# Use of CFD modelling to optimise the design of upper-room UVGI disinfection systems for ventilated rooms

**C.J. Noakes[1*], P.A. Sleigh[1], L.A. Fletcher[1], C.B. Beggs[2]**

[1]Aerobiological Research Group, School of Civil Engineering, University of Leeds, Leeds LS2 9JT, UK

[2]School of Engineering, Design and Technology, University of Bradford, Bradford BD7 1DP, UK

Corresponding author: Dr Catherine Noakes. Email:C.J.Noakes@leeds.ac.uk
Tel: +44 113 3432306. Fax: +44 113 3432265

**Abstract**

The installation of upper-room ultraviolet germicidal irradiation (UVGI) devices in ventilated rooms has the potential to reduce transmission of infections by an airborne route. However the performance of such devices is dependant on several factors including the location of the lamp and the ventilation airflow in the room. This study uses a CFD model to evaluate the performance of UVGI devices by considering the cumulative UV-C dose received by the bulk room air in a ventilated room. By evaluating the UV dose rather than the resulting microorganism inactivation the methodology can be used to optimise UVGI systems at the design stage, particularly when the source location of bioaerosol contaminants is not known. The study investigates the relationships between the lamp location, lamp power, ventilation system and room heating in a small, ventilated room. The results show that with ventilation air supplied at low level and extracted at high level the UVGI system performs better than with the air supplied at high level and extracted close to the floor. In addition the results show the presence of a heater in the room is unlikely to have a detrimental effect on performance and may promote mixing to increase the extent of disinfection.

**Keywords**

CFD, Ultraviolet disinfection, airborne infection, ventilation, modelling

## INTRODUCTION

UV-C light produced by lamps with high spectral emissions at 254 nm has been known for many years to have a lethal effect on microorganisms. The photons of light are absorbed by the microorganism deoxyribonucleic acid (DNA), to produce pyrimidine dimers and other photoproducts which can result in irreparable damage [1]. This sensitivity of microorganisms to UV-C light has been exploited by manufacturers to develop ultraviolet germicidal irradiation (UVGI) devices for the disinfection of air, water and surfaces for use in a wide range of applications including health care facilities, domestic water supply and the food industry. Such devices eliminate the health and safety risks associated with chemical disinfection, however they must be used with care as direct exposure to UV-C irradiation can cause

damage to the skin and eyes. This is of particular concern with in-room air disinfection devices, which are more likely to be accessible than air supply or water disinfection units located inside closed ducts or pipes. For this reason, in-room UV air disinfection devices are usually either enclosed wall mounted units with a small fan to pass the air through the UV field, or shielded open field units located above head-height that rely on air currents in the room to expose the airborne microorganisms to the UV irradiation, but do not allow room occupants to be directly exposed to the light.

The inactivation of microorganisms in the presence of UV-C irradiation is dependant on both the susceptibility of the microorganism to the irradiation, Z ($m^2/J$) and the dose of UV irradiation received, D ($W/m^2$ s), which is defined as the product of the UV intensity, E ($W/m^2$), and the duration of exposure, t (s). ). The performance of any UV device against a particular microorganism is generally described in terms of the fraction of microorganisms surviving following irradiation, given by

$$\frac{C_t}{C_o} = e^{-ZD} \tag{1}$$

where $C_o$ is the initial microorganism concentration ($cfu/m^3$) and $C_t$ is the concentration following UV irradiation ($cfu/m^3$). This therefore depends on both the intensity of the UV-C irradiation and the passage of the air through the UV field. Enclosed UV disinfection devices have the advantage that all the air passing through the device is subject to a known UV dose and the disinfection effectiveness can be accurately evaluated. However for general room air cleaning they are limited by the device flow rate and its ability to draw a significant quantity of the room air through the UV field, hence enclosed devices are generally most effective in small, poorly ventilated spaces or located close to a known bioaerosol contaminant source. Open-field devices on the other hand are more suitable for general room disinfection as they utilise the movement of air within the room to pass bioaerosol contaminants through the open UV field above the occupants heads. They are capable of disinfecting large volumes of air, however the UV dose received by bioaerosol particles is not easily evaluated as it depends on both the ventilation system in the room and the additional convection due to heat sources within the room. The location of upper-room UV devices within a ventilated room is therefore critical to their performance.

It is possible to evaluate the interaction between an upper-room UV field and the airflow in a room, using computational fluid dynamics (CFD) modelling techniques. CFD simulations numerically solve the momentum, energy transport and turbulent energy equations, which govern the three-dimensional airflows in ventilated rooms. Results from such simulations enable variables of interest such as air velocity, pressure and temperature as well as the effects of a UV field to be analysed for a given set of boundary conditions.

CFD models of UV air disinfection to date have concentrated on predicting the inactivation of an airborne microorganisms emitting from point sources. Memarzaeh [2] and Alani et al [3] used Lagrangian particle tracks to evaluate the paths of microorganisms through a UV field, summing the UV dose received by each particle to calculate the resulting inactivation. Noakes et al [4] proposed and validated an alternative Eulerian methodology to couple the UV inactivation of airborne microorganisms with the airflow to enable the UV inactivation to be directly evaluated at any point in the space and visualised as concentration contours of viable microorganisms. Application of this methodology [5] to evaluating the performance of upper-room UV devices against a point source contaminant in a ventilated room demonstrated the complexity of the airflow in a typical room and the limitations of analytical models currently used in assessing upper-room UV devices.

