Minimizing the exposure of airborne pathogens by upper-room ultraviolet germicidal irradiation: an experimental and numerical study

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There has been increasing interest in the use of upper-room ultraviolet germicidal irradiation (UVGI) because of its proven effectiveness in disinfecting airborne pathogens. An improved drift flux mathematical model is developed for optimizing the design of indoor upper-room UVGI systems by predicting the distribution and inactivation of bioaerosols in a ventilation room equipped with a UVGI system. The model takes into account several bacteria removal mechanisms such as convection, turbulent diffusion, deposition and UV inactivation. Before applying the model, the natural die-off rate and susceptibility constants of bioaerosols were measured experimentally. Two bacteria aerosols, Escherichia coli and Serratia marcescens, were tested for this purpose. It was found out that the general decay trend of the bioaerosol concentration predicted by the numerical model agrees well with the experimental measurements. The modelling results agree better with experimental observations for the case when the UVGI inactivation mechanism dominates at the upper-room region than for the case without UVGI. The numerical results also illustrate that the spatial distribution of airborne bacteria was influenced by both air-flow pattern and irradiance distribution. In addition to predicting the local variation of concentration, the model assesses the overall performance of an upper-room UVGI system. This model has great potential for optimizing the design of indoor an upper-room UVGI systems.

Keywords: air disinfection; CFD; ultraviolet germicidal irradiation; ventilation

1. INTRODUCTION

Ultraviolet germicidal irradiation (UVGI) is defined as the use of ultraviolet radiation to kill or inactivate micro-organisms. The wavelength of UV rays used for disinfecting air and surfaces ranges from 200 to 320 nm [1]. The germicidal effect of UV light on micro-organisms was first noted in the late nineteenth century and has since been investigated and applied to improve indoor air quality by controlling and reducing airborne transmission of pathogens [2–6]. One of its most popular applications is the upper-room UVGI system. In such a system, a UVGI lamp fixture fitted with multiple louvres is installed in the upper part of a room so that the irradiation is generated in the upper air zone only, thus minimizing human exposure [7–8]. Advantages of using an upper-room UVGI installation in indoor environments include low initial and running costs, less maintenance and easy relocation. A large volume of air can be disinfected without overexposing people to UVC [9]. Recently, an upper-room UVGI has been recommended by the Centers for Disease Control and Prevention (CDC) as a supplemental approach for preventing transmission of tuberculosis in isolation rooms [10]. However, the application of a UVGI system requires comprehensive understanding of the influences of environmental factors on the inactivation rates of airborne bacteria by UVGI [11].

The surviving fraction of bacteria exposed to ultraviolet irradiance in a ventilated room is generally expressed as [12]

$$C_i = C_0e^{-(k_n+k_v+k_{uv})t} \quad \text{or} \quad \frac{dC_i}{dt} = -(k_n+k_v+k_{uv})C_i, \quad (1.1)$$

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where $C_0$ is the initial concentration of airborne bacteria (CFU m$^{-2}$); $k_s$ is the rate of natural die-off under calm environment, including natural die-off, gravitational settling and decay of airborne bacteria by other natural processes (s$^{-1}$); $k_r$ is the rate of removal of airborne bacteria by ventilation (s$^{-1}$); and $k_w$ is the rate of inactivation of airborne bacteria by the UVGI system (s$^{-1}$), which usually depends on the bacteria susceptibility to UV irradiance and the irradiance intensity. It should be noted that no wall loss is accounted for $k_w$, which is valid as wall loss is negligible for bacteria with supermicrometre sizes. Each of these rates ($k_s$, $k_r$ and $k_w$) can be determined through experiments under specific conditions. According to equation (1.1), the natural-log $C_t$ value is a linear function of time. The slope of the linear function is the total bioaerosol removal rate. The higher the inactivation rate, the faster the decreases in $C_t$. It should be noted that equation (1.1) can also be interpreted as a general description of the local balance of bioaerosol.

