Modelling the Performance of Upper Room Ultraviolet Germicidal Irradiation Devices in Ventilated Rooms: Comparison of Analytical and CFD Methods

Running Head: Modelling upper-room UVGI devices

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Abstract

Models to evaluate upper room ultraviolet germicidal irradiation (UVGI) devices can be used to improve the understanding of the behaviour of UV devices in ventilated rooms, and to enable more confident predictions to be made of their performance. This paper presents two- and three-zone mixing models for investigating the effect of upper room UVGI devices in a typical ventilated room. The results from these analytical models are compared to a CFD simulation of the same room that incorporates the biological inactivation of microorganisms in the presence of an ultraviolet field. The study demonstrates that analytical mixing models give reasonably good average zone concentrations and are therefore useful in estimating overall performance. However, CFD simulations are necessary to fully examine the interaction of the room airflow with the inactivation of microorganisms due to the UV field.

Keywords: CFD, mixing models, airborne infection, ultraviolet, ventilation,

INTRODUCTION

Transmission and control of airborne infection

Airborne transmission is a significant mechanism of infection for many diseases, including childhood infections such as measles, mumps and chickenpox as well as bacterial infections such as tuberculosis. Aerosolised infectious agents may be introduced to the air through actions such as coughing, sneezing and vomiting, which release large numbers of contaminated droplets. These droplets evaporate leaving the infectious agent in the form of *droplet nuclei* [1], which can remain suspended in air for many hours, with the potential to infect anyone in the vicinity.

The airborne route of infection is of particular concern in hospitals where it has been implicated in nosocomial outbreaks of *Staphylococcus aureus* (including MRSA) [2,3,4] and *Acinetobacter* spp. [5,6]. It is also thought that the high attack rates experienced during Norovirus outbreaks in hospitals may be due to dispersion via aerosols [7]. The threat of bioterroism has also heightened awareness of the risks posed by airborne infections such as anthrax [8]. These concerns together with the global rise in tuberculosis (TB) [9], in particular the increased prevalence of drug-resistant strains [10,11], have prompted a resurgence of interest in using engineering measures to control airborne pathogens. This interest includes the use of upper room

ultraviolet germicidal irradiation (UVGI) devices to disinfect indoor air. Such devices emit ultraviolet light at wavelengths close to 254 nm, which causes lethal damage in the DNA of microorganisms.

Early investigations into the use of UV-C irradiation to disinfect room air were carried out by Wells *et al.* [1], who demonstrated that upper room UV devices were effective in reducing the incidence of infections such as measles in school children. Riley *et al.* [12] carried out further studies demonstrating the ability of upper room UVGI to reduce the concentration of airborne *M. tuberculosis* and the *Bacille Calmette-Guerin* (BCG) strain of *M. bovis* in enclosed spaces. In the 1990's a resurgence of interest in UVGI prompted a number of experimental studies into the effectiveness of upper-room UVGI systems under a range of climatic conditions [13,14,15]. Small-scale experimental studies have also been undertaken which demonstrated that relative humidity can significantly affect the susceptibility of microorganisms to ultraviolet light and that this effect varies between different microorganisms [16,17]. Photoreactivation effects, where sub-lethally damaged microorganisms self-repair in the presence of visible light, have also been shown to influence the UV susceptibility of airborne microorganisms [18,19].

Ventilation Models

The contamination and subsequent ventilation of air can have a significant impact on the airborne spread of infections in both individual rooms and entire buildings. In most cases the air in rooms is not fully mixed, with short-circuiting occurring that may lead to contaminant concentration gradients and potentially high-risk areas in some environments. In addition to the above experimental studies a number of authors have developed analytical models to examine the effect of UVGI systems in both fully and partially mixed rooms [20,21,22,23]. These studies are generally based on zone-mixing models [24,25] which can be used to estimate contaminant concentrations and the effectiveness of ventilation systems at removing contaminants in cases where short-circuiting occurs. These types of models can be used to estimate concentrations in different regions of a single room, or in a series of interconnected rooms within a building. In the case of a single room, these models assume that the space is divided into two or more zones, with the air in each zone being fully mixed, but with incomplete mixing between the zones.

Zone-mixing models applied to the analysis of upper room UVGI systems define upper room zones that contain a UV field and lower room zones that do not. Riley

and Permutt [20] presented a two zone transient model for the decay of airborne microorganisms in the presence of a UV field, which they used in the evaluation of their data. Nicas and Miller [21] recognised that high contaminant concentrations are generally present close to the contaminant source and proposed a transient three-zone model with upper and lower room zones and a near field zone around an infectious patient. They applied this model to existing experimental data in a ventilated room and highlighted that incomplete mixing limited the effectiveness of upper-room UVGI devices at reducing the airborne concentration close to the source. Beggs and Sleigh [22] developed models for both a fully mixed and a two-zone room, for one particular ventilation regime. Their theoretical study examined the relationship between inter-zonal air velocity and room ventilation rate, and showed that upper room UVGI devices are more beneficial in rooms with low ventilation rates. This was also shown in a more recent study by Noakes et al [23], who used a steady-state two zone model to examine the impact of the ventilation regime on the effectiveness of upper-room UVGI devices.

CFD models

The zone-mixing models described above are useful for estimating exposure to airborne contaminants in rooms and the efficiency of a ventilation system, however they do not take into account the variation of room air velocities or allow regions of exceptionally high or low concentrations to be identified. More accurate assessments of bioaerosol concentrations in rooms may be made using computational fluid dynamics (CFD) analysis software to find solutions to the momentum, energy transport and turbulent energy equations, which govern the complex 3-D airflows in ventilated rooms. Results from such simulations enable variables of interest such as air velocity, pressure and temperature to be analysed in the room for a given set of boundary conditions.

CFD modelling has gained favour amongst building and ventilation designers over recent years, and has been applied in many studies to assess room airflows, comfort factors and contaminant dispersal [26,27]. However CFD modelling of the effect of UV lamps on airborne microorganisms has so far received little attention. Memarzaeh [28] and Alani *et al.* [29] both used particle-tracking methods to model the effectiveness of upper room UV fields in typical isolation rooms. An alternative method, used in this study, was described by Noakes *et al* [30]. This method couples the UV inactivation equation with a scalar transport equation for the contaminant dispersion. This enables the germicidal effect of the UV field to be examined for the

whole of the room space by allowing it to be shown as concentration contours or 3D surface plots.

The main objective of this paper is to compare the concentration of microbial contaminants in a ventilated room, predicted using simple zone-mixing models, with the results produced by CFD simulations. Two and three zone models of a typical ventilated room are modified to incorporate the effect of upper room UV lamps on microbial contaminant removal, and expressions are developed for steady-state contamination. These analytical models are compared to the results of CFD simulations of a typical UV fixture located in a 32 m^3 ventilated room. Results are presented to show the relative merits of both the analytical and numerical approaches and to estimate the accuracy of predictions from the analytical models for the study case.