Although all these models have provided valuable information on the effectiveness of upper-room UV systems, as design tools they are limited for two reasons:

(i) In many environments the species of microorganisms that may be present in the air are not known. CFD models that determine the actual inactivation of airborne microorganisms require knowledge of the required inactivation dose (particle-tracking models [2,3]) or the microorganism UV susceptibility constant, Z, [4,5] to evaluate the UV effectiveness.

(ii) In environments such as multi-occupancy hospital wards, schools, office buildings etc. airborne contaminants could be emitted from one or more sources that may be located anywhere in the room or brought in by the ventilation system. Hence, except for certain cases such as isolation rooms, the source location is not generally known at the building design stage. It is

therefore unrealistic to design an upper-room UVGI system based on a single source location, assessing either the dose received by individual particles [2] or the overall inactivation [5].

To address these limitations this paper presents a study of the effectiveness of upper-room UV devices, by examining the UV dose that is received by the bulk room air as it passes through the UV field, rather than assuming possible sources and species of microorganisms. This is based on an alternative methodology, that has previously been applied in the disinfection of water [6], where the UV dose is treated as a transported scalar. By calculating the distribution of the steady-state cumulative UV dose throughout the room for different ventilation systems and UV lamp combinations, the study demonstrates how the airflow and UV field interact and how CFD simulations can be used to optimise the potential for disinfection in a particular room.

## CFD MODEL DEFINITION

A CFD model was formulated using the CFX 5.6 software package (ANSYS CFX, Harwell, UK) to simulate the airflow in a 32m$^3$ room (4.26m length × 3.35m width × 2.26m height), mechanically ventilated at a rate of 6 air changes per hour (ACH). The geometry is based on an aerobiological test chamber at the University of Leeds, which is similar in size to a single occupancy side ward or a treatment room in a hospital. A schematic of the room including four wall mounted UV fittings is shown in Figure 1.

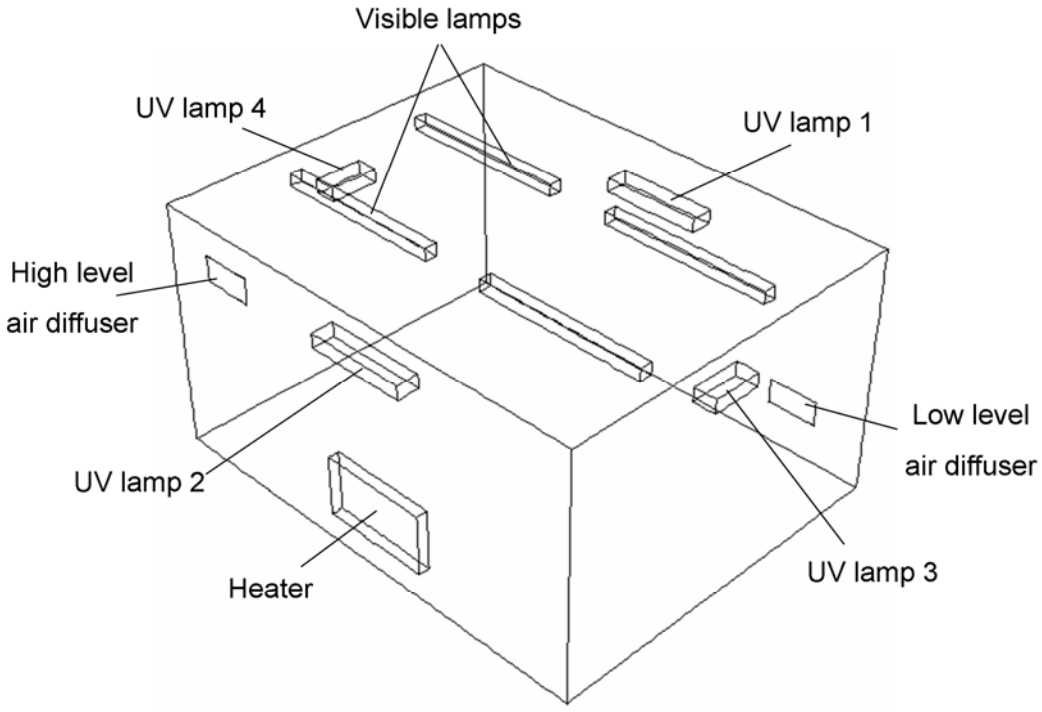



Figure 1: Schematic of the ventilated test room, showing UV fittings and the supply and extract diffusers

The airflow was simulated on an unstructured tetrahedral grid containing approximately 500000 cells and refined at the walls and the inlets and outlets. Turbulence was modelled using the standard k-epsilon turbulence model. Simulations were carried out for two ventilation regimes; (A) supply air in through the low level diffuser and extracted at high level, and (B) with the airflow reversed such that air enters the room via the high-level diffuser and exhausts at low level. Both diffusers were of a louvered design with overall dimensions 0.23 × 0.46 m. The low level diffuser was located 0.47m from the corner and 0.37m from the floor and the high level diffuser 0.45m from the opposite corner and 0.26m from the ceiling. In each airflow regime a velocity boundary condition was imposed on the louver representing the supply opening, with the inlet diffuser modelled by a series of velocity profiles representing horizontal louvers in regime B and $45^{o}$ downward facing louvers in regime A. The total flow rate in both cases was specified to give an overall volume flow rate of 0.0533 $m^3/s$, equivalent to a room air change rate of 6 ACH. A static pressure boundary condition of –10 Pa was imposed at the exhaust to replicate the

slightly negative pressure seen in the actual experimental chamber, and the no slip condition was applied on all the walls. Simulations were carried out initially with isothermal flow conditions and then with the addition of a heater with a constant surface temperature of either 40 $^{o}$C or 60 $^{o}$C. In all cases the supply air temperature was assumed to be 20 $^{o}$C.