The efficiency of a UVGI system in inactivating bioaerosols has much to do with the UV-susceptibility of the bioaerosols, the irradiance distribution patterns and the degree of air mixing in the room [9,13,14]. The susceptibility of bioaerosols to UVGI damage varies for the micro-organism species and may also correlate to the environmental factors. It can be quantified for each micro-organism species by a susceptibility constant, termed the $z$-value. In literature, a wide range of $z$-values for particular bioaerosols has been reported. For two bioaerosols commonly used for testing the inactivation efficiency of a UVGI system, *Escherichia coli* and *Serratia marcescens*, the reported $z$-values range from 0.17 to 0.72 m$^2$ J$^{-1}$ and from 0.02 to 2.2 m$^2$ J$^{-1}$, respectively [9,15–17]. The differences in reported values could be due to differences in the experimental setups (e.g. chamber versus in-duct setups) as well as in the environmental conditions (e.g. temperature and humidity).

The irradiance field produced by a UVGI system is not uniform in most cases and can be measured or calculated by the inverse-square law [18,19] or the view factor approaches [20,21]. However, UVGI fixture with inclined multi-louvres is normally used to generate collimated, parallel rays irradiating to the indoor upper region in order to shield the UV rays from being directly viewed by occupants. The shading of UV rays by the louvres was ignored in most studies owing to the complex configuration of the louvre, reflector and fixture geometries. In our previous work, a mathematical model based on radiation view factor approach was introduced to predict the irradiance field of a UVGI system [22]. The effects from both the inclined louvres and the fixture side walls have been taken into account, and the reflector was simplified by a fictitious plane surface to facilitate the view factor calculation.

Most previous work took the assumption that bioaerosols are distributed uniformly in the ventilated room to evaluate the effectiveness or performance of a UVGI system [9,11–13,23]. Therefore, the average concentration of bioaerosols within a space, e.g. a room, was adopted. However, it has been recognized that the air is not fully mixed in most real indoor environments. On the basis of this point, several multiple-zone mixing models have been developed [18,24,25]. In such kinds of models, indoor space is divided into two or three zones. For the two-zone model, irradiation is assumed to occur only in the upper zone. In a three-zone model, the field surrounding the contaminant source is added as a third zone. The concentration of bioaerosols in each zone field is assumed uniform, and the air flow is balanced in all zones by considering the flow rate through the zonal interface [18]. These models provide a simple approach to estimating the overall performance of an upper-room UVGI systems. Nevertheless, the complex spatial airflow pattern, the most significant factor on bioaerosols transmission in indoor environments, is not well accounted for in these models [26–31]. The flow rate of an air current that carries bioaerosols in a space can significantly affect the micro-organism’s residence time at the upper-room field, and thus affect the dose it accepts of the UV irradiation [2,14,32]. In this sense, numerical modelling based on first-principle transport theories that fully resolves the local airflow and bioaerosols concentration may be a better and more accurate way to study the performance of UVGI systems [19].

Actually, a Eulerian–Eulerian modelling approach, coupled with computational fluid dynamics (CFD), has become very popular in numerical studies of airborne particle’s transport in indoor environments. By this approach, both the carrier phase and the dispersed phase are treated as continuum. The local airflow is obtained by solving the mass, momentum, energy and turbulence transport equations. The particle spatial distribution is obtained by solving the concentration transport equation in such a way that all kinds of particle transport mechanisms such as convection, diffusion, settling and deposition can be accounted for easily. The drift flux model, which is a simplified form of the Eulerian methods, was developed for bioaerosols/particle dispersion simulation in indoor environments [33]. By being incorporated with the semi-empirical particle deposition model [34], it was further applied to analyse the bioaerosols dispersion in indoor environments [28,31,35–37].

The study described herein aims to develop the drift flux model to optimize the design of indoor upper-room UVGI systems. More comprehensive removal mechanisms such as convection, turbulence diffusion, deposition and UVGI inactivation for bioaerosols are incorporated into the model. The model predicts the bioaerosols distribution in a full-scale ventilation chamber equipped with a UVGI system. This model provides an efficient way to assess the performance of an upper-room UVGI systems and is very useful for practical engineering design.