ANALYTICAL UV INACTIVATION MODELS

Two-Zone Model

A schematic of a two-zone model of a typical ventilated room with an upper-room UV field is shown in Figure 1. The room is divided into two zones, volume V_1 and V_2 m^3 with a ventilation flow rate, Q m^3/s into zone 2 (lower) and out of zone 1 (upper). The short-circuiting caused by non-ideal ventilation and resulting in incomplete mixing is represented by an inter-zonal flow rate, Q_{ex}, given by

$$Q_{ex} = \beta Q \tag{1}$$

β is a dimensionless mixing factor, which describes the inter-zonal air flow rate relative to the absolute room ventilation rate. The higher the value of β, the more times the air is exchanged between the zones and the better the room mixing. The inter-zonal flow rate can also be defined as [22]

$$Q_{ex} = \frac{A v_{\text{int}}}{2} \tag{2}$$

where A (m^2) is the cross-sectional area of the interface and v_{int}(m/s) is the inter-zonal velocity. In the case modelled here the ventilation is a piston type regime [24], so the zone transfer rate in the overall ventilation direction is $(1+\beta)Q$ to reflect both the main ventilation flow and the effect of short circuiting. It is assumed that the UV field is in the upper zone only with a constant irradiance, E (W/m^2), and that the contamination is injected uniformly into the lower zone only, at a rate of q colony

forming units per second (cfu/s). These inputs and outputs to the room result in overall contaminant concentrations C_1 and C_2 (cfu/m^3) in the upper and lower zones respectively.

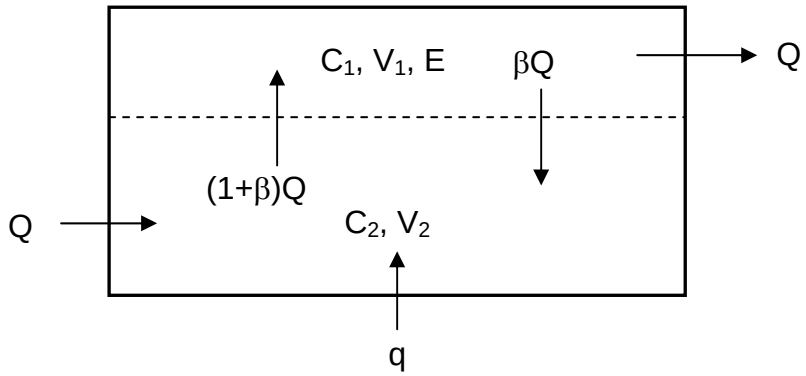


Figure 1: Schematic of a two-zone ventilation model with an upper room UV field

With UV disinfection in the upper zone (zone 1) and clean supply air, the contaminant concentration in each zone may be expressed by the following equations

$$V_1 \frac{dC_1}{dt} = (1+\beta)QC_2 - \beta QC_1 - QC_1 - ZEV_1C_1 \quad (3)$$

$$V_2 \frac{dC_2}{dt} = q + \beta QC_1 - (1+\beta)QC_2 \quad (4)$$

The rate of contaminant removal by UV irradiation is represented by the final term in equation (3)[20], which when integrated in the absence of other removal mechanisms yields the familiar first-order decay equation

$$C(t) = C_o e^{-ZEt} \quad (5)$$

Here C_o is the initial concentration in the space and Z (m^2/J) is the UV susceptibility constant of the study microorganism. The value of Z can be found experimentally using an aerosol test rig such as that described by Fletcher *et al*. [19], and depends on the species and strain of microorganism present, as well as physical conditions such as temperature and humidity. Typical values of Z for a range of microorganisms are given in several papers including Kowalski *et al*. [31] and Peccia *et al*. [17]. The effectiveness of the UV-C devices is also hampered by the presence of visible light, which can induce repair mechanisms in sub-lethally damaged microorganisms [32].

This photoreactivation may be included in the susceptibility constant for a particular case [18] or added in to the decay equation as an additional term [32].

Under steady state conditions, the rate terms dC_1/dt and dC_2/dt in equations (3) and (4) are zero, leaving contaminant balance expressions that can be solved to yield the expressions for C_1 and C_2,

$$C_1 = \frac{q}{Q + K} \tag{6}$$

$$C_2 = \frac{q(Q + \beta Q + K)}{Q(Q + K)(1 + \beta)} \tag{7}$$

where the UV contaminant removal constant ZEV_1 is denoted by K.
The resulting values can be volume averaged to find the overall room concentration, C, which is given by equation 8 when $V_1 = V_2$

$$C = \frac{q}{2Q}\frac{(2Q + 2\beta Q + K)}{(Q + K)(1 + \beta)} \tag{8}$$

With no UV irradiation ($K=0$) the above expressions reduce to general room mixing equation such as those given by Brouns and Waters [24].

Three-Zone Model

The two-zone mixing model can be modified to include a third zone containing the contaminant source, as proposed by Nicas and Miller [21]. This case is shown schematically in Figure 2.

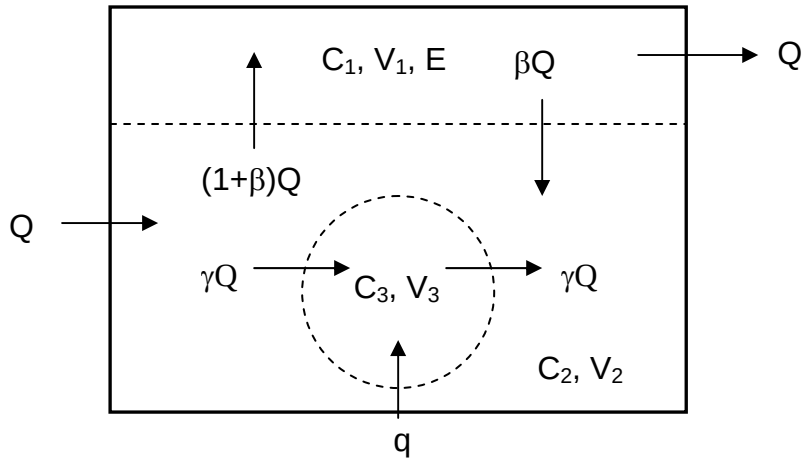


Figure 2: Schematic of a three-zone ventilation model with an upper room UV field

As with the two-zone model it is assumed that the UV field is in the upper zone with a constant irradiance, *E* (W/m^2), but in the three-zone model the contamination is injected uniformly into zone 3 at a rate of *q* cfu/s. The inter-zonal transfer between the upper and lower zones (1 and 2) is still represented by βQ and $(1+\beta)Q$, where as the transfer between the lower and near-source zones (2 and 3) is denoted as γQ, where γ is a second mixing factor. It is assumed that the near-source zone (zone 3) is located such that there is no direct transfer of air between this zone and the upper zone (zone 1). With clean supply air, the contaminant concentration in each zone is now given by:

$$V_1 \frac{dC_1}{dt} = (1+\beta)QC_2 - \beta QC_1 - QC_1 - ZEV_1C_1 \quad (9)$$

$$V_2 \frac{dC_2}{dt} = \beta QC_1 + \gamma QC_3 - (1+\beta)QC_2 - \gamma QC_2 \quad (10)$$

$$V_3 \frac{dC_3}{dt} = q + \gamma QC_2 - \gamma QC_3 \quad (11)$$

As in the two-zone model, steady-state solutions can be found for equations 9 to 11 by setting $dC_i/dt = 0$. This yields the following expressions for the contaminant in each zone:

$$C_1 = \frac{q}{Q+K} \quad (12)$$

$$C_2 = \frac{q(Q+\beta Q+K)}{Q(Q+K)(1+\beta)} \quad (13)$$

$$C_3 = \frac{q((1+\beta)(Q+K)+\gamma(Q+\beta Q+K))}{\gamma Q(Q+K)(1+\beta)} \quad (14)$$

CFD MODEL WITH UV INACTIVATION

The CFD model was formulated using the CFX 5.5.1 software package for a 32m^2 room with the same ventilation regime as in the above analytical model. This model is of an existing mechanically ventilated, climatically controlled aerobiology test room at the University of Leeds, which is used to carry out experiments on airborne microorganisms. A schematic of the room is shown in Figure 3.

