Passes Before Leaving the Room

		Particle Flow Rate (number/s)		Average Resident Time (s)		Number of Passes to UV Zone
	ACH	Wall UV Zone	Pendant UV Zone	Wall UV Zone	Pendant UV Zone	
Case 1	2	587	off	24.7	-	3
Case 2	6	491	off	8.29	-	3
Case 3	2	off	540	-	26.8	3
Case 4	6	491	387	8.29	8.61	3

Table 3. The Percentage of Particles Inactivated by UVGI at the Exhaust (Susceptibility, z = 0.0012 [cm^2/W.S])

	ACH	Wall Lamp	Pendant Lamp	Dose Received in Wall Lamp Zone S. W/cm^2	Dose Received in Pendant Lamp Zone S. W/cm^2	Inactivated by UVGI
Case 1	2	on	off	1416	-	82%
Case 2	6	on	off	475	-	43%
Case 3	2	off	on	-	914	67%
Case 4	6	on	on	475	293	60%

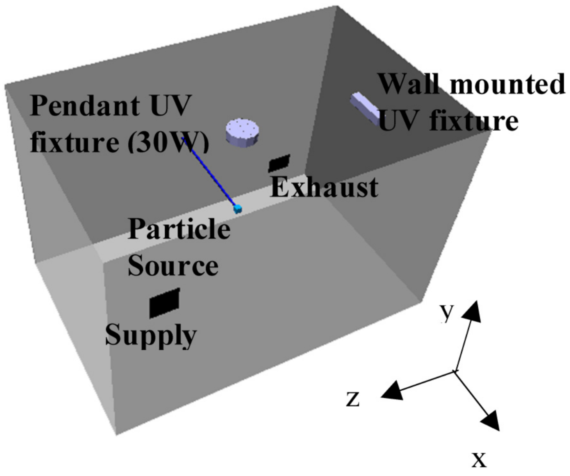

Figure 2 *Configuration of the test chamber.*

lizer. The air supply and exhaust were located on the opposite walls. The walls were well insulated. The heat dissipation from the UVGI units was negligibly small in comparison with the ventilation flow rate, and, thus, isothermal condition was considered to be present in the room. Total grids used in the CFD calculation were 387,660 (60 × 71 × 91). Inlet diffuser was modeled as a fixed flow rate device with uniform velocity distribution over the entire face. The iteration procedure was considered to converge when the total residual of each individual parameter was less than 0.5% of its characteristic value. In the same test chamber, two different scenarios were considered to demonstrate the Eulerian and the Lagrangian system models:

- *Scenario 1*: The particles were generated at a constant flow rate of 12 lpm. The number of viable organisms generated was approximately 11,000 per minute (183/s). This scenario was intended to simulate a typical hospital waiting area where constant sources of airborne bacteria are generated from waiting patients, which is a suitable application for the Eulerian system model. The proposed Eulerian system model was run for this scenario.
- *Scenario 2*: Two thousand particles were released from the nebulizer at a given moment. This scenario was intended to simulate the cough of a patient in a hospital isolation room, for which the Lagrangian system model is more suitable. The 2,000 particles were then individually tracked for 6,000 seconds. Detailed information regarding the Lagrangian system model used to calculate this scenario can be found in Memarzadeh and Jiang (2000).

For each of the two scenarios, our cases were studied within ventilation flow rates of 2-6 ACH and the two UVGI being on or off as outlined in Table 3. The results presented in the next section were based on consideration of a droplet diameter of 1 μ and density of 1000 kg/m^3 (water).

RESULTS

The results discussed in this section are mainly focused on the Eulerian system model calculations (scenario 1). The data obtained from the Lagrangian system model calculations (scenario 2) are presented in Table 4 just for comparison.