2. METHODOLOGY

2.1. Mathematical model: the drift flux model

2.1.1. Air flow

The air flow in full-scale indoor environments is usually featured by turbulence. We adopted the renormalization group $k$-$\varepsilon$ model, which is more appropriate and
shows better agreement with the measured data than the standard \( k-e \) and other turbulence or laminar models [38,39]. Enhanced wall function was applied for the near wall region, as the maximal \( y^+ \) is less than 6.6 in the near wall region in our simulations. To achieve similarity of the model conditions with the real indoor environment, the exit angle of the air was set 45° inclined at the diffuser inlet. Thus, the flow from a real four-way diffuser is simulated.

2.1.2. Transport of bioaerosol droplets

According to the drift flux model, the airborne particle/droplet transport equation is

\[
\frac{\partial C_i}{\partial t} + \nabla \cdot [(u + v_{s, i}) C_i] = \nabla \cdot [(D_{i} + e_{p, i}) \nabla C_i] + S_i, \tag{2.1}
\]

where \( C_i \) is the particle concentration of particle size group \( i \), \( v_{s, i} \) is the particle settling velocity, \( e_{p, i} \) is the particle eddy diffusivity and \( D_{i} \) is the Brownian diffusion coefficient. For small particles, it is assumed that \( e_{p, i}/v_{i} \approx 1 \), where \( v_{i} \) is the carrier fluid turbulence viscosity. Several physical transport mechanisms of droplet (2 \( \mu \)m in diameter) transport are considered in equation (2.1), such as convection, turbulent diffusion and Brownian diffusion. Because thermophoresis force is evident only for ultrafine particles [37], thermophoresis is neglected herein.

The inactivation of bioaerosols by natural processes, deposition and UV irradiation are accounted for in the source or sink term of equation (2.1). \( S_i = S_{n, i} + S_{w, i, \text{uv}} \) where \( S_{n, i} \) and \( S_{w, i, \text{uv}} \) corresponds to natural die-off and deposition loss and UVGI mechanism, respectively. The sink term due to deposition and natural die-off is computed by

\[
S_{n, i} = -\left( \sum_{j} \frac{(v_{i, j} A_{w})}{V_{\text{cell}, i}} + k_{n} \right) C_{0, i}, \tag{2.2}
\]

where the summation in brackets is taken over all wall faces of the first layer grids near the wall; \( C_{0, i} \) is the local concentration of the near-wall cell. The local deposition velocity \( v_{i, d, i} \) is evaluated according to the three-layer model developed by Lai & Nazaroff [34], \( A_{w} \) is the face normal vector and \( V_{\text{cell}, i} \) is the cell volume.

The sink term of bioaerosols inactivated owing to UVGI can be evaluated as

\[
S_{w, i, \text{uv}} = -Z E_{p} C_{i}, \tag{2.3}
\]

given the fact that \( k_{w, i} \) is proportional to the irradiance intensity, \( E_{p} \) (W m\(^{-2}\)). The irradiance field from a UVGI fixture is predicted by the model proposed by Wu et al. [22]

\[
E_{p} = \sum_{i=1}^{N} I_{i, d, i} F_{d, i - 2, i}, \tag{2.4}
\]

where \( I_{i, d, i} \) is the UV output intensity of the fictitious subsurface corresponding to the \( i \)th slot. \( F_{d, i - 2, i} \) is the view factor between the observation point and the slot \( i \). Given the UV lamp output, the louvre and the fixture dimensions, the earlier-mentioned model predicts the irradiance intensity at any location in space. Details of the model can be found in the literature [22]. The spatial irradiation distribution of the UVGI system used in this study has been measured and modelled in our previous study [22] and very good agreement was found. A typical result at \( z = 2.05 \) m along centre line E–E of the chamber is shown in figure 1.