The series of simulations undertaken were designed to examine the performance of each of four UV devices placed on the walls of the chamber, at a height of 2m from the floor, as shown in Figure 1. In each case the lamps were specified by defining a 3-dimensional UV field within the chamber [5]. Lamps 1 and 2, located on the two long walls of the chamber, were based on the field created by a Lumalier WM-236 device with a nominal UV-C output of 24 W. Lamps 3 and 4, on the short walls of the chamber, were based on Lumalier WM-136 devices with only 12 UV-C W output. The UV irradiation field for each of the devices was modelled by fitting empirical equations to photometric data, supplied by the manufacturer and confirmed by measurements, to describe the field intensity, $E_p$ (W/m$^2$), at any point P(x,y,z) in the room. Figure 2 shows the UV field for lamp 1, plotted on an x-z plane through the centre of the fittings.

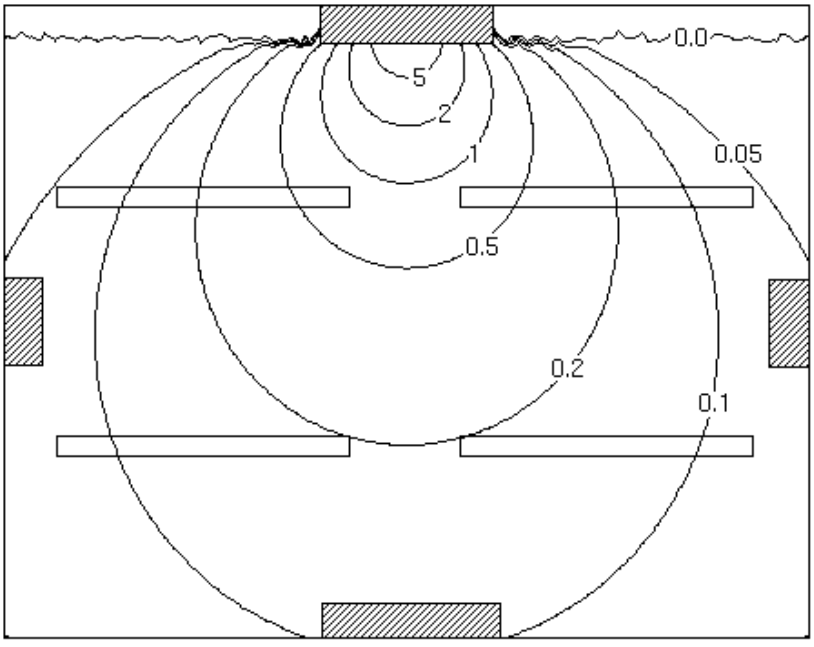



Figure 2: Typical UV field for lamp 1 on a horizontal plane through the fittings.
All values of field intensity, $E_p$, in W/m$^2$.

The model for the UV dose distribution was developed by considering how the dose varied with both the UV field intensity and the airflow in the room. In a uniform UV field, E ($W/m^2$), the incremental UV dose, $\Delta D$ ($J/m^2$), received by airborne microorganisms in time $\Delta t$ is given by the expression

$$\Delta D = E\Delta t \tag{2}$$

Therefore the rate of change of dose within this field is given by

$$\frac{dD}{dt} = E \tag{3}$$

which will be a constant for a uniform field. In a real situation the field is non-uniform and the dose therefore depends on both time and space. In this case equation 2 can be modified to consider the rate of change of dose at a point P(x,y,z) in the room, where the UV field intensity is $E_p$. Here the rate of change of dose is given by

$$\frac{dD}{dt} = E_p(x, y, z) \tag{4}$$

As the cumulative UV dose is simply a measure of the UV irradiance received by the air it can be treated as a passive scalar quantity that is transported with the air. As it is not a physical variable, it does not diffuse within the air. It is therefore only necessary to consider the convective transport and it can be modelled using the scalar transport equation

$$\frac{\partial D}{\partial t} + \nabla \bullet (\underline{U}D) + E_p = 0 \tag{5}$$

Solving this equation, subject to boundary conditions of D = 0.0 at the air supply inlet and dD/dn = 0.0 at the extract and walls, for steady-state conditions, in conjunction with the governing momentum and energy equations, yields the distribution of UV dose throughout the room. The cumulative UV dose received by the bulk air in the room is used as a means of evaluating the performance of the UV lamps and the level of “protection” that they provide to the room occupants. The higher the dose received

by the air the more likely it is that any infectious material present will be inactivated, reducing the risk of disease transmission for occupants.

## SCOPE OF STUDY

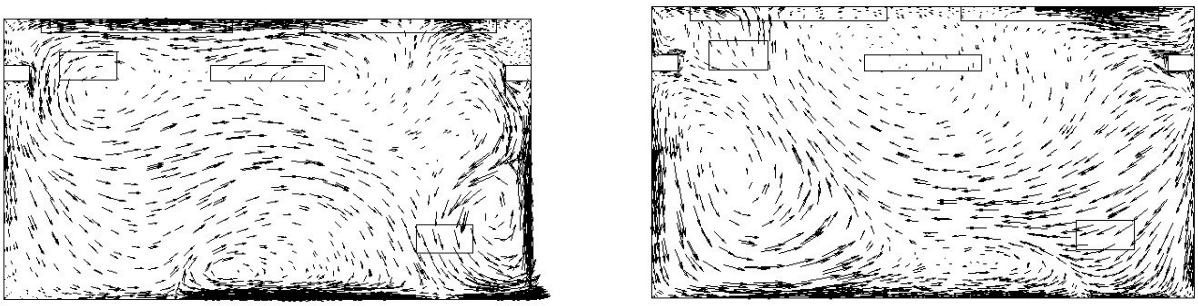
The CFD study was carried out in two stages. The first stage of the study considered isothermal airflows, and examined the effect of the room ventilation system and the lamp placement on the UV dose throughout the room. The second part of the study examined the impact of a heater on the dose distribution. The heater was located as shown in Figure 1, and was assumed to operate with a surface temperature of 40 $^{o}$C or 60 $^{o}$C. In all cases the inlet air remained at 20 $^{o}$C. At each stage all four UV lamps and the effect of both ventilation regimes were considered; regime A with the supply air at low level and extracted at high level, and regime B with the supply and extract reversed.

