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A Computational Study of UV Disinfection Performance within a Naturally Ventilated Hospital Ward

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Abstract

Ultraviolet Germicidal Irradiation (UVGI) is an effective infection control measure for use in indoor environments including healthcare settings. This article describes a numerical study of upper-room UVGI installations in a six-bed Nightingale hospital ward. Three UVGI fixtures were deployed inside the space with each occupying an individual zone. A total of fifty different fixture configurations were determined by combining a location parameter with a Design of Experiments (DoE). Each configuration was assessed using Computational Fluid Dynamics which calculated the UV dose distribution. Results show that the vertical position of the fixtures is an important parameter and so is the choice of wall to mount them on.

Keywords – CFD; UVGI; dose; hospital ward; natural ventilation

1. Introduction

The airborne transmission of pathogens including tuberculosis and influenza pose a significant threat to human health [1,2]. This is especially the case in healthcare settings such as hospital wards which inevitably contain a high concentration of viruses and bacteria. These have the potential to infect both patients with weakened immune systems and healthcare workers. In order to reduce the infection risk, improvements in hospital ward design and the application of disinfection systems can offer significant benefits.

One such strategy, upper-room Ultraviolet Germicidal Irradiation (UVGI) was developed for use in healthcare facilities long before antibiotics gained widespread use [3,4]. These systems produce an irradiance field which is limited to the upper air zone in the room of interest. Provided that the wavelength of the UV field is close to 254 nm, this has the potential to disinfect the air by killing bacteria, viruses and fungus spores which pass through the field [5]. Numerous experimental studies have verified the disinfection performance of UVGI for a range of

microorganisms in various settings [6-9].

One of the major difficulties of implementing upper-room UVGI systems is that the disinfection performance relies on the ventilation patterns which are responsible for transporting the microorganisms through the UV field. It follows that the position of the UVGI fixtures and their interaction with the ventilation characteristics is the dominant factor for maximizing disinfection. The majority of past numerical studies have focused on relatively small rooms which are mechanically ventilated [10-12]. To the authors' knowledge, there are no known studies of UVGI performance in large healthcare environments. The focus of this investigation is to simulate UVGI within a naturally ventilated hospital ward, for a range of UV field configurations using Computational Fluid Dynamics (CFD).

2. Methodology

In order to simulate natural ventilation and predict UVGI performance, a number of steps are required. The following sub-sections describe these.

2.1 Geometry, Boundary Conditions and Grid Structure

Figure 1 shows a computer model of the hospital ward used in the study which was generated using Gambit (version 2.4). It measures 7.2m wide, 3.4m high and 10.5m long (including the small corridor extension) leading to a volume of 200m^3. This is based on a real ward at St. Lukes Hospital in Bradford, UK (Bradford Teaching Hospitals NHS Foundation Trust).

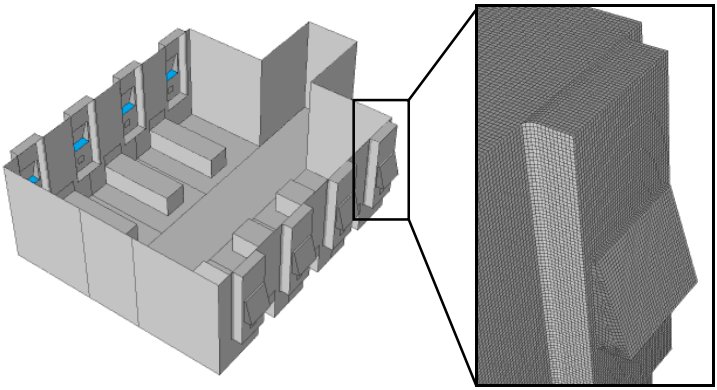

Fig. 1 Computer model of the Nightingale hospital ward used in the computations with local grid structure (inset).

The ward contains six simplified beds, three per side wall and ventilation is supplied via open casement windows. Cross ventilation is assumed and so fresh air enters the windward openings using velocity inlet boundary conditions before exiting through the leeward openings which are pressure outlets. The flow direction through each inlet matches the angle of the windows which was verified during an experimental study [13]. Each inlet measures 0.8m x 0.2m and a velocity magnitude of 0.438 m/s is used.