2.1.3. Numerical procedure

The solution of the particle transport equation (2.1), which includes the natural inactivation, deposition and UVGI disinfection mechanisms, was coded into the commercial CFD software FLUENT through user-defined subroutines. The pressure-implicit with splitting of operators algorithm was employed to decouple the pressure and velocity fields. The second-order upwind scheme was used to discretize the convective terms of all transport equations. The domain geometry and boundary conditions are configured to match the experimental settings. Uniform distribution of airborne bacteria was assumed initially. In all simulation cases, the steady air-flow field was obtained first, and then the transient transport equation for the particle concentration was solved with a time step of 0.1 s. Each case ran for 720 s. Grid-independence tests were performed with different numbers of non-uniform grids: 483 840; 699 360 and 815 920 cells. It was found that the air flow predicted by FLUENT for these meshes are almost the same (5% variation). To save calculation resources, 483 840 cells were used.

The test bacteria were assumed to be spherical with a diameter of 2 \( \mu \)m and a density of 1000 kg m\(^{-3}\). Owing to the low bioaerosol concentration measured in the experimental chamber, coagulation was assumed to be absent. Deposition of the particles was modelled as a flux towards the wall, as shown in equation (2.2).

Some variables were introduced as follows to describe the overall performance of the upper-room UVGI system. The fraction or percentage of bioaerosols disinfected by UVGI (\( P_k \)) after time \( t \) is defined by

\[
P_k = \frac{\int_0^t \int_0^1 \frac{S_{w, i, \text{uv}}}{C_{0, i}} dV \, dt}{C_{0, i} \int_0^1 dV} \times 100\%, \tag{2.5}
\]
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where $V$ is the volume of the room ($m^3$). Because $S_{uv,t}$ is the concentration of bioaerosols inactivated by UVGI in unit volume and in unit time, the numerator gives the accumulated amount of bioaerosols inactivated by UVGI system in the room after time $t$. The denominator gives the total amount of bioaerosols in the room. Similarly, the percentage of bioaerosols deposited on the wall surface and inactivated by natural mechanisms ($P_{DN}$) after time $t$ is

$$P_{DN} = \frac{- \int_0^t \int_U S_{uv,t} dV dt}{C_0 \int_U dV} \times 100\%, \quad (2.6)$$

and the percentage of bioaerosols removed by ventilation ($P_V$) after time $t$ is

$$P_V = \frac{\int_0^t \int_{A_o} vC_{o,t} dA dt}{C_0 \int_U dV} \times 100\%, \quad (2.7)$$

where $v$ is air velocity at the outlet, $C_{o,t}$ is cell concentration at the outlet and $A_o$ is the outlet area.

It is straightforward to get the percentage of total suspended bioaerosols ($P_S$) in the room at time $t$

$$P_S = \frac{\int_U C_{a,t} dV}{C_0 \int_U dV} \times 100\%. \quad (2.8)$$

2.2. Experiments

All experiments were conducted inside a mechanically ventilated, environmentally controlled chamber of $2.25 \times 2.3 \times 2.3$ m$^3$ ($L \times W \times H$). The structure of the chamber and locations of the sampling points are shown in figure 2. A UVC germicidal fixture (TB-12-W, American Ultraviolet) was mounted at the centre of one of the side walls. The UVC fixture holds a 16-W UVC lamp. Detailed measurement of UVC irradiance was as reported previously [22]. The external walls of the chamber are fibreglass-insulated, and there is one door and no windows. HEPA-filtered clean air is supplied by a conventional ventilation system through one ceiling-mounted four-way diffuser. There is one ceiling-mounted outlet. The temperature and relative humidity of the chamber were controlled and monitored during the experiments.