As a public health measure, an upper room UVGI system is only effective if it can disinfect the air in the lower zone of a room, as room occupants interact with the air in this space. UVGI systems are most commonly employed in situations where there is a high risk of respiratory infection, and has received particular attention in minimising the transmission of tuberculosis [7,8]. As a consequence of this, the results presented in this study were analysed by considering the room in two zones, to examine the impact of the UV lamps on both occupied or unoccupied areas of the room. The upper zone was defined as the upper 0.5m of the room space and contained the UV lamps. The lower zone is considered to be the zone where any occupants would be located and was defined as the rest of the room. For each simulation the volume averaged UV dose was calculated in both of these zones. The results were also examined by plotting velocity vectors and contours of UV dose on planes through the room. Vectors are plotted on a vertical plane through the centre of the room such that the viewer is facing the low level diffuser. UV dose contours are plotted on a horizontal plane through the room located at 1.5m above the floor. This is intended to represent a typical breathing level for room occupants, and hence the highest risk region for the transmission of respiratory infections.

## RESULTS

### Effect of Ventilation Regime

Figure 3 shows the velocity vectors on a vertical plane through the room for the two ventilation regimes under isothermal flow conditions. It is clear from the two figures that the airflow is complex in both cases, with significant recirculation. The difference between the two ventilation systems is also apparent with the general flow in opposite directions in the two figures. In both cases the flow on this particular plane is counter-intuitive to expectation from the ventilation system. For example in Figure 3(a) the ventilation supply air enters through the low level diffuser (bottom right) and exits at high level (top left), yet the airflow appears to be in the opposite direction. However closer inspection of the simulation results reveals that this apparent inconsistency on the two dimensional plots is due to the high velocities close to the inlet which draw air in the bulk of the room towards the inlet, setting up a complex recirculation pattern within the room, which can only be revealed by examining the results three dimensionally. A similar mechanism at the high level supply is responsible for the opposite recirculation seen in ventilation regime B (Figure 3(b)). Although it is not possible to present the airflow over the whole room in these figures, the vectors plotted on the chosen planes give some insight into the airflow and mixing in each case.



(a) Ventilation regime A: In low, out high (b) Ventilation regime B: In high, out low.

Figure 3: Velocity vectors on a vertical plane for ventilation regimes A and B under isothermal flow conditions.

Figure 4 shows the effects of the lamp placement and the ventilation rate on the volume average UV doses for both zones. As expected, the average UV dose for

lamps 3 and 4 is generally lower than for lamps 1 and 2 as they have only half the power. However the airflow regime has a significant impact on the performance of equivalent power lamps. With lamp 2 switched on similar average doses are achieved in both zones with either ventilation system. However with lamp 1 switched on there is a greater variation in average dose between zones and ventilation regimes, despite having the same UV-C output as lamp 2. With ventilation regime A, entering at low level and exhausting high, the average lower zone dose is almost the same as for lamp 2, but the upper zone dose is lower. When the ventilation flow is reversed (B), so that air enters through the high level diffuser, the performance of lamp 1 is lower than for lamp 2 in both zones.

Similar variations in the average zone doses are seen for lamps 3 and 4. In both ventilation cases the mean upper zone dose is less than in the lower zone and ventilation system A results in a better lamp performance than system B. This is particularly noticeable in the case of lamp 3 where air supply through the high level diffuser results in average doses approximately 50% lower than in regime A. In addition, despite having only half the UV power output, under ventilation regime A lamps 3 and 4 achieved similar results to lamp 1 with ventilation regime B.