Figures 3 and 4 show the streamlines that start from the nebulizer for the four cases for scenario 1. The concentrations of total particles, whether inactivated or alive, at the vertical

Table 4. The Percentage of Particles Inactivated by UVGI at the Exhaust after 6000 Seconds of Tacking [Susceptibility, z = 0.0012(cm^2/μW.S)]

	ACH	Percentage of Vented	Average Dose at Exhaust S. W/cm^2	Inactivated by UVGI
Case 1	2	64%	1057	72%
Case 2	6	92%	247	26%
Case 3	2	64%	557	49%
Case 4	6	92%	391	37%

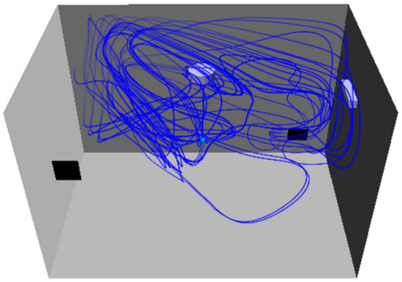

Figure 3 *Streamlines for cases 1 and 3 (2 ACH).*

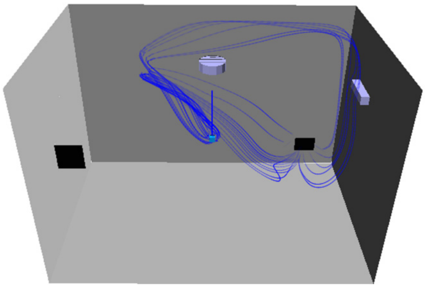

Figure 4 *Streamlines for cases 2 and 4 (6 ACH).*

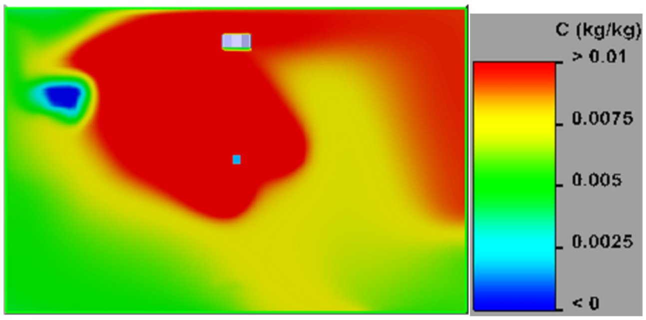

Figure 5 *Concentration distribution for cases 1 and 3 (2 ACH).*

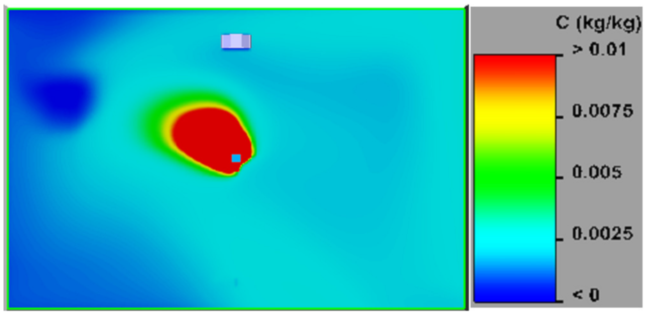

Figure 6 *Concentration distribution for cases 2 and 4 (6 ACH).*

plane cutting through the nebulizer are plotted in Figures 5 and 6. It is clearly seen from the streamlines that the particles make several passes to the UV zone before being vented out. At the lower supply flow rate, 2 ACH, the particle concentration level in the room for cases 1 and 3 is substantially higher than that for cases 2 and 4, where the flow rate is 6 ACH. Table 2 shows that, at the same flow rate, the particles spend a longer time in the pendant UVGI zone on average than in the wall-mounted zone. This is because the pendant zone is closer to the ceiling where the particle velocity is lower due to the effects of the solid boundary.

The results also show:

- The percentage of UVGI inactivation is higher when the ventilation flow rate is lower.
- The flow rate of particles that enter the UV zone is roughly three times as high as the generation rate for 2 ACH and 2.6 times for 6 ACH. In case 1, for example, the flow rate of particles entering the UV is 587/s, compared with a particle generation rate of 183/s.
- As the supply flow located between the two UV zones suppresses the particles' upward movement, the total particles in the lower UV zone, the UV zone of the wall-mounted unit, and particle flow rate into this UV zone are all higher than those of the pendant unit UV zone.