2.2.1. Generation and collection of airborne bacteria

*Escherichia coli* (ATCC 10536) and *S. marcescens* (ATCC 6911) are Gram-negative bacteria used in testing bioaerosols. *Escherichia coli* is regarded as highly susceptible to UVGI and are commonly used bioaerosols in UVGI system design [14,17,40]. Stock solutions of *E. coli* and *S. marcescens* were inoculated into nutrient agar plates (Oxoid), and the plates were incubated at 30°C for 24 h. The incubation and harvesting methods were as described by Lai et al. [17] and Wong et al. [41]. The harvested cells were then transferred to 50 ml sterilized distilled water in a 24-jet collision nebulizer (BGI) for aerosolization. The final bacteria concentration was $10^8$ CFU ml$^{-1}$.

Airborne bacteria were aerosolized from the nebulizer, which was operated at 138 kPa with filtered compressed air. The nebulizer was placed in a ventilated chamber next to the test chamber, and the airborne bacteria were delivered at breathing level (1.68 m above the floor) into the centre of the test chamber through a permanently installed copper pipe. The delivery site was located between the air supply and exhaust, in accordance with the CDC’s recommendation that clean air should first flow to less-contaminated areas, then flow across the infectious source and into the exhaust [12].

A Reuter Centrifugal Sampler was used for bioaerosol sampling and was also placed in a ventilated chamber next to the test chamber. It operates on the principles of centrifugation and impaction; air is drawn via the impeller at 50 l min$^{-1}$, and the bioaerosols in the air are deposited onto the surface of agar strips (tryptic soy agar), which are placed inside the impeller. A 50 l air sample was collected for each testing, and preliminary results showed that this sampling volume was negligible when compared with the volume of chamber.

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A decay method was used to evaluate the UVGI inactivation effects [12,14]. Prior to each experiment, the mechanical ventilation system equipped with two HEPA filters was turned on for 1 h at an air-change rate (ACH) of 6 to remove the background bioaerosols. A 500 l sample was obtained before and after the cleaning process to verify the absence of bacteria in the air. The aerosolization was stopped after the steady state of air concentration of bacteria was reached, i.e. at 30 min according to preliminary test results. It is very important to create a homogeneous mixing before experiments, an air-mixing fan (55 W) was placed on the floor inside the chamber and turned on for the last 5 min of aerosolization to ensure that air in the chamber was close to well mixed at the initial condition.

2.2.2. Determination of the decay rates and z-values
To determine the different decay rates equation (1.1), several air samples (50 l) were obtained within 30 min under the following conditions: no UVGI and no ventilation (UVGI off and ventilation off) ($k_n$); UVGI off and ventilation on ($k_v$); UVGI on and ventilation off ($k_{uv}$). Each experimental condition was repeated at least twice for sampling at three different sampling points (points A, B and C) and at two heights (1.68 and 2.05 m); 1.68 m was taken to represent the breathing level in the non-irradiance zone, whereas 2.05 m was taken to represent the upper air zone with the highest UV intensity. Prior to the experiment with UVGI, the UVC germicidal fixture was warmed up for at least 30 min and shielded with a black paper cover. The cover was attached to a rope that extended outside the chamber, and, to achieve UVGI-on conditions, the cover was removed by pulling the rope. Studies have shown that the effectiveness of an upper-room UVGI system is much more obvious at relatively low ventilation rates than at higher rates [18,19,42]. Hence, for our first experimental and numerical study for predicting the inactivation effectiveness of the UVGI system on bioaerosols, an ACH of 2.9 was used for 71 ± 6% relative humidity.

In addition, the z-values for *E. coli* and *S. marcescens* were determined under the UVGI-on ventilation-off condition at 2.05 m and calculated as the normalized equivalent air-change rates (EACs) to the average $E_p$ [11,43]

$$Z = \frac{\ln C_{\text{off}}/C_{\text{on}}}{D} = \frac{E_{\text{AC}}}{E_p}, \quad (2.9)$$

where $C_{\text{on}}$ and $C_{\text{off}}$ are the concentrations of bioaerosols measured under UVGI-on and UVGI-off conditions; $E_p$
is the mean irradiance of the UV-effective zone; \( D (J \, m^{-2}) \) is
the UV dose, defined as \( E_p \) times \( t \).