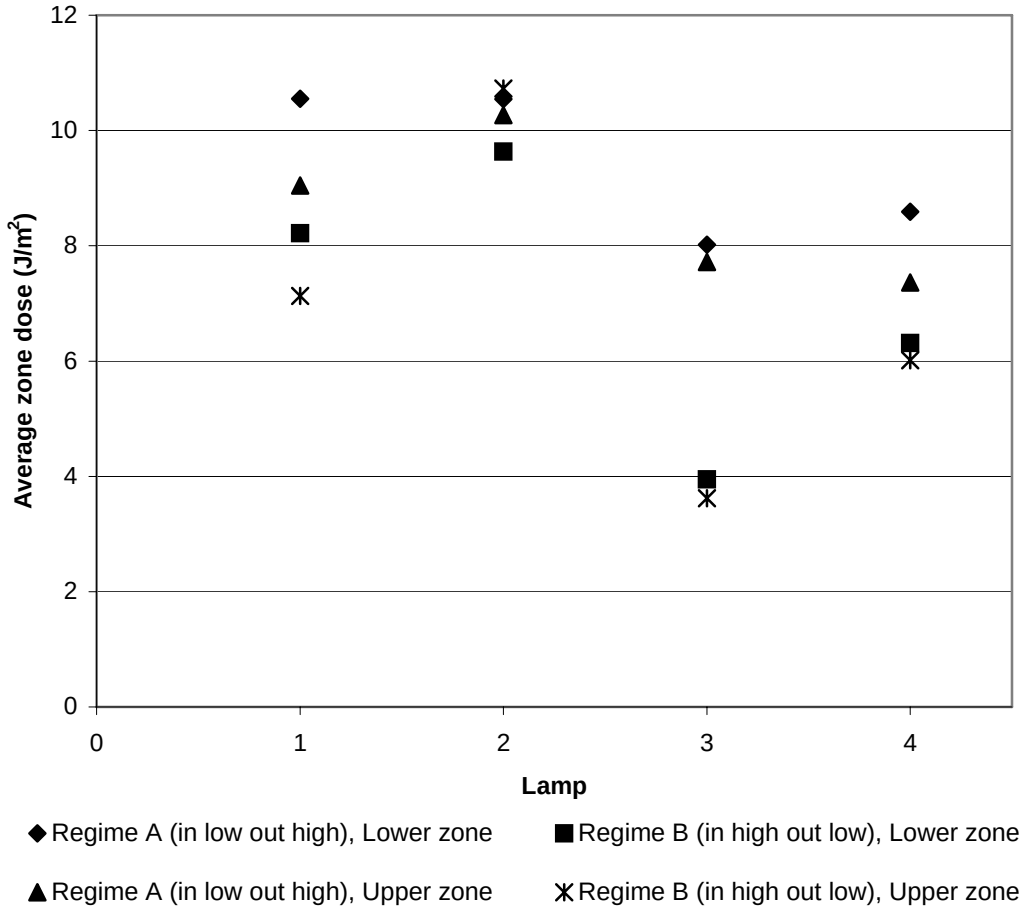
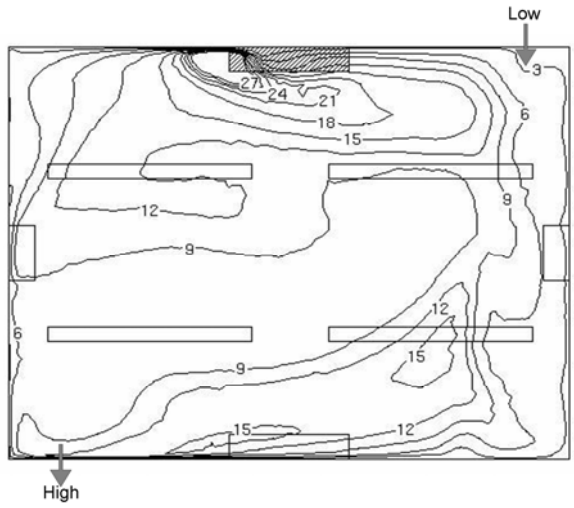



Figure 4: Effect of ventilation regime and lamp placement on average UV dose in upper and lower regions of the room.

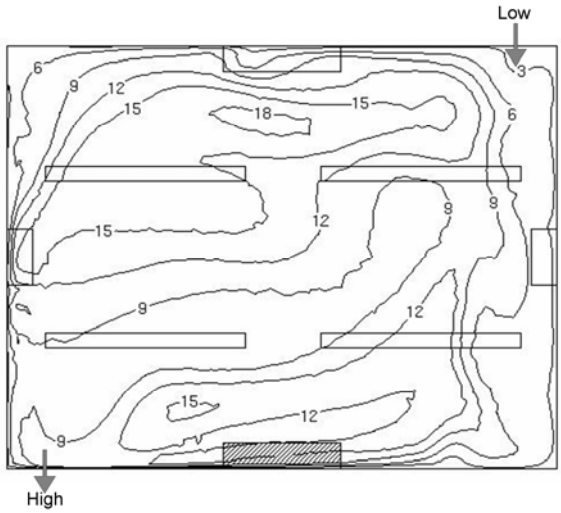
Figures 4 and 5 show contour plots of the UV dose distribution for lamps 1 and 2 on a horizontal plane at a height of 1.5m above the floor of the room. Figure 4 shows the dose distribution for lamps 1 and 2 with ventilation regime A. Although the results in Figure 4 shows that the average dose is very similar for both lamps with this ventilation regime, it can be seen from Figure 5 that the distribution differs at this location. With lamp 1 switched on (Figure 5(a)) the dose is very high in the region below the lamp with a large region in the centre of the room where the dose is lower. With lamp 2 on (Figure 5 (b)), the contour plot shows some similarities, however the dose is more evenly distributed across the room.

The second case in Figure 6, where the ventilation system is reversed also shows the variation in the dose distribution. In both cases the contour patterns are similar with regions of high dose below lamp 1 and a large region of low dose in the centre of the

room. The regions of higher dose are generally larger with lamp 2 switched on, which concurs with the higher average dose results for the lower zone presented in Figure 4.

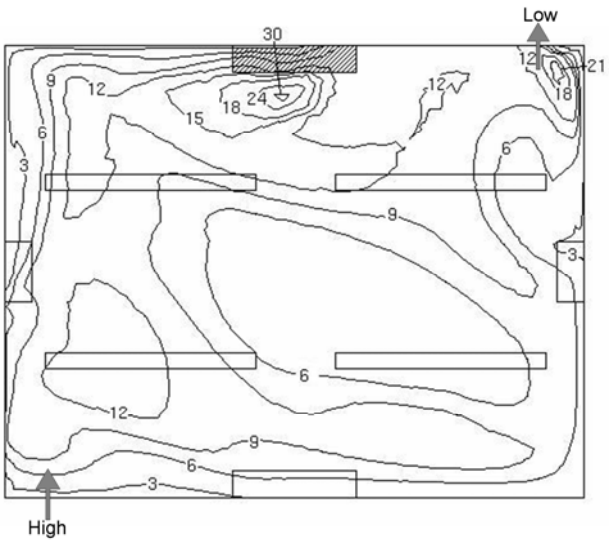



(a) Lamp 1 on.