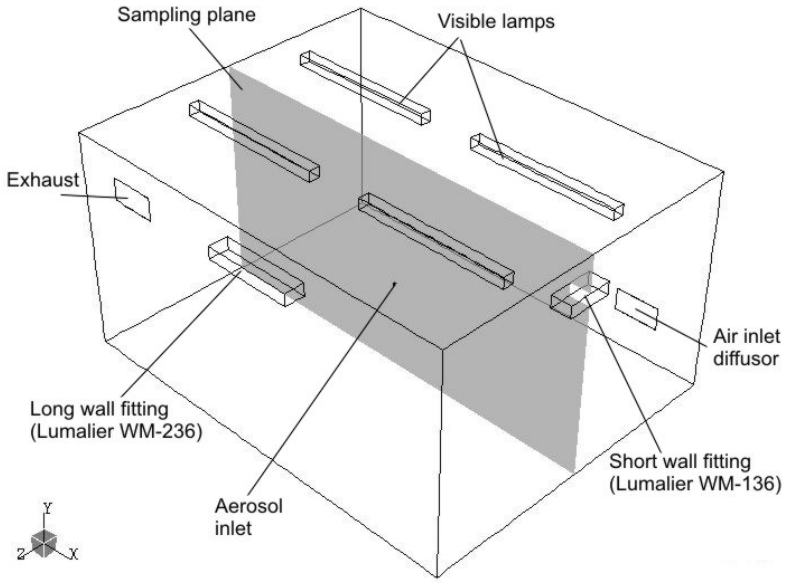


Figure 3: Schematic of the ventilated test room, showing UV fittings and inflow/outflow boundaries

The room simulation was carried out using a tetrahedral grid containing approximately 350000 cells, refined at the walls and around features. The model was based on a Reynolds Averaged Navier-Stokes (RANS) formulation of the governing equations with the turbulence modelled using a standard κ-ε turbulence model with a medium intensity of 0.5 at the air inlet. The inlet diffuser grill was modelled by a series of velocity profiles representing the angled louvers, with the total flow rate defined by an air change rate. A static pressure was imposed at the exhaust, and the no slip condition applied on all the walls. All the simulations were assumed to be isothermal as during real experiments the inlet air temperature is generally close to the indoor ambient value, the visible lamps are switched off and the room contains no other significant heat sources.

The distribution of airborne microorganisms was included in the CFD model by representing them as a scalar concentration that moves only with the airflow. As aerosolised microorganisms are generally very small (typically 5 μm in diameter), and can remain suspended in air for many hours, it was not considered necessary to represent them as a separate phase in the CFD model. The inactivation of microorganisms due to the UV is coupled with the scalar transport equation, as shown in Noakes *et al.* [29] to give

$$\frac{\partial \phi}{\partial t} + \nabla \bullet (\underline{U}\phi) - \nabla \bullet (D\nabla \phi) - ZE_p\phi = 0 \qquad (15)$$

Here;

ϕ is the concentration of microorganisms per unit volume (cfu/m^3)

$\underline{U}$ = *(u,v,w)* is the velocity of the transportive fluid, ie. air (m/s)

D is the kinematic diffusivity (m^2/s)

The final term in equation (15), $ZE_p\phi$, is a sink term that describes the rate of inactivation due to the UV field, where E_p is the UV irradiance at a point P in the room, and *Z* is the microorganism UV susceptibility constant as defined previously.

In the actual experimental facility, aerosolised microorganisms are generated by a 6-jet Collison nebuliser (CN 25, BGI Inc, USA) and enter the centre of the room through a tube with a perforated ball at the end to distribute the microorganisms evenly in all directions. This aerosol inlet was represented in the CFD model by a small cube in the centre of the room with an air velocity of 1m/s and a microorganism concentration of 500 cfu/m^3 defined at each surface. These values were based on the known performance of the nebuliser and resulted in a total microorganism input rate of 1.2 cfu/s. The room contains two UVGI devices, a short wall fitting (Lumalier WM-136) and a long wall fitting (Lumalier WM-236) which may be used individually or together to produce three UV fields.

Solution of the scalar transport equation (15) was carried out together with the fluid momentum and energy equations to allow the effect of both the airflow and the UV irradiation field on the microorganism distribution in the space to be analysed. In all the simulations 2nd order discretization of the governing equations was used and the simulations were considered to be converged when the RMS residuals for all equations were less than 5x10^{-6} and the global imbalance in the transported scalar (microorganism concentration) was less that 0.1%. To compare the CFD results with those from the analytical models, simulations were carried out to model the microbial contaminant levels under steady-state conditions, with and without the influence of UV lamps. The removal of microorganisms due to natural decay is not included in either the CFD or analytical models.

RESULTS

CFD simulations and analytical calculations were carried out for ventilations rates of 3, 6 and 9 air changes per hour (AC/h) for the four UV irradiances shown in table 1.

UV fitting	No UV	Short wall	Long wall	Long + Short wall
Average upper zone irradiance (W/m^2)	0	0.0494	0.0706	0.120

Table 1: Four UV field arrangements with average upper zone UV irradiances used in analytical solutions

In each case the room height was 2.26m with the UV zone (zone 1) assumed to occupy the upper 0.5m of the room space. In the three-zone model the near-source zone was taken as a sphere of radius 0.4m located centrally in the room, at the point where the microorganisms were introduced. Steady-state CFD solutions were found by assuming the contamination of the room space was continuous for all time, and all the solutions were found for a microorganism with a UV susceptibility constant Z = 0.1 m^2/J, a value typical for airborne *Serratia marcescens* [19].

The UV irradiation field, E_p, for the two upper-room UV devices was modelled in the CFD simulations by fitting empirical equations to the manufacturers' photometric data allowing the irradiation field to be determined at any point in the room. The UV irradiances quoted in Table 1 are average values for the upper zone, calculated using the CFX software. In the analytical model this average value is applied across the whole upper zone. Figure 4 shows the combined UV field for both devices plotted on a horizontal plane through the centre of the devices at a height of 2.05 m.