3. RESULTS

3.1. Natural die-off rates \((k_n)\) and \(z\)-values of the test bioaerosols

The patterns of natural die-off of \( E. coli \) and \( S. marcescens \) at \( z = 1.68 \, m \) and \( z = 2.05 \, m \) are shown in figure 3a,b and figure 4a,b, respectively. Assuming well-mixed air, the slope of \( \ln(C) \) concentration regressed over time gives the values of \( k_n \). The mean \( k_n \) of \( E. coli \) was 4.74 and 4.56 \( (\text{s}^{-1}) \) at \( z = 1.68 \) and 2.05 \, m, respectively, whereas the mean \( k_n \) of \( S. marcescens \) was 5.66 and 13.48 \( (\text{s}^{-1}) \) at \( z = 1.68 \) and 2.05 \, m, respectively.

Because \( k_n \) at different heights varied within one magnitude, taking the experimental uncertainty into consideration, it is assumed that the \( k_n \) remains constant. Consequently, the mean \( k_n \) of \( E. coli \) and \( S. marcescens \) can be determined from the overall value and were 4.65 and 9.57 \( (\text{s}^{-1}) \), respectively.

It has been demonstrated that \( E_p \) can be evaluated according to the mean irradiance in the UV-effective zone upon application of an upper-room UVGI system [14]. In our cases, the irradiance was recorded in the UV-effective zone in the upper-room area (\( z = 2.0–2.1 \, m \)) only and the detailed measurement results of the irradiance at different points of the chamber were presented in our previous study [22]. Hence, the \( k_{uv} \) determined at 2.05 \, m was used to calculate the \( z \)-value, and \( E_p \) was calculated by the predicted irradiance in UV-effective zone. By using the data shown in figure 3c,d and figure 4c,d, the calculated \( z \)-values of \( E. coli \) and \( S. marcescens \) were 0.044 and 0.089 \, m\,J\,^{-1}, respectively, equation (2.9).

3.1.1. Modelling results

With the measured \( z \)-value and natural die-off rate \( k_n \), the improved drift flux model is ready to predict the temporal and spatial distribution of bioaerosols under two different conditions that match the experimental setup.

Case 1: Ventilation only. To investigate the ventilation removal effect, the ventilation system was turned on after aerosolization, and UVGI was turned off in the experiment. Decay curves of the test bacteria obtained at sampling sites A, B and C by numerical simulation are compared with experimental measurements, as shown in figure 5.

It can be seen that the \( E. coli \) concentration decays more quickly at site B than at the other two sampling points at \( z = 1.68 \, m \). This is also observed for \( S. marcescens \). This trend is well captured by the numerical model (figure 5a,c). In the upper zone (\( z = 2.05 \), the
measured decay rates are almost the same at sites A and B, but much lower at site C for both *E. coli* and *S. marcescens*. In the upper zone (\(z = 2.05\)), sites A and B are much closer to the inlet than site C. The fresh air induced by the inlet dilutes the concentration more quickly, while in the lower zone (\(z = 1.68\)), such dilution effect by the inlet becomes much weaker. It should be noted that the ventilation scheme is well-mixing. This implies that ventilation is an important factor that affects aerosol distribution indoors, as reported in the literature [28,31,44]. However, our simulation results show similar decay trends for sites A and C in both elevations. This discrepancy may be caused by the under-prediction of turbulence near the inlet by the model, as the strong turbulence induced by the four-way diffuser is difficult to model. Future comprehensive tests on airflow are required to confirm the cause of the discrepancy.

**Case 2: UVGI with ventilation.** In this case, the UV lamp was turned on during the experiment while the source terms due to the inactivation by UVGI was calculated in the transport equation (2.1) in the numerical simulation. The time series of the normalized local concentration at points A, B and C at \(z = 1.68\) and 2.05 m are illustrated in figure 6.