In the Lagrangian system calculations for scenario 2, since the particle-tracking results are time-dependant, a time frame is always involved when results are presented. The results presented in Table 4 are based on a 6,000-second tracking time. Comparing the percentage of inactivated particles in Tables 3 and 4, it is found that, although the values are not identical, the Eulerian and Lagrangian approaches predict the same tendency in terms of the effect of ventilation flow rate and configuration of UV lamps on inactivating airborne bacteria by UVGI. The difference in the actual values is expected as the two system models are modeling different scenarios.

SUMMARY

An analytical model for evaluating the UV dose in steady-state situations using the Eulerian system is proposed. In comparison with available experimental data, the proposed model predicts the percentage of particles inactivated by UVGI well. The proposed model is used to study the effects of the ventilation flow rates and configurations of UV fixtures on inactivation of airborne bacteria in a test chamber. The Lagrangian system model was also applied in the same test chamber for a similar scenario. The following conclusions are drawn from this study:

1. The results from cases 1 and 2 show that increasing the ventilation flow rate reduces the resident time of particles in the UV zone from 24.7 to 8.3 seconds. The number of particles entering the UV zone is also reduced because the total number of particles in the room is decreased. It results in a 35% reduction of the total dose received by particles.
2. The wall-mounted UVGI slightly outperforms the pendant UVGI in terms of total dose received by particles due to the fact that the pendant lamp is too close to the ceiling; therefore, fewer particles can enter this zone.
3. The results obtained from the Eulerian and Lagrangian system models are quite consistent in terms of predicting the same effect of ventilation flow rate and UV lamp configuration changes for similar physical scenarios.

REFERENCES

Alani, A, D. Dixon-Hardy, and M. Seymour. 1998. Contaminants transport modelling, EngD in Environmental Technology Conference.

Alani, A., I.E. Barton, M.J. Seymour, and L.C. Wrobel. 2001. Application of Lagrangian particle transport model to tuberculosis (TB) bacteria UV dosing in a ventilated isolation room. *Int. J. Environ. Health Res.* 11:219-228.

Beggs, C.B., and P.A. Sleigh. 2002. A quantitative method for evaluating the germicidal effect of upper room UV fields. *Journal of Aerosol Science* 23:1681-1699.

Chang, J.C., S.F. Ossoff, D.C. Lobe, M.H. Dorfman, R.G. Quall, and J.D. Johnson. 1985. UV inactivation of pathogenic and indicator microorganisms. *All. Environ, Microbiol* 49:1361-1365.

Federal Register. 1993. Draft guidelines for preventing the transmission of tuberculosis in health care facilities, 2d ed. Notice of Comments Period 58(195).

FLOVENT. 1995. *FLOVENT® Reference Manual*. Flomerics, FLOVENT 0994/1/1.

Macher, J.M., L.E. Alevantis, Y-L. Chang, and K-S Liu. 1992. Effect of ultraviolet germicidal lamps on airborne microorganisms in outpatient waiting room. *Appl. Occ. Environ.Hyg,* 7:505-513.

Memarzadeh, F., and Z. Jiang. 2000. New research identifies a methodology for minimizing risk from airborne organisms in hospital isolation rooms. *ASHRAE Transactions* 106(2):731-747.

Mortimer, V.D., and R.T. Hughes. 1995. The effects of ventilation configuration and flow rate on contaminant dispersion. American Industrial Hygiene Association Conference and Exposition.

Xu, P., J. Peccia, P. Fabian, J.W. Martyny, K.P. Fennelly, M. Hernandez, and S.L. Miller. 2002. Efficacy of ultraviolet germicidal irradiation of upper-room air in inactivation airborne bacterial spores and mycobacteria in full-scale studies. *Atmospheric Environment* (37):405-419.