A recent computational study on a very similar geometry showed that grid independent solutions for the airflow patterns could be obtained using structured hexahedral cell sizes of 0.035m [13]. To minimize discretisation error, an even smaller local grid spacing of 0.025m was employed which leads to a global cell count of 9.4 million.

2.2 Airflow Simulation

A steady-state isothermal simulation was conducted using Fluent (Version 13.0Sp2) for a ventilation rate of 6 air changes per hour (ACH) as this is the recommendation in UK hospitals [14]. Double-precision real number representation was employed in conjunction with second order discretization for all governing flow equations (i.e. mass, momentum and turbulence); this ensured that round-off and discretization errors were minimized. Turbulence was simulated using the Reynolds Stress Model (RSM) [15] which accounts for anisotropic turbulent structures in contrast to simpler Reynolds Averaged Navier-Stokes (RANS)-based models.

The extra transport equations required by the RSM initially led to convergence difficulties. To remedy this, firstly the pressure-based solver (segregated) was used for a total of 25000 iterations. This solution was used to initialize the second phase (also 25000 iterations) which required the density-based (coupled) solver in conjunction with lower under-relaxation factors. The strategy led to clear convergence and residual levels of between 1e-5 and 1e-8 for all quantities.

2.3 Dose Model

Recent CFD studies have shown that the dose, D, (J/m^2) received by the air from UV fixtures can be used to assess performance [10,12,16] with the aim being to maximize this parameter. The present study utilizes a passive scalar approach whereby the dose distribution depends on the irradiance field, E, (W/m^2) and the velocity vector field, $\underline{U}$, (m/s) given by:

$$\nabla \cdot \left(\underline{U} D\right) + E = 0 \tag{1}$$

2.4 UV Field and Fixture Positions

As mentioned earlier, knowing where to position UV devices within a room to maximize dose has not been explored for large spaces before. A decision was taken to use a total of three wall-mounted UV fixtures within

the ward and to assess the performance for many different positions. The irradiance field per fixture is based on experimental measurements [12] of the Lumalier WM236 (Lumalier Corporation, Memphis, Tennesse) which has a total output of 72W (24W UVC). Each fixture measures 0.92m wide, 0.22m deep and 0.120m high with a series of stacked louvers producing a 0.075m high collimated UV field. Figure 2(a) shows the irradiance field in the horizontal plane with three fixtures active when viewed above the ward.

Taking the geometry of the space into consideration, it is logical to position each of the three devices above each bed and in between windows so that there is one fixture per zone, see Figure 2(b).

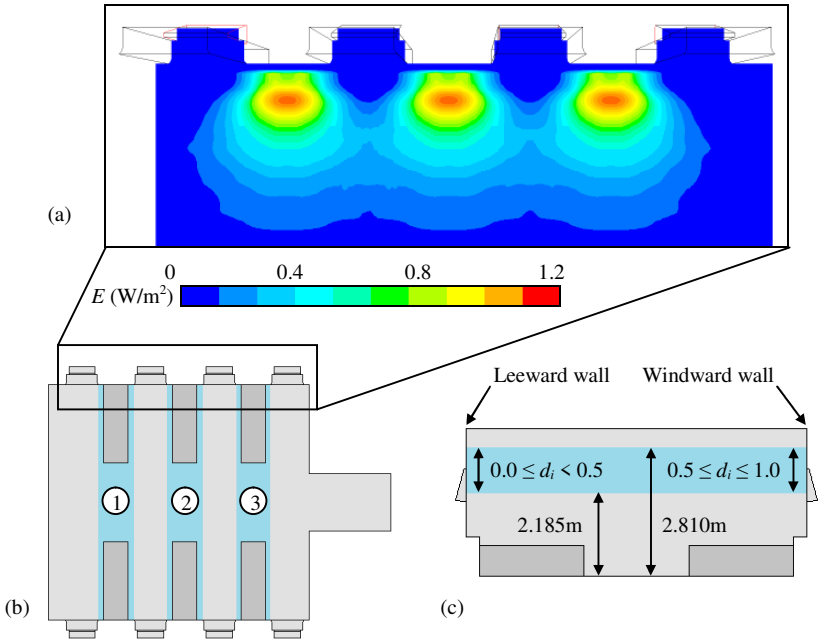

Fig. 2 (a) Top view of the irradiance field produced by three UV fixtures mounted on one wall of the hospital ward and schematics showing (a) top view of the ward with zones 1-3 labeled and (b) side view with the location parameter, d_i, and the possible locations for the i^{th} UV fixture.