Compared with ventilation cases, *E. coli* decays more quickly at the \(z = 2.05\) m plane under UVGI with ventilation (cf. figures 5b and 6b). There is a significant difference in the concentrations monitored at points A and C, probably due to the much greater irradiance intensity at point A than at point C at this plane (\(z = 2.05\) m). As the \(z\)-value of *S. marcescens* is higher than *E. coli*, the concentration ratio of *S. marcescens* at point A fell below 0.3 before \(t = 120\) s, and it took a longer time for the concentration of *E. coli* to reach dimensionless concentration 0.3. The numerical results agree well with the measured value, especially at \(z = 2.05\) m.

In comparing case 2 (figure 6) with case 1 (figure 5), the concentration of both bacteria decays quicker under UVGI than under ventilation only at the UV effective plane at \(z = 2.05\) m; this is mainly due to the inactivation effect of the UVGI system. However, it is very interesting to note that the decay rate of airborne bacteria at the \(z = 1.68\) m plane also improved. This improved decaying trend is more prominent in the first 120 s and in the region near the inlet. This implies that although irradiance was recorded in the UV effective-zone only, disinfection occurs when the airborne bacteria travel to the upper-zone from the breathing zone under a well-mixed ventilation scheme. The precise practical value of the system rests in this property, because the UVGI system is not to be installed at a low level that would present a risk of human exposure.
Furthermore, during the simulation process, the local spatial disinfection rate achieved by UVGI ($S_{\text{uv},i}$) was calculated and saved at the end of each time step. The disinfection rate equation (2.5) is obtained by integrating the CFD grid data over the space and the flow time.

I t is a n important h a t $S_{\text{uv},i}$ is not perfectly correlated to the irradiance field, and much lower values are found near the air inlet. This is more evident for $S. marcescens$ than for $E. coli$ (figure 7a,c). This result proves that the UVGI efficacy is significantly affected by the air-flow pattern even under a well-mixed ventilation condition.

The $S_{\text{uv},i}$ contour at the central plane of the room ($x = 1.15$ m) revealed that the disinfection occurred in the effective irradiance zone.

### 3.1.2. Overall simulation result

The overall simulation results are given in figure 8. In case 1, the natural die-off rates of $E. coli$ and $S. marcescens$ differ, although the ACH is the same. The $P_{DN}$ of $E. coli$ and $S. marcescens$ after 720 s are 24.1 and 40.3 per cent, respectively, whereas the $P_S$ of $E. coli$ and $S. marcescens$ obtained by equation (2.8) are 36.2 and 25.4 per cent, respectively (figure 8a,d). It is observed that $E. coli$ survives more easily owing to its lower natural die-off rate; however, $E. coli$ removed by the ventilation is higher. The $P_V$ of $E. coli$ and $S. marcescens$ after 720 s were 40 and 34.3 per cent, respectively (figure 8c).

In case 2, owing to the inactivation effects of the upper-room UVGI system, the percentage of suspended $E. coli$ and $S. marcescens$ concentrations were lower than in case 1. After 720 s, the $P_S$ of $E. coli$ and $S. marcescens$ were 26.8 and 16.0 per cent, respectively, and the $P_V$ were 33.6 and 26.5 per cent, respectively (figure 8a,c). As the $z$-value of $E. coli$ was smaller than that of $S. marcescens$, the $P_K$ of $S. marcescens$ and $E. coli$ after 720 s were 23.3 and 18.0 per cent, respectively (figure 8b). In this case, the $P_{DN}$ of $E. coli$ and $S. marcescens$ after 720 s were smaller than that recorded in case 1, and they were 21.6 and 34.2 per cent, respectively, with UVGI operating (figure 8d).

### 4. DISCUSSION

We performed a full-scale experiment to determine the natural die-off rates and susceptibility constants for both $E. coli$ and $S. marcescens$ under an upper-room UVGI system. The results show that $S. marcescens$ was more vulnerable to disinfection by UVGI. The
-value of *E. coli* obtained in this study was lower than the values reported previously while the z-value of *S. Marcescens* was within the range reported in the literatures [9,15–17].