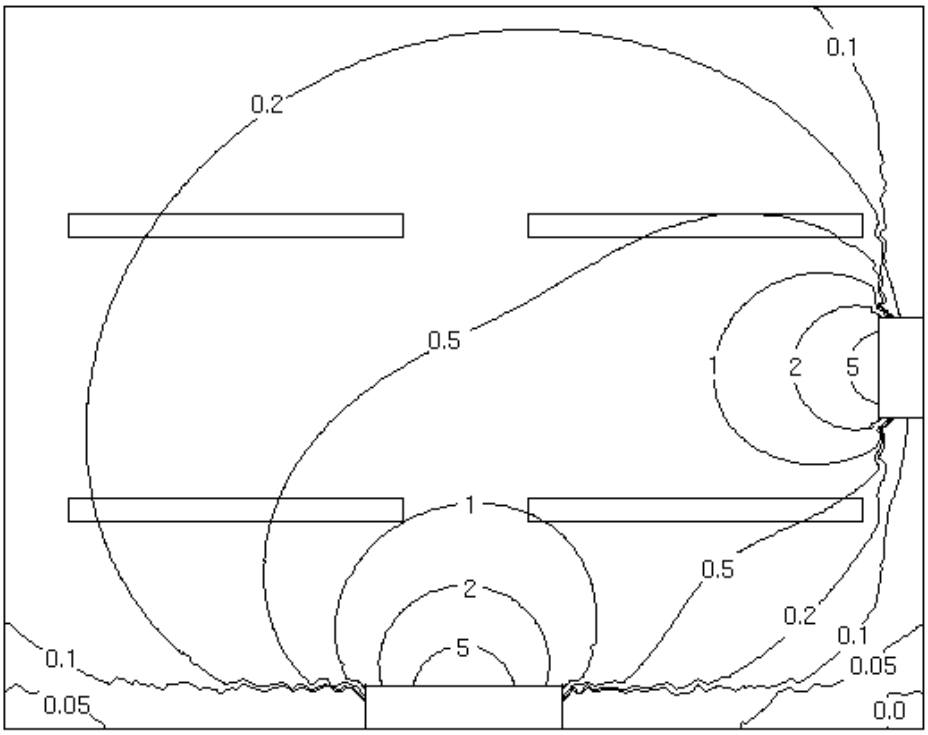


Figure 4: Combined UV irradiance field for both UV devices.
Irradiance contours in W/m^2.

Evaluation of mixing factors

In order to compare any solutions from the analytical models with CFD simulations, suitable mixing factors β and γ must first be established for use in the analytical models. In a real room, the value of β can be determined using equations (1) and (2) together with the average vertical velocity measured at the upper-lower zone interface. In the absence of measured data, the inter-zonal velocity (v_{int}) can be calculated from the CFD solution as the average absolute vertical velocity across a plane separating the upper and lower zones, as shown in table 2. From this value and the ventilation flow rate it is possible to calculate the values of β, also given in table 2.

AC/h	Q (m^3/s)	A (m^2)	v_{int} (m/s)	β
3	0.026875	14.27	0.01338	3.55
6	0.053767	14.27	0.02792	3.70
9	0.080625	14.27	0.039858	3.53

Table 2: Calculated values of β from CFD solutions.

Suitable values of β can also be found by comparing the microorganism concentration from a CFD solution with analytical solutions. Figure 5 uses the two-zone analytical model (equations 6 and 7) to examine the effect of the mixing factor, β, on the concentrations in the upper and lower zones of the room at an air change rate of 6 AC/h and an average upper zone irradiance of 0.12 W/m^2.

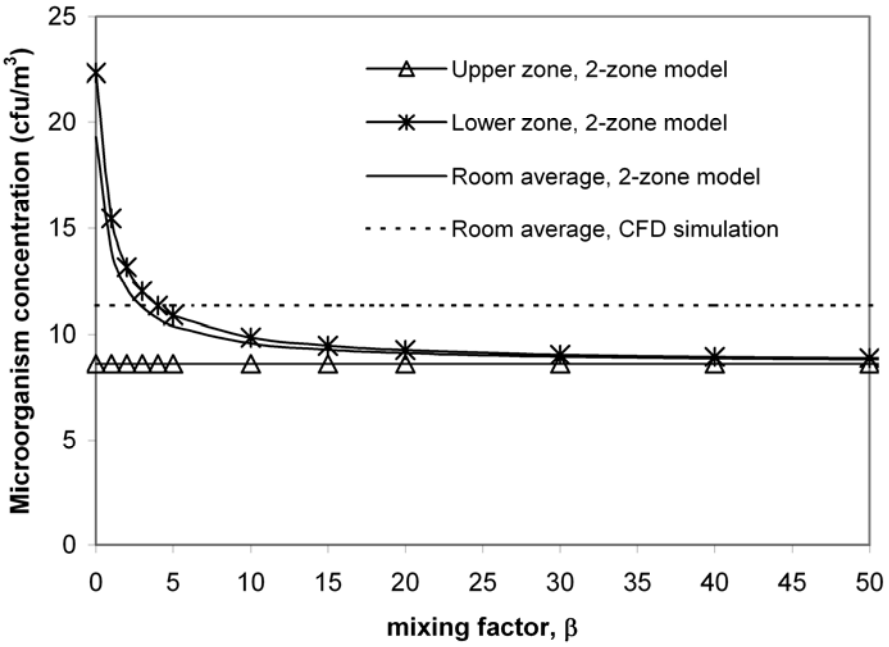


Figure 5: Effect of mixing factor, β, on predicted room concentrations at 6 AC/h and an average upper room irradiance of 0.12 W/m^2

Figure 5 shows that only the lower zone concentration is dependant on beta for this particular ventilation regime, with the concentration reducing exponentially towards the constant value in the upper zone as β is increased. The volume-averaged concentration value also has a dependency on β, and in this case is closer to the lower zone concentration as the lower zone volume is much larger than the upper UV zone. Plotting the average room concentration from the CFD solution on the figure indicates that the average concentration is the same for both methods when $\beta \sim 3.6$, which compares well to the calculated value given in table 2.

It is noticeable that all the values of β calculated in table 2 are very similar, despite the difference in the air change rate. This does not mean that the mixing is better at

lower air change rates, as the actual inter-zonal flow rate is given by βQ, where Q is proportional to the air change rate. However, it does indicate that the number of times the air is passed between the two zones remains constant despite changes in the ventilation rate. This behaviour was also suggested in a theoretical study by Beggs and Sleigh [22], who proposed that the increase in the ventilation rate led to a proportionally higher inter-zonal velocity but a constant value of β. The lack of significant variation with ventilation rate seen in the CFD study indicates that the airflow pattern in the room remains similar for changes in the ventilation rate. As the calculated values of β have been shown to be almost constant, a value of $\beta = 3.6$ is chosen as a suitable value for the remaining calculations in this study.

Suitable values for γ are also necessary for calculations using the three zone model. These can also be found from the CFD simulations in a similar way to β. In this case a spherical zone in the centre of the room of radius 0.4 m was defined in the post-processing software. The average velocity across the surface of the sphere was taken as the interface velocity, v_{int}, and the interface area in equation (2) was taken as the surface area of the sphere. Table 3 shows the values of γ calculated using equations (1) and (2) with γ substituted for β.

AC/h	Q (m^3/s)	A (m^2)	v_{int} (m/s)	γ
3	0.026875	2.01	0.01981	0.74
6	0.053767	2.01	0.04056	0.76
9	0.080625	2.01	0.06380	0.80

Table 3: Calculated values of γ from CFD solutions.

Calculating γ from measurements in a real room is not quite as straightforward as calculating β, due to the zone being spherical. However, it still should be possible to obtain a reasonable estimation by measuring the average velocity at a number of points equidistant from the source. The radius of the sphere can then be taken as the distance between the measurements and the source, and the value of γ calculated as above.

It is noticeable that the calculated values of γ are much lower than the values of β in Table 2. However like β, there is little variation in the value of γ as the ventilation rate is altered, and a value of $\gamma = 0.76$ is therefore chosen for the following comparisons.

Comparison with two-zone model

Figure 6 shows the predicted average room concentrations from the two-zone analytical model and the CFD simulations at a range of air change rates and UV irradiances. It is clear from this figure that the analytical model predictions of the average microorganism concentration in the whole room, with β = 3.6, are very similar to the values calculated in the CFD simulations.