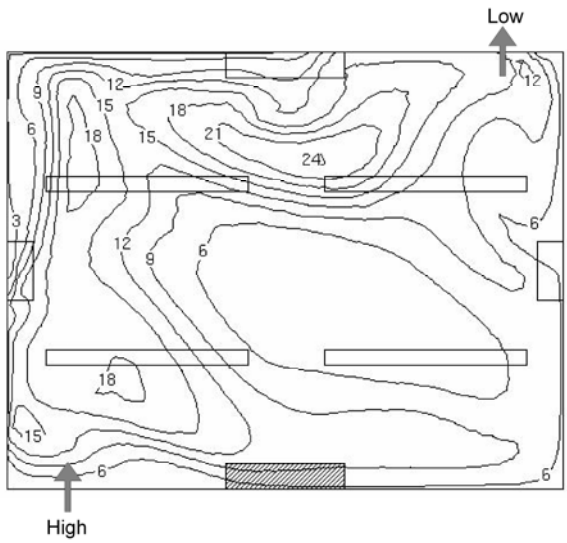



(b) Lamp 2 on.

Figure 5: Dose distribution on a horizontal plane at height 1.5 m (breathing zone) for ventilation regime A, in low, out high. All dose values in J/m$^2$.




(a) Lamp 1 on.




(b) Lamp 2 on.

Figure 6: Dose distribution on a horizontal plane at height 1.5 m (breathing zone) for ventilation regime B, in high, out low. All dose values in J/m$^2$.

Further insights into the interaction between the airflow and the UV irradiation can be gained by considering a simple ventilation model of the room. By treating the dose as a transported scalar, the rate of change of dose in a fully mixed room of volume V ($m^3$) with ventilation rate Q ($m^3/s$) can be given by

$$\frac{dD}{dt} = E - D\frac{Q}{V} \tag{6}$$

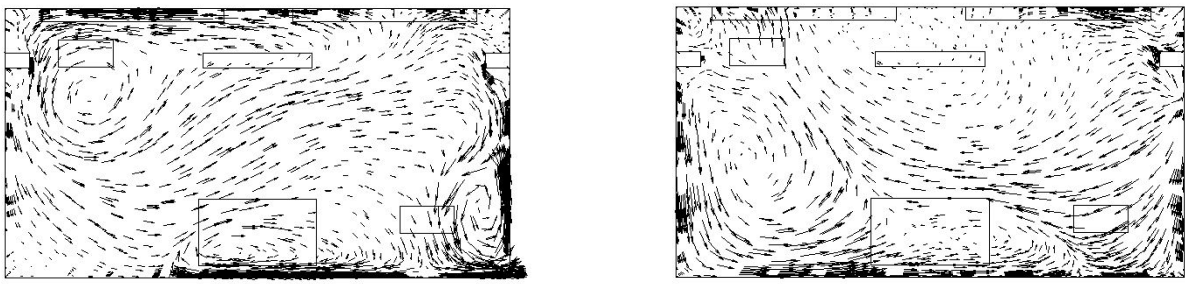
Therefore at steady state the average dose in the room is given by

$$D = E\frac{V}{Q} \tag{7}$$

In this expression V/Q is the average residence time, equivalent to the reciprocal of the air change rate, and in this case equal to 600 s.

**Effect of Heating**

Figure 7 shows velocity vectors representing the airflow on a vertical plane through the room for both ventilation regimes and the heater with a surface temperature of 40°C. Comparison of these figures with the isothermal vectors in Figure 3 indicates that the overall airflow pattern is broadly similar for both ventilation regimes with and without the addition of a heater. The addition of a heater to ventilation regime A results in a change in the direction of the vectors through the centre of this plane, which suggests that there may be increased mixing between the upper and lower regions of the room. However, in the case of ventilation regime B, there is very little difference between the plotted vectors with and without a heater. The flow fields with the heater surface temperature at 60°C are not presented here, as examination of the velocities revealed that there was a minimal difference compared to the results with the heater temperature set at 40°C.



(a) Ventilation regime A: In low, out high

(b) Ventilation regime B: In high, out low.

Figure 7: Airflow streamlines for ventilation regimes A and B with a heater with a surface temperature of 40°C

Figures 8 and 9 show the effect of the heater on the average lower zone dose for the four lamps with the ventilation supply at low and high level respectively. The results in Figure 8 show that with the supply air at a low level (A), the effect of the heater on the airflow generally results in a better performance of the UV lamps. With lamps 2 or 4 switched on there is little difference with the heater in the room, despite lamp 2 being located directly above the heater. However for lamps 1 and 3 the change in the airflow due to the heater results in a higher average dose. This is particularly noticeable for lamp 1, where the average dose is increased by approximately 20%. The results in Figure 8 also show that raising the surface temperature of the heater from 40 $^{o}$C to 60 $^{o}$C has a negligible impact on the average dose in the lower zone. In the second case, where the ventilation direction was reversed (B), the results in Figure 9 show that the heater has a minimal impact on the lower zone dose for any of the lamps studied, at either heater surface temperature.