Our modelling approach consists of two parts, one for predicting the UV irradiance intensity in space for an upper-room UVGI system and the other for predicting the bioaerosols spatial concentration by considering a variety of transport and fating mechanisms in an indoor environment. The former accounts for the shading effects from both the fixture side walls and louvres. The latter is based on the well-developed drift flux model and accounts for ventilation, natural die-off, deposition and UV inactivation removal mechanisms. In recently reported studies, micro-organisms have been treated as particles, but natural die-off rates have been neglected [19]. In our model, natural die-off, deposition and UVGI disinfection were considered. The simulation results showed that the concentration of airborne bacteria was lower in the indoor space near the inlet or with high irradiance; Both *E. coli* and *S. marcescens* decay much more quickly in these regions, and the concentration becomes less than 50 per cent of the original ambient value in 2 min. Thus these indoor regions can be considered as droplet-free zones. This observation implied that both air-flow and irradiance distribution play dominant roles on the transport of airborne bacteria. The disinfection rates of *E. coli* and *S. marcescens*, as we introduced to measure the spatial UVGI inactivation effect, revealed that the UVGI disinfection to airborne bacteria is limited to the upper-room irradiance effective zone. However, the strong ventilation near the inlet

![Figure 7. Contour plots of \( S_{\text{uv},i} \) at 120 s: (a) *E. coli* at \( z = 2.05 \) m; (b) *E. coli* at \( x = 1.15 \) m; (c) *S. marcescens* at \( z = 2.05 \) m and (d) *S. marcescens* at \( x = 1.15 \) m.](http://rsif.royalsocietypublishing.org/Downloaded from on June 20, 2017)
dilutes the concentration of bioaerosols and may diminish the UVGI efficiency. The assumption of a uniform concentration in space made by the previous studies, apparently, cannot tackle this effect. The UVGI performance may not be estimated accurately when it is applied under different ventilation conditions and thus the human exposure risk may increase. It is straightforward to infer from the results of the present study that a single UVGI fixture should not be installed near the inlet diffuser to maximize its performance otherwise.

Similar E. coli and S. marcescens decay patterns were found at $z = 1.68$ and $2.05$ m plane under a well-mixed ventilation scheme without UVGI. Under UVGI with ventilation, although the bioaerosols are exposed to irradiance only in the upper zone, UVGI also can sterilize the air below breathing level owing to circulation and turbulence of the indoor air. When the ventilation rate is lower, airborne particles have a larger residence time indoors, and will be exposed to the irradiance zone longer and receive a higher UV dose. Thus the relative effectiveness of UVGI systems will be greater, for example, during the winter time when windows are closed in many regions.

With the use of an upper room UVGI system, suspended airborne bacteria can be effectively reduced. Compared with the case of ventilation only, our simulation results show that the suspended fraction ($P_s$) of E. coli and S. marcescens were reduced by another 9.4 per cent of the total amount at 720 s, which means an additional improvement of removal by 25.9 and 37.0 per cent, respectively (figure 8). The additional reduction was due mainly to inactivation by UVGI. As exactly shown in figure 8c,d, all the bacteria removal mechanisms are coupled and the other mechanisms such as ventilation and deposition become weaker when UVGI is turned on. The inactivation of bioaerosols cannot be simply obtained by superimposition of all mechanisms. In previous studies, inactivation by UVGI might be over-estimated because a completely mixed room air condition was assumed [9,13].

5. CONCLUSIONS

We developed an improved model to evaluate distribution of the UV irradiance intensity and bioaerosols in indoor environment with an upper-room UVGI system. The UVGI inactivation efficiency was also analysed. To our knowledge, this is the first application of the drift flux model in describing the performance of an upper-room UVGI system. The model predictions match well with the experimental results. The model was shown to be useful in assessing the performance of an upper-room UVGI systems and may help engineering design. The model not only predicts the...
concentration of spatial bioaerosols but can also is able to describe the overall performance of an upper-room UVGI system.

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