International Journal of Applied Engineering Research ISSN 0973-4562 Volume 13, Number 21 (2018) pp. 14897-14902

Comparative CFD Investigation of Upper Room UVGI Efficacy with Three Different Ventilation Systems

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Abstract

The use of upper room ultraviolet germicidal irradiation (UR-UVGI) has been proven to be an effective and energy efficient method for minimizing bacterial and viral disease transmission in indoor environments. The aim of this paper is to investigate numerically the performance of UR-UVGI in three different ventilation systems: mixing, downward, and displacement ventilation. A detailed three-dimensional computational fluid dynamics (CFD) model is developed in the Eulerian domain to simulate the dispersion and UV inactivation of *Staphylococcus aureus*, a common type of airborne bacteria, in a two-bed patient room. The room is simulated with and without the presence of UR-UVGI for each of the concerned ventilation systems while the bacteria generation and air exchange rate remain unchanged in all simulated cases. Results revealed that UR-UVGI can achieve an efficacy of 99.8% in the occupied zone of both mixing and downward ventilation systems when a UV output of 36 W is delivered to the room, whereas an efficacy of 78% is achieved in the case of displacement ventilation.

Keywords: Computational fluid dynamics (CFD), mixing ventilation, downward ventilation, displacement ventilation, airborne bacteria dispersion, upper room ultraviolet germicidal irradiation (UR-UVGI).

List of symbols

ACH	air changes per hour
C	concentration of microorganisms (cfu/m^3)
cfu	colony forming unit
D	Brownian diffusivity (m^2/s)
D_t	particle Eddy diffusivity (m^2/s)
E	UV irradiance (W/m^2)
U	air velocity (m/s)
udf	user defined function
Z	bacteria susceptibility to UV (m^2/J)

Greek Symbols

η	*UVGI* efficacy (disinfection rate)

INTRODUCTION

Microbial contamination of indoor air is known to cause serious health issues to occupants. Some airborne infectious diseases are related to huge death tolls over the years such as Tuberculosis (TB), Severe Acute Respiratory Syndrome (SARS), and most recently Ebola. Viboud et al. [1] reported a total of 1.87 million deaths caused by TB infections in about 22 countries. The World Health Organization (WHO) reported 8,098 people infected with SARS worldwide, 774 of whom died, during the outbreak in 2003 [2]. Moreover, 28,616 Ebola cases were reported in Liberia, Guinea, and Sierra Leone, with 11,310 deaths during the 2014-2015 outbreak [3].

Infected people continuously emit pathogen-carrying droplets when breathing, talking, coughing, and sneezing. The saliva droplets that are smaller than 20 μm evaporate in milliseconds to become droplet nuclei (1 – 5 μm) and sustain in air for prolonged periods of time [4]. Airborne cross-infection usually occurs when those infectious particles are inhaled by non-infected people. Another mode of disease transmisson is the "droplet" mode that is induced by larger pathogen-particles that deposit onto surfaces and are transferred by touch to exposed individuals [5].

Several experimental studies showed that the air exhaled by infected people can have bacterial concentrations up to 13,000 colony forming units per cubic meter (cfu/m^3) varying according to the disease type and expiratory activities [6,7].

The World Health Organization [8] recommends that bacteria concentration not to exceed 500 cfu/m^3 in office spaces and 200 cfu/m^3 in hospitals. These requirements are traditionally satisfied by increasing the fresh air intake to dilute the bacteria concentration to acceptable levels. However, this results in additional energy cost that might be substantial in the case of intense bacteria generation.

A plausible method for reducing airborne bacteria concentrations in indoor spaces is the use of UR-UVGI that disinfects the air at relatively low energy cost. This system uses UVC light to damage the DNA of microorganisms preventing their multiplication. The primary safety issue concerning UR-UVGI is that occupants may be exposed to direct or reflected UV rays for long periods of time. The maximum permissible UV irradiance in the occupied zone based on 8-hour exposure is 0.2 μW/cm² [9]. It is then recommended that UV fixtures be installed at minimum height of 2 m to prevent any occupant's eye or skin injury [10].

Basically, air mixing between the lower occupied zone and upper irradiated zone is quite important to ensure effective disinfection of the room air and then reduce airborne cross infection among occupants. The indoor air distribution has a great effect on the UR-UVGI performance since it influences the dispersion patterns of infectious droplet nuclei [11,12] and then determine the UV dose received by the pathogens.

Upper room UVGI systems were proven to achieve high disinfection rates in conventional ventilation systems where turbulent jets of fresh air mix up with the indoor air [13,14]. Zhu et al. [15] concluded from CFD simulations that air exchange rate is the decisive factor in evaluating the

effectiveness of *UR-UVGI* in indoor spaces and that the use of a ceiling fan would improve the germicidal performance. On the other hand, limited research has addressed the UVGI performance with other air distribution systems such as localized and displacement ventilation.

Kanaan et al. [16] showed by simulation that the use of UR-UVGI is a promising solution for preventing disease transmission in localized air-conditioning systems even within the same environmental zone.