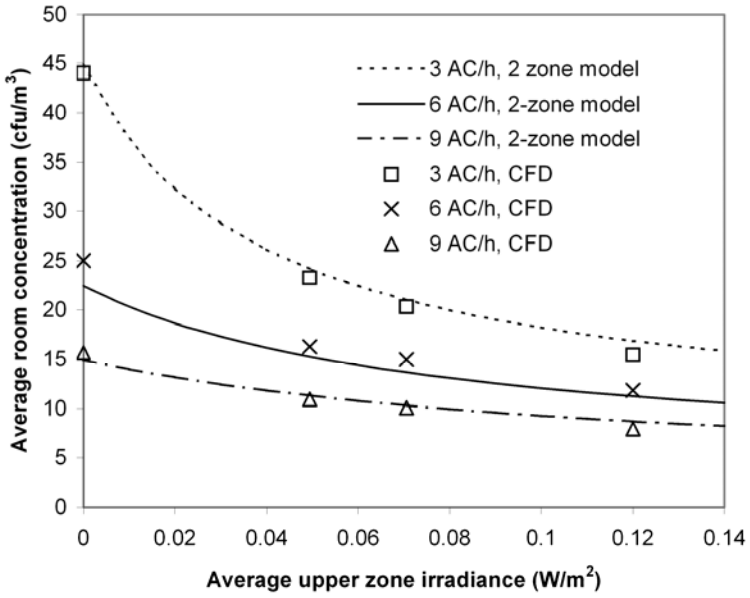


Figure 6: Comparison of analytical and CFD predictions of average room concentration

A more detailed comparison is made in Figure 7 where the average zone concentrations from the two-zone model are compared with calculated concentrations in equivalent zones in the CFD solutions, at a ventilation rate of 6 AC/h.

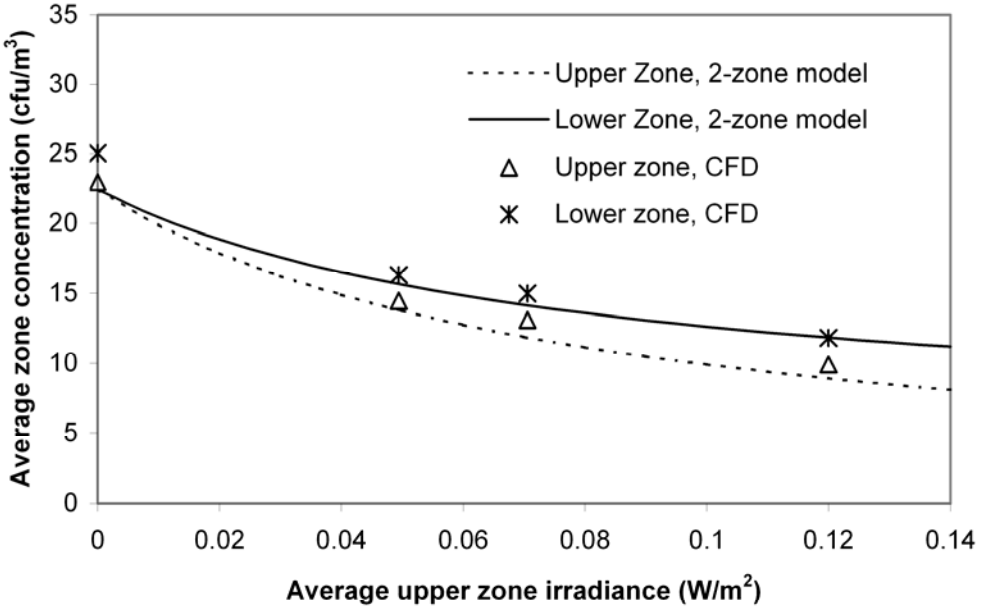
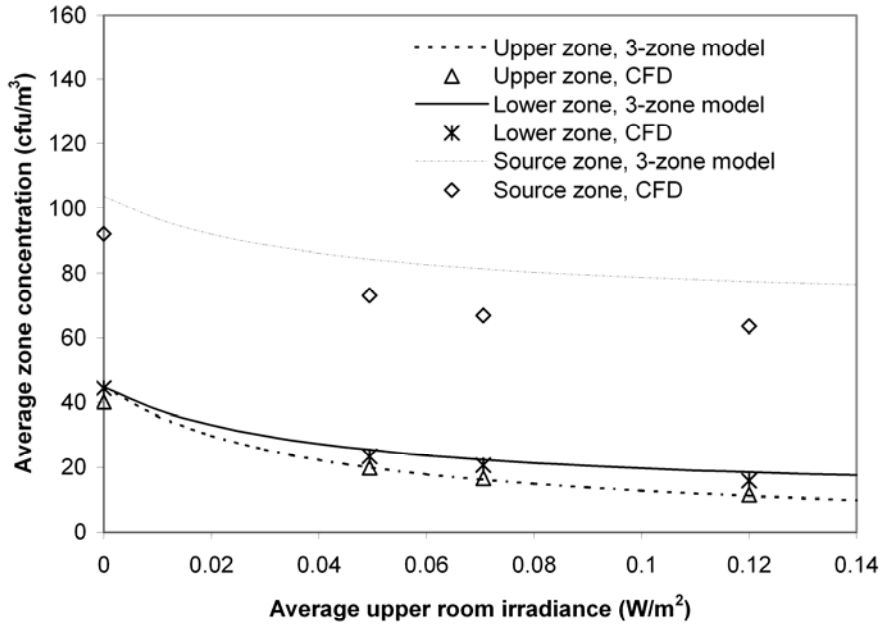


Figure 7: Comparison of zone concentrations from CFD solutions with two-zone model at 6 AC/h.

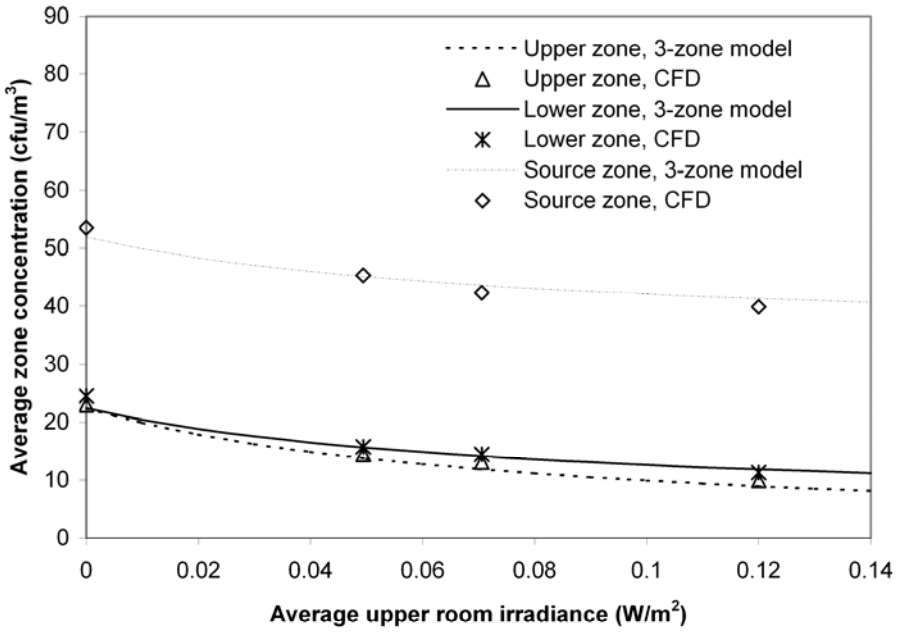
The results in Figure 7 again show that the two-zone model gives average concentrations that compare well to the results from the CFD solutions. However, this result highlights that the two-zone model gives more realistic predictions with an upper room UV field than without. In the absence of a UV field the two-zone model predicts that the upper and lower zone concentrations are equal, while the CFD solution indicates that the air movement in the room results in the lower zone concentration being higher than the upper zone. The CFD solution predicts that the difference between the zone concentrations remains approximately constant for all UV field strengths, however the two-zone model predicts that the difference increases with increasing UV irradiance. This same effect is also seen at higher and lower ventilation rates.