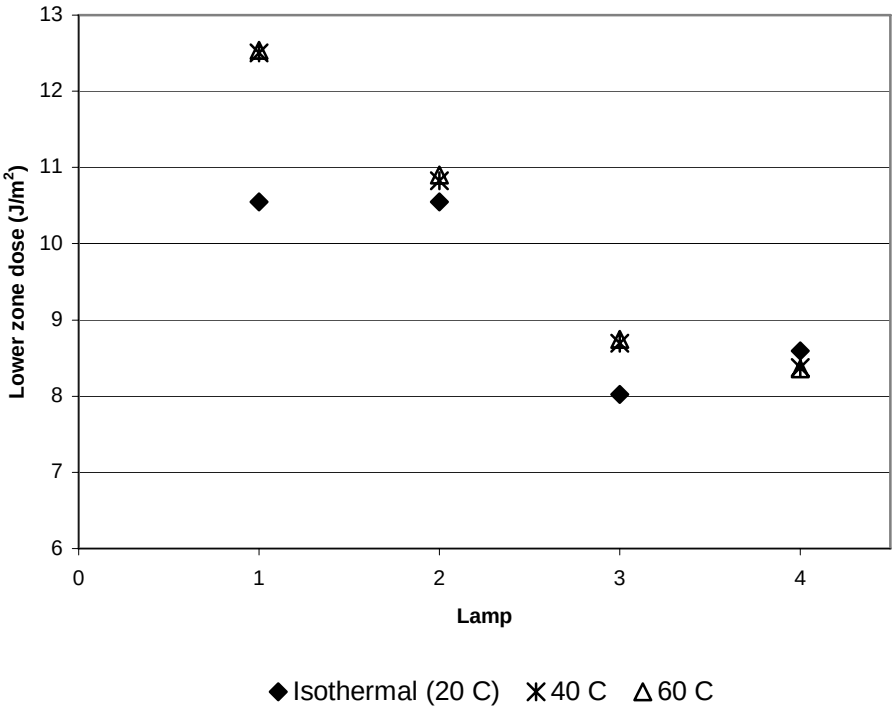



Figure 8: Effect of room heating and lamp placement on average UV dose in the lower region of the room for ventilation case A.

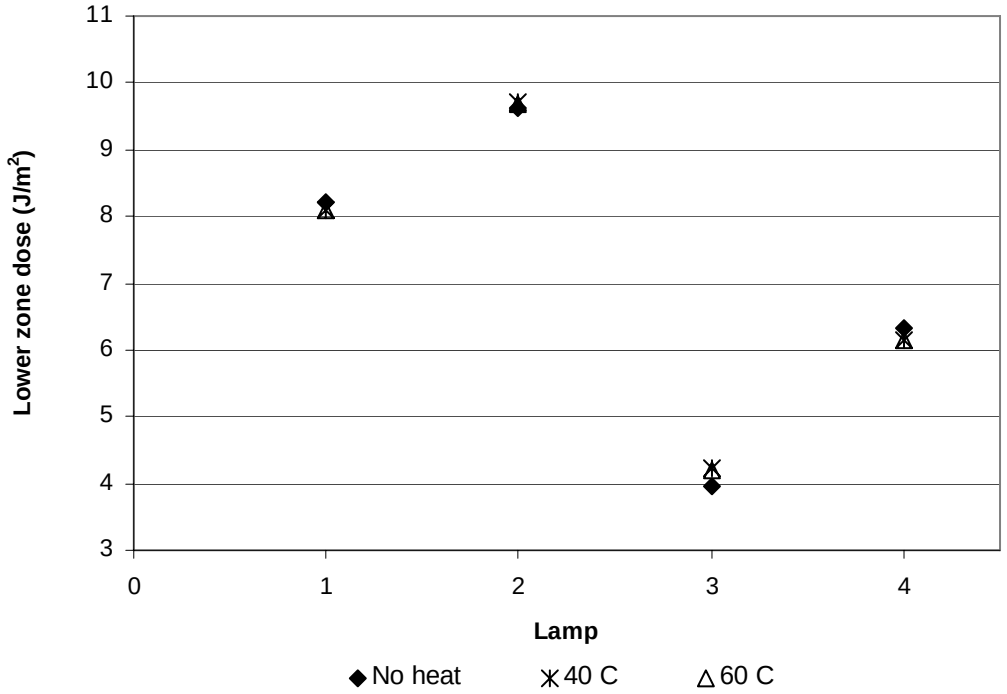



Figure 9: Effect of room heating and lamp placement on average UV dose in the lower region of the room for ventilation case B.

## DISCUSSION

Understanding the interaction between a room's ventilation system and the disinfection effectiveness of upper-room UV lamps is of crucial importance when designing a UVGI air disinfection system. This study demonstrates how a CFD model can be used to investigate this relationship using a simple room with two different ventilation systems, a variable output heater and two UV lamps in four different locations.

The study results clearly show that both the room airflow and the UV lamp location can have a significant impact on the effectiveness of air disinfection in the room. In all the simulations carried out here the variation in dose with lamp location is more apparent when the ventilation air is supplied at high level rather than at low level, as shown by Figure 4. For example in the isothermal cases for ventilation regime B the average UV dose in the lower region of the room is reduced by up to 38 % by locating the WM-136 UV lamp in position 3 rather than position 4. However with the ventilation air supplied at low level (A), lamp 3 performs better than lamp 4 but the

difference is less than 5%. Similar results are also seen with lamps 1 and 2, with again a greater variation in performance when the ventilation air is supplied at high level.