In displacement ventilation systems, cool air is supplied near the floor at relatively low velocity and moves upward, as it gets warmer, transporting air pollutants to the upper room. The room air is exhausted at the ceiling level. Displacement ventilated spaces are virtually divided into two zones: clean lower zone with unidirectional air flow and contaminated upper zone with air recirculation. The interface between the two zones is called the stratification height which should be above the occupants' heads as an indoor air quality requirement. When UR-UVGI is used, the air in the upper UV zone is effectively disinfected before leaving the room due to air recirculation in this zone. This enhances the opportunity for making use of the return air to achieve energy savings without compromising the microbial air quality in the occupied zone [17]. This paper investigates using CFD the performance of UR-UVGI in a typical two-bed patient room with three different ventilation systems that are mixing, downward, and displacement ventilation.

METHODOLOGY

The transport and UV inactivation of airborne bacteria in a two-bed patient room are determined by CFD simulations using ANSYS Fluent 15.0 [18]. The performance of UR-UVGI is assessed with three different ventilation systems i.e mixing, downward, and displacement ventilation. The room is simulated with and without UV and the UR-UVGI efficacy in disinfecting the air in the occupied zone and upper zone as follows:

$$\eta = 1 - \frac{C_{UV,ON}}{C_{UV,OFF}} \quad (1)$$

Where $C_{UV,\ ON}$ and $C_{UV,\ OFF}$ are the steady-state bacterial concentrations in the indoor air with and without UVGI respectively.

Simulated space

The simulated space is a 4.5m × 4m × 3m hospital room that contains two simplified beds with two underlying patients represented by rectangular blocks each measuring 1.75 m long, 0.5 m wide, and 0.2 m high and having a body surface temperature of 32°C. The patients are facing up and each emitting 1,400 cfu/min of *S. aureus* by breathing. The mouth openings are assumed circular of area 1.2 cm^2 [19]. An exhalation flow rate of 0.7 L/s [20] with temperature of 34°C is used in the simulations. Two bare 18 W UVC lamps are installed at a height of 2.3 m on two opposite walls as shown in Fig. 1. The room walls are assumed to be adiabatic. For mixing ventilation, a wall-mounted supply grill and a ceiling-mounted exhaust opening are used (Fig. 1.a), while both are placed in the ceiling for the case of downward ventilation (Fig. 1.b). For displacement ventilation, the supply grill is located near the floor and the exhaust grill is mounted on the opposite wall near the ceiling (Figure 1.c). The positions of air openings are selected to be symmetrical to the midplane (y-z) in all simulated cases. Another criterion for openings positioning is to protect the patients from air drafts when relatively high supply velocities are used. All ventilation systems provide cold air supply at 18°C and the air simulations are carried out with the same ventilation rate of 4 ACH.

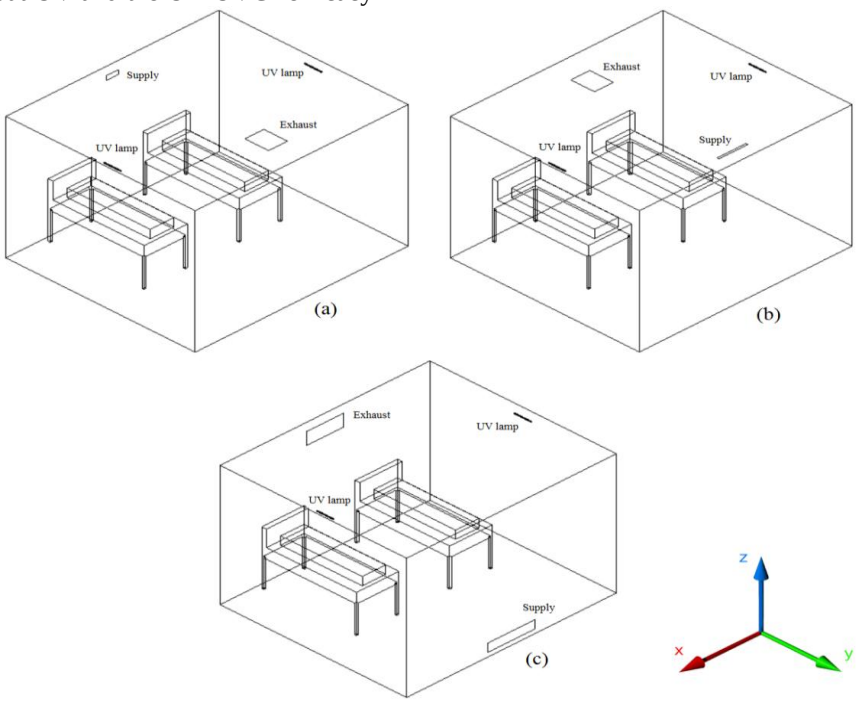

Figure 1. Schematic of the patient room with (a) mixing ventilation, (b) downward ventilation, and (c) displacement ventilation