Comparison with three-zone model

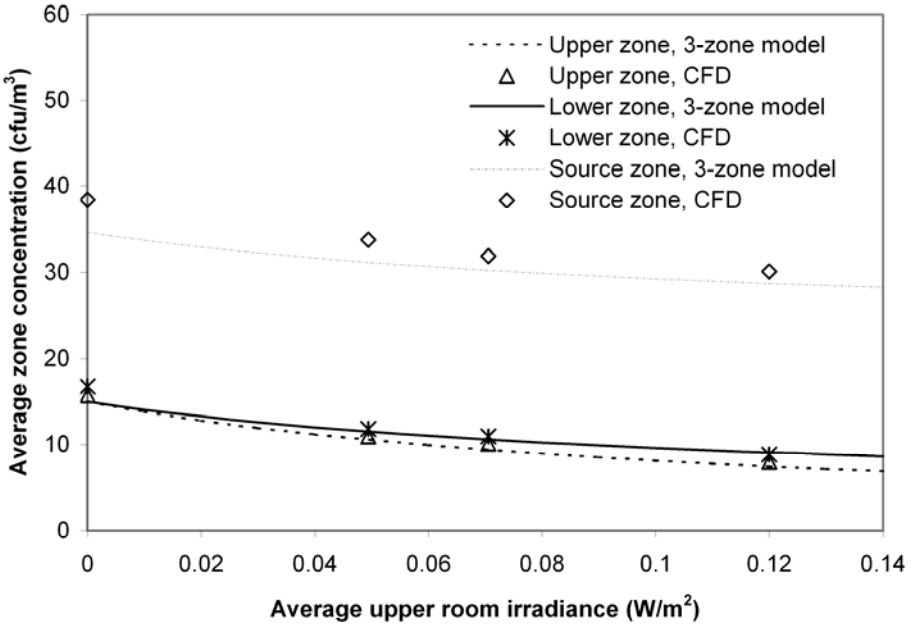
Figure 8 compares the average zone concentrations from the three-zone model with concentrations calculated for three equivalent zones in the CFD model. In this case results are shown for ventilation rates of 3, 6 and 9 AC/h.



(a) Ventilation rate 3 AC/h



(b) Ventilation rate 6 AC/h



(c) Ventilation rate 9 AC/h

Figure 8: Comparison of zone concentrations from CFD solutions with three-zone model at three ventilation rates.

Figure 8 shows that the three-zone model also generally compares well with the CFD solutions over the range of ventilation rates and UV intensities studied. In both the CFD solutions and the three-zone model predictions, the concentration close to the contaminant source is significantly higher than the average concentration in either of the other two zones, even as the UV irradiance is increased. This agrees with Nicas and Millers' [21] finding that UVGI is not effective at reducing near-source concentrations in partially mixed rooms. It is noticeable that there is more variation, particularly at low ventilation rates, between the CFD and analytical predictions of the near-source concentration than there is for the other zones. This may be due to the sensitivity of the near-source concentration to the value of γ. This is indicated in Figure 9 where the three zone concentrations are plotted against γ for a ventilation rate of 6 AC/h and an average upper zone UV irradiance of 0.12 W/m^2. The result indicates that only the near-source zone concentration is dependent on γ, and a relatively small change in the value of γ can lead to a large difference in the predicted zone concentration.

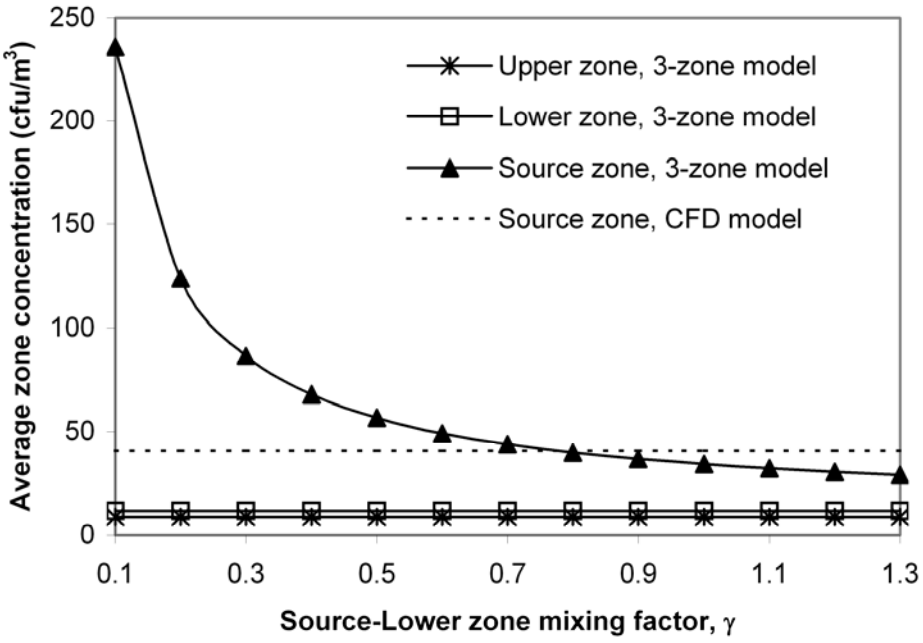


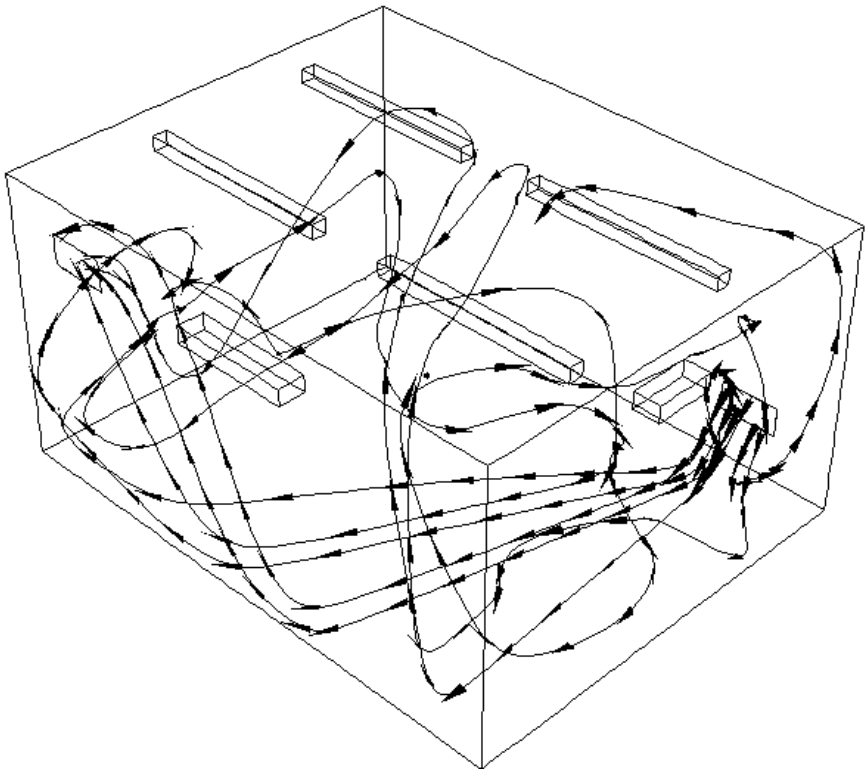
Figure 9: Effect of γ on the near-source zone concentration at 6 AC/h