This difference in the performance of the two ventilation systems highlights the importance of the ventilation system in mixing the room air and transporting it throughout the room. The poorer performance of ventilation system B suggests that it is less effective at both passing the room air through the UV field and also redistributing the disinfected air around the room. On the other hand the smaller variation in lamp performance with location seen with ventilation system A suggests that this regime promotes air mixing within the room. The contour plots in Figures 5 and 6 also demonstrate this; case B results in a much larger range of UV doses across the sample plane. For example in the case of lamp 2, the high level inlet (B) results in doses of up to 24 $W/m^2$ close to two of the walls lamps, but reduced to 6 $W/m^2$ in the centre of the room. In contrast the low level inlet (A) with the same lamp shows a much more even spread of UV dose, with the maximum dose 18 $W/m^2$ and the minimum in the central region of the room at 9 $W/m^2$. These results indicate that ventilation system A provides a more evenly distributed level of protection for room occupants, regardless of the lamp location. This is critical if the system is to be an effective public health measure as, unless the contaminant source location is known, it is important that the UVGI system offers equal protection to all the room occupants, rather than favouring those in certain locations.

The same trend in the lamp performance with the ventilation system is also seen in the second stage of the study, where the room contained a heater. However, it is clear from Figures 8 and 9 that the heater has a much more significant impact with a low level ventilation inlet than with a high level inlet. With the exception of lamp 4, where there is a small reduction, the presence of a heater results in an increase in the lower zone dose for ventilation case A, particularly in the case of lamp 1. However with the ventilation inlet at high level there is little difference from the isothermal solutions for any of the cases. These results suggest that in the low inlet cases, the heater promotes the air mixing in the room resulting in a generally better distribution of the UV dose in the lower zone, while with a high level inlet the heater makes little difference to the distribution. This is also suggested the airflow velocity plots, which show that the addition of a heater has a more noticeable impact on the airflow in ventilation regime

A than in regime B. However, the most important finding from a design perspective is that the presence of a heater is unlikely to have a significantly detrimental effect on the performance of an upper-room UVGI system for either ventilation system, and in some cases may have a significant positive impact. In addition, the temperature of the heater made very little difference in any of the cases, suggesting that this again need not be a major consideration in the design of UVGI systems.

Although the simulations carried out in this study are limited to a ventilation rate of 6 ACH, a previous study [5] used CFD and analytical techniques to study the same room with the low level inlet (A) at ventilation rates of 3, 6 and 9 ACH. The results from this study showed that under isothermal flow conditions, a change in the ventilation rate did not significantly change the airflow pattern in the room. Increasing the ventilation rate merely increased the air velocities in the room without a noticeable impact on the air mixing in the room. Although these findings cannot strictly be generalised to the non-isothermal and high level ventilation results in the current study, it is likely that similar trends in flow patterns will be seen. Therefore the findings of this current study are likely to be applicable at a range of ventilation rates.

## CONCLUSIONS

The simulations carried out in this study demonstrate the importance of considering the room ventilation system in conjunction with UV lamp placement when designing a UV disinfection system. For the room studied here the following conclusions can be drawn about the relationships between the airflow and the UV lamp performance:

(1) In all the cases examined here ventilation system A (low level supply, high level extract) generally resulted in a higher average UV dose in the occupied region of the room, than ventilation system B (high level supply, low level extract).

(2) Ventilation system B showed a significant dependence of UV dose on the lamp location, indicating that the lamp location is critical to the UV disinfection effectiveness. This was less variable with the ventilation system A, suggesting that in this case the lamp location is not as critical.

(3) The presence of a heater in the room does not significantly reduce UV lamp performance for any of the cases studied, and with ventilation system A has a positive benefit on the lower zone UV dose for three of the lamps studied.

Although the simulations carried out here are for a single room with a very simple ventilation system, it is likely that similar behaviour would be seen with different room designs.

**ACKNOWLEDGEMENTS**

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

**REFERENCES**

1. Chandrasekhar D, Van Houten B: In vivo formation and repair of cyclobutane pyrimidine dimers and 6-4 photoproducts measured at the gene and nucleotide level in *Escherichia coli*: Mutation Research 2000; 450: 19-40

2. Memarzadeh F: Assessing the efficacy of ultraviolet germicidal irradiation and ventilation in removing Mycobacterium tuberculosis: NIH, Division of Engineering Services, Bethesda Md 2000

3. Alani A, Barton IE, Seymour MJ, Wrobel LC: Application of Lagrangian particle transport model to tuberculosis TB bacteria UV dosing in a ventilated isolation room: International Journal of Environmental Health Research 2001;11: 219-228

4. Noakes CJ, Fletcher LA, Beggs CB, Sleigh PA, Kerr KG: Development of a numerical model to simulate the biological inactivation of airborne microorganisms in the presence of ultraviolet light: Journal of Aerosol Science 2004; 35: 489-507

5. Noakes CJ, Beggs CB, Sleigh PA: Modelling the Performance of Upper Room Ultraviolet Germicidal Irradiation Devices in Ventilated Rooms: Comparison of Analytical and CFD Methods: Indoor and Built Environment 2004; 13: 477-488

6. Wright NG, Hargreaves DM: The use of CFD in the evaluation of UV treatment systems: Journal of Hydroinformatics 2001; 3: 59-70

7. Riley RL, Knight M, Middlebrook G: Ultraviolet susceptibility of BCG and virulent tubercle bacilli: American Review of Respiratory Disease 1976; 113: 413-418

8. Beggs CB, Kerr KG, Donnelly JK, Sleigh PA, Mara DD, Cairns G: An engineering approach to the control of *Mycobacterium tuberculosis* and other airborne pathogens: a UK hospital based pilot study: Transactions of the Royal Society of Tropical Medicine and Health 2000; 94: 141-146