The height of each fixture (per zone) can be varied from 2.185m up to 2.810m in steps of 0.025m, giving 25 possible vertical positions. Furthermore, each device can be located on either the windward or the leeward wall, extending the number of possible fixture locations to 50. This can be controlled conveniently using a single, normalized, location parameter, d_i, for the i^{th} zone. For $0.0 \leq d_i < 0.5$ the fixture is mounted within

the prescribed height range on the leeward wall, and for $0.5 \leq d_i \leq 1.0$, the fixtures are located on the windward wall, see Figure 2(c).

2.5 Design of Experiments

Given that there are three design parameters (d_1, d_2 and d_3) and each one has 50 possible values, there are a total of 125000 (50^3) potential combinations of the three UV fixtures. To conduct so many simulations would be prohibitive and so, for a given simulation budget, a Design of Experiments (DoE) can be used to select suitable combinations of design parameters. To do this, an Optimal Latin Hypercube (OLH) DoE [17] consisting of 50 points was chosen to evenly sample the design parameter space as shown in Figure 3. Here, each point represents a combination of UV fixtures within the ward.

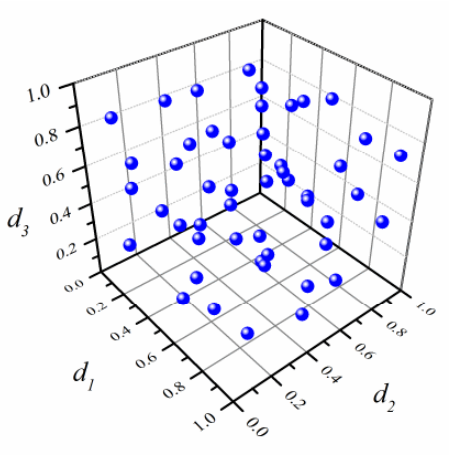

Fig. 3 Design of Experiments used to determine UV lamp configurations using the location parameter d_i.

2.6 Dose Simulations

The planar UV field for each device was stored as a fixed-value data set in the location of interest. In order to facilitate moving the UV field within the ward, the upper air region was separated into single layers of cells (each 0.025m thick). For a particular device position, the field was stored in three vertically-stacked layers of cells giving a total band thickness of 0.075m, This matches the height of the collimated irradiance field produced by the fixtures. In doing this, the field was assumed constant in the vertical direction; the validity of this approach for UVGI modeling was verified in [12]. Dose simulations were run by solving the scalar transport equation (1)

on the converged flow field; this was done by turning the flow and turbulence equations off. Solution convergence for each of the 50 scalar simulations (i.e. one per UV fixture combination) was attained in approximately 200 iterations.

3. Results and Discussion

Figure 4 reveals the airflow structure produced by the cross-ventilation regime. The incoming air enters the ward through the inlet windows and ceiling-level entrainment is evident. Some of the air exits through the leeward windows whilst the remainder is forced downwards and turned back on itself in which serves to mix the airflow in the center of the ward.

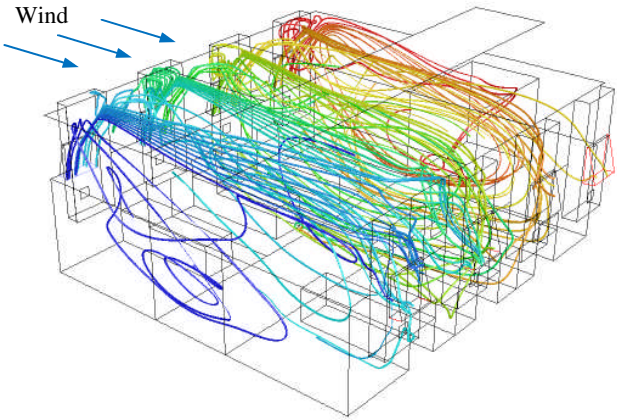

Fig. 4 Illustration of the pathlines generated from the cross-ventilation regime. Pathlines colored by particle identity (not flow variables) for clarity.

To illustrate a typical dose distribution, Figure 5 shows contour plots of the dose (J/m^2) in the vertical direction. For the case shown, fixtures in zones 1 and 2 are leeward-mounted, with the zone 3 fixture mounted on the windward wall. Both leeward fixtures are effective at increasing the dose in the lower patient level, which occurs by virtue of the mixing present. The incoming fresh air passes through the high-intensity UV field and returns back towards the windward side. For the windward mounted fixture the dose level is higher in its immediate vicinity (white region), however some of this air exits the ward and a lower dose is evident in the patient zone, particularly on the leeward side.

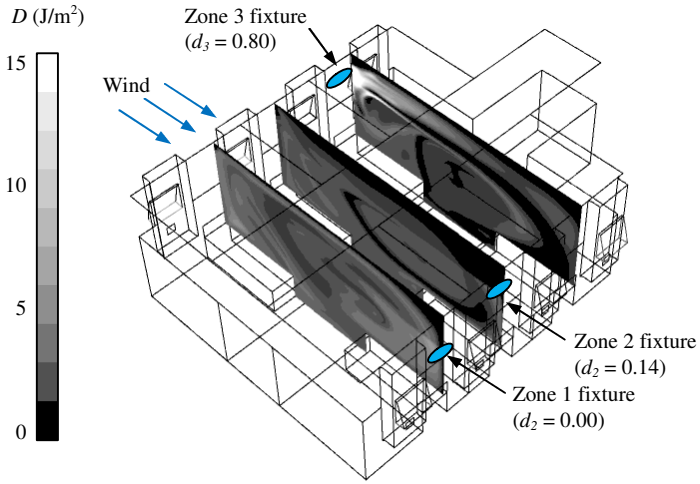

Fig. 5 Contour plot of the dose distribution resulting from one combination of UV fixtures with two mounted on the leeward wall (zones 1 and 2) and the remaining one on the windward size (zone 3).

The dose distribution in Figure 5 illustrates how different the local dose levels are depending on which wall the UV fixtures are mounted on. To assess the global characteristics, the volume-averaged ward dose, D_w, is defined to compare each of the fifty cases considered. Figure 6 shows how this quantity varies as a function of the location parameter per fixture (i.e. d_1, d_2 and d_3).

Figure 6(a) considers the location of the fixture in zone 1. Whilst scatter exists in the data there is a clear trend showing that the leeward fixture positions are generally better than the windward ones. However, the highest dose values occur when the fixture is at the bottom of the prescribed height range on either wall (i.e. $d_1 = 0.0$ [leeward] and $d_1 = 1.0$ [windward]). This shows that in zone 1 of the ward which is adjacent to a flat side wall, the UV fixture can be positioned on either wall at the bottom of the height range (2.185m).

In the center of the ward (zone-2) there is noticeably less scatter in the data and the windward fixture positions lead to higher doses compared to the leeward ones. In this region the highest doses occur when the fixture is placed in the upper region on the windward wall (i.e $d_2 \approx 0.5$-0.65 which corresponds to a height range of 2.625-2.810m). The trends seen in zone 3 of the ward are very similar to those in zone 2 but with more scatter; this can probably be explained by the fact that there is a small corridor extension in this region which clearly affects the ventilation patterns and thus dose. Again the best location to place the UV fixture is high on the windward wall, however this is at a specific height of 2.735m ($d_3 = 0.56$).

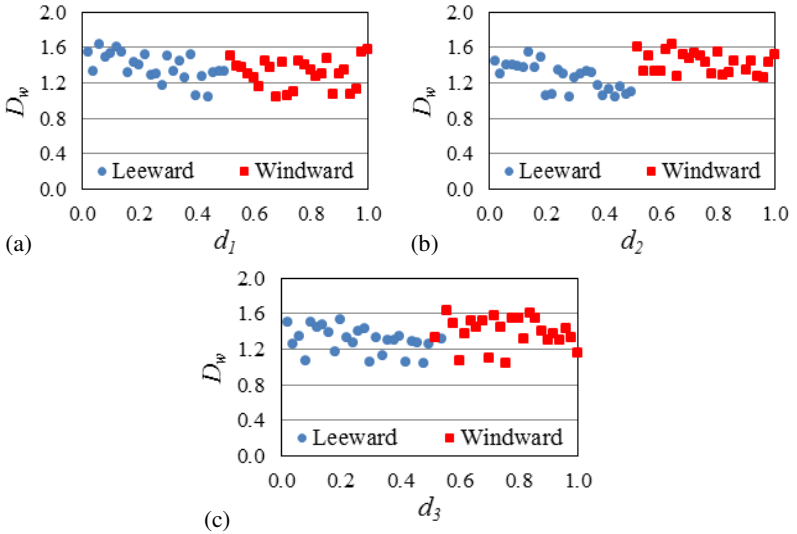

Fig. 6 Plots showing the relationship between the UV fixture position parameters (d_1, d_2 and d_3) and the volume-averaged dose in the ward, D_w.

Overall, the results show that the global dose experienced in the ward is highly sensitive to the UV fixture configuration. This is illustrated by the differences in the minimum dose (D_w = 1.04 J/m^2) and the maximum (D_w = 1.63 J/m^2) for the fifty configurations studied. Mounting the fixtures high on the windward wall in zones 2 and 3 appear to be most effective in these regions. In zone 1, the best results occur when the fixture is mounted low-down but either the windward or the leeward walls are suitable.

Clearly, these results apply to this particular ward layout for cross ventilation at a rate of 6ACH. In naturally ventilated spaces the flow patterns can be very different from one moment to the next [13] and so other ventilation rates should be considered in future studies. In terms of the dose simulations the UV reflections are not taken into account, however a recent experimental study showed that reflections in small rooms are negligible [12] and it is reasonable to assume this would be the case in a large hospital ward.

The study considered the dose distribution which depends on the UV field and the airflow patterns. Measuring dose experimentally is not possible and so the CFD results have to be relied upon in generating the dose distribution. It follows that validation of the airflow/UV distribution is particularly important and experimental data was used in defining the UV field [12] and to inform the boundary conditions [13]. Knowing how much dose can inactivate a given microorganism depends on its susceptibility and

factors such the temperature and humidity [7,8]. To complicate matters further, photo-reactivation and dark repair mechanisms serve to counteract inactivation; these are not even understood experimentally and so it is extremely difficult to incorporate them in CFD simulations with any accuracy. Furthermore the susceptibility of a given microorganism (such as Tuberculosis) can vary quite considerably from one laboratory-based study to the next. As such, significant research is required before the relationship between dose and inactivation can be established. This aspect should be the focus of future parametric studies.

Another important point to consider is that the irradiance field produced by UVGI fixtures is harmful to the occupants and so one of the major design constraints is to position such fixtures in the upper region of the space being considered. Although this study highlighted the sensitivity of fixture position on dose levels, optimizing the layout to give the best overall performance requires the application of formal optimization techniques. Metamodeling is particularly relevant and this is being explored in ongoing studies.

4. Conclusions

A numerical study of natural cross-ventilation applied to a six-bed Nightingale ward was investigated. A series of fifty simulations were carried out to investigate how the placement of upper-room UV disinfection fixtures influences the air disinfection potential. Results show that both the fixture height and choice of wall to mount each one have a marked effect on the performance. Broadly speaking, mounting fixtures on the windward wall proves to be effective at increasing the average dose in the ward. However, the results are specific to the ward layout and the ventilation rate studied. A logical extension is to consider other ventilation rates and applying formal optimisation techniques in search of the optimum fixture locations. Work is on-going in this area.

5. Acknowledgment

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