CFD microorganism distributions

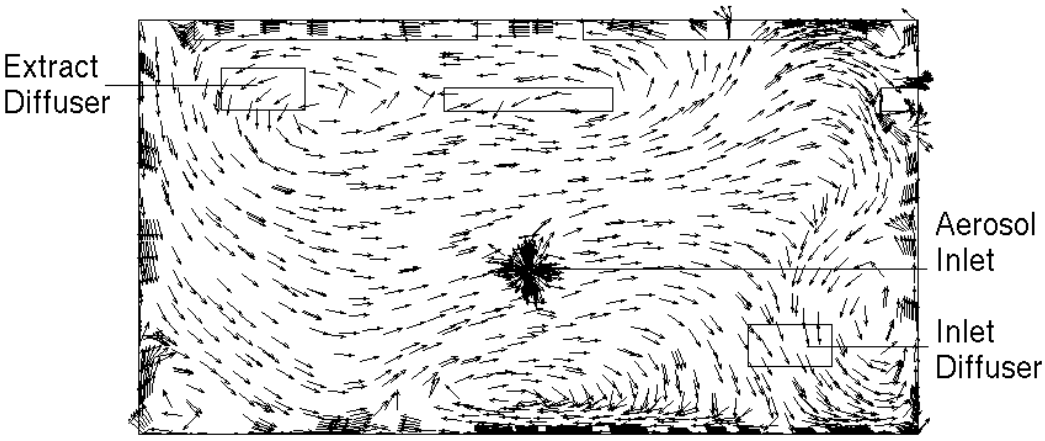
The results presented above show that the two- and three-zone models compare reasonably well with the average concentrations in equivalent zones calculated from the CFD solutions. However, the main benefit of using CFD simulations in this case is that they allow the concentration distribution to be examined across the whole domain, without resorting to using average values.

Figure 10 (a) shows a plot of streaklines from the air supply diffusor, to illustrate the airflow in the room for a ventilation rate of 6 AC/h. The plot indicates that the air enters the room at a 45 degree angle, and spreads out parallel to the floor towards the opposite wall. Some of the airstreams travel directly to the extract, however others follow convoluted paths through the room before being exhausted. The airflow is also shown in Figure 10 (b) by plotting tangential velocity vectors on the sampling plane through the centre of the room (Figure 3). These vectors indicate that there are a number of locations in the room where recirculations occur, and that on this particular plane the overall flow direction is from left to right. This is opposite to that which may be expected given the location of the inlet and exhaust diffusers, and indicates that the room airflow is not intuitive. The figure also shows that the relatively high velocity at the aerosol inlet (centre of the figure) has little impact on the room airflow, as the mass flow rate into the room at this point is low compared to the

overall ventilation rate. Although in these figures it is not possible show the complete airflow in the room, they give an indication of the overall behaviour, and demonstrate the complexity.



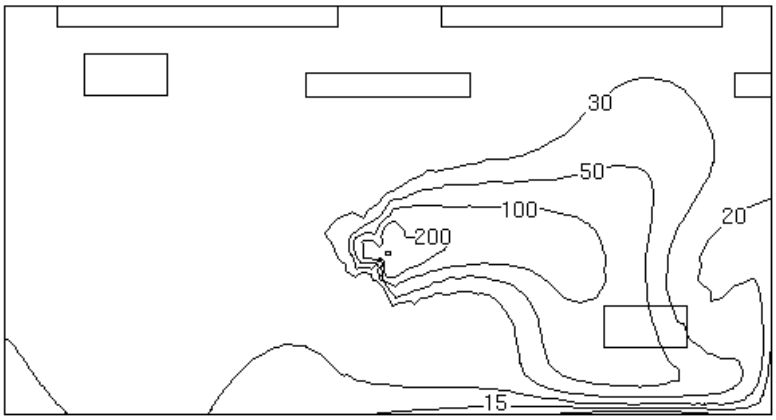
(a) Streaklines generated from the air supply inlet



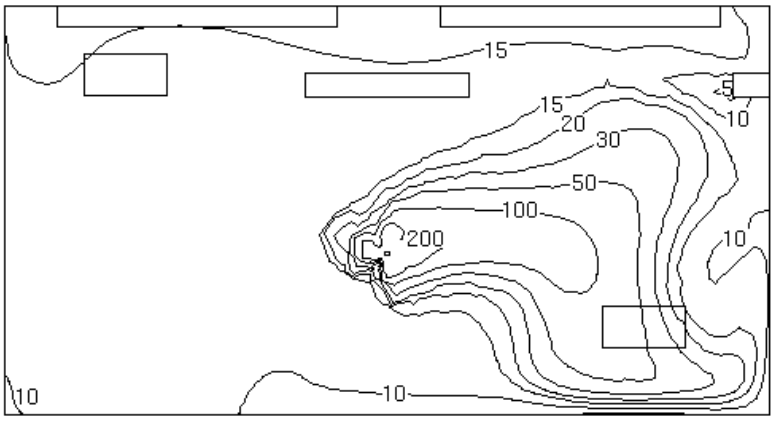
(b) Normalised velocity vectors tangential to the sampling plane

Figure 10: Airflow in the room at a ventilation rate of 6 AC/h

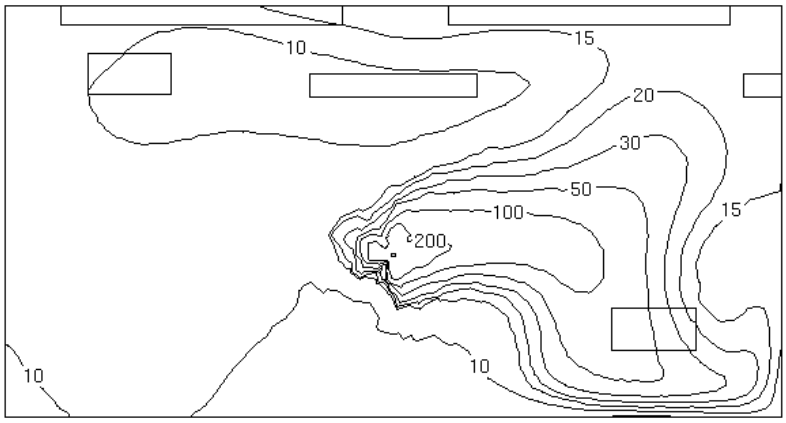
Figure 11 shows microorganism concentrations for the test room at 6 air changes per hour with no upper room UV (a) and with three different UV fields (b,c,d). These results are plotted on a sampling plane through the centre of the room, as indicated in Figure 3.



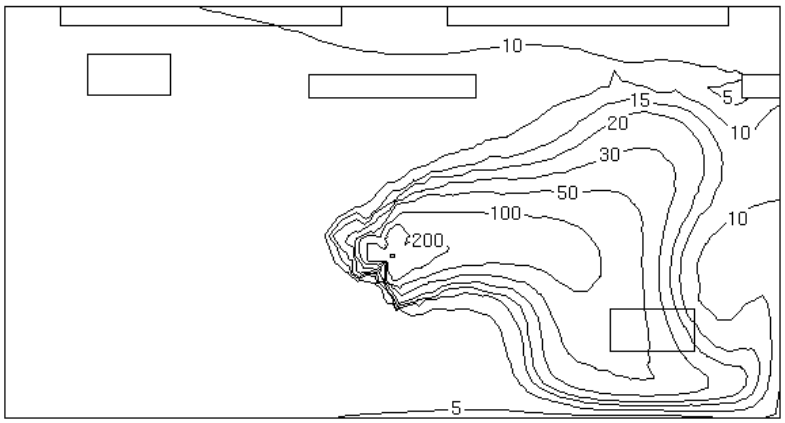
(a) No upper room UV



(b) Short wall UV fitting on



(c) Long wall UV fitting on



(d) Both wall UV fittings on

Figure 11: Microorganism concentration contours at 6 AC/h for four UV fields. In each case the contour values are cfu/m^3.

The plots in Figure 11 demonstrate the effect of the airflow pattern on the concentration as well as the influence of three UV fields. In each case the highest concentration shown is 200 cfu/m^3, however it is plotted like this for clarity, and the concentration very close to the source is actually as high as 500 cfu/m^3. In all cases the highest microorganism concentrations are located on the supply air side of the nebuliser, indicating that the microorganisms are being entrained into the inlet air stream, rather than being carried straight to the exhaust. This is an important finding as it is not intuitive and may have implications for locating lamps in real rooms. The most dangerous location in the room would be thought to be “downstream” from the source, however in this particular room this is not the case, as the highest concentrations are found towards the air inlet.

This finding is also important with respect to comparing the CFD solutions with the analytical models. It is clear from all the plots that although the concentration is highest close to the source, the near-source zone is not spherical as proposed in the three-zone analytical model. The entrainment of the microorganisms into the inlet air stream means that the lower room zone (zone 2 in both analytical models) actually has a lower than average concentration on the exhaust side of the nebuliser and a higher than average concentration on the air inlet side.

The plots in Figure 10 show the reduction in microorganism concentration throughout the room for all three UV fields. The results indicate that the upper region of the room experiences the most significant reduction with the greatest effect seen with both UV devices in operation. However the UV field has little effect on the near source concentration, with similar contours seen in all four plots. The effect of the lamp

location on the room concentration is demonstrated in Figures 11 (b) and 11 (c). In Figure 11 (b), where the short wall fitting is in operation, the lowest plotted concentration is directly in front of the lamp and the concentration at the top right of the plot is lower than in Figures 11 (a) and 11 (c). Similarly the concentration in Figure 11 (c) is lowest in the centre of the figure, in line with the long wall fitting.

DISCUSSION

Understanding the environmental conditions when designing a UVGI air disinfection system is of crucial importance to the effectiveness of the devices. The room size, ventilation characteristics, climatic conditions and number, type and location of the UVGI devices all impact on the overall performance of the system. The analytical and CFD modelling techniques discussed in this paper are all useful tools that engineers and risk assessors can use to better understand the behaviour of UV devices in ventilated rooms, and be able to more confidently predict their performance.

This study has considered analytical models and CFD simulations, both of which may have a role in evaluating UVGI fittings. Analytical models are quick and inexpensive to use, and for the simple room presented in this study give accurately predict average inactivation levels for both upper and lower zones when compared to CFD simulations. Zone mixing models can be used effectively to design and evaluate simple upper room UV systems, and can be easily developed to analyse a range of different ventilation systems [25]. Both the two- and three-zone models give similar predictions for the overall effectiveness and therefore either could be used to carry out this type of evaluation. However when using these analytical models to carry out risk assessments it is important that the user is aware of their limitations.

Both the models are dependant on determining suitable mixing factors, and as this study has indicated, a room may not be well mixed. Brouns and Waters [24], demonstrated that for a two-zone model with equal upper and lower zone volumes, the room is within 10% of fully mixed at a value of β = 4.5. For the room in this study where the upper zone has the smaller volume, Figure 5 indicates that β should be greater than 10 for the room to be within 10% of complete mixing. The value of β = 3.6 predicted from the CFD simulation for the study room indicates that the mixing is much lower. The mixing factor, γ, between the lower and source zones in the three-zone model also has a significant impact on the solutions, as shown in Figure 9. As an overestimate of this factor could lead to an underestimation of the source zone

concentration, it is advisable to carry out calculations over a range of values of γ when using this model to assess risk.

The study indicates a second limitation of the two-zone model, in that it cannot predict the high concentration present close to the contaminant source, which may lead to an under estimation of the risk in this region. The three-zone model predicts the high concentration well and gives a much better indication of the actual microorganism distribution in the room. However, the results from the CFD model indicate that the high-risk area may extend beyond the near-source zone due to entrainment of the microorganisms into the air stream. This again may lead to underestimates of the room concentration, particularly in the lower zone. As this is also the “breathing zone” for any occupants of the room, the underestimate could again have implications for assessing exposure risk in this area.

The CFD simulations facilitate a deeper understanding of how the UV devices interact with the flow field. For example, as shown in this study, the airflow patterns and microorganism concentrations are not necessarily intuitive. For more critical applications or rooms with complex airflows and geometry the CFD simulations can be used to optimise the impact of UVGI devices. In applications, such as hospital wards, the room ventilation may be supplied and extracted in more than one location and air may move between several connected rooms. In addition, there are likely to be heat sources in the rooms such as radiators and people, which will influence the airflow by creating convection currents. Furthermore it is also possible that there is more than one source of contamination in some situations. In such cases, simple zone models become difficult to apply, and CFD simulations are necessary to fully examine the airflows and their interaction with the UVGI devices.

CFD simulations can provide invaluable information for researchers investigating the efficacy of UVGI devices and lamp manufacturers looking to develop improved products. However, it must be remembered that CFD is a complex and expensive technique that requires significant computational resources and a high level of training. Although the accessibility of CFD software has significantly improved in recent years, it is important to fully consider the required outcomes and whether a simpler method will suffice when looking to evaluate UVGI performance.

CONCLUSIONS

From the above upper-room UV study comparing two- and three-zone analytical models with equivalent CFD simulations, the following conclusions can be drawn:

- With suitable mixing factors, both analytical models predict average zone concentrations that compare well to the CFD simulations, with the three-zone model giving the better estimate of the high concentration close to the source in the situation modelled here.
- The choice of mixing factors is important if realistic predictions are to be made using the zone mixing models. For risk assessment applications it is recommended that calculations are undertaken for a range of mixing factors.
- CFD simulations indicate that the airflow in rooms may only be partially mixed and that the distribution of microorganisms may not be intuitive.
- Although the analytical models are suitable for making overall estimates of UVGI system performance, CFD simulations are necessary to fully model the interaction of the room airflow with the microorganism inactivation caused by the UV field.

Acknowledgements

The authors would like to acknowledge the support of the Engineering and Physical Sciences Research Council (EPSRC) who funded this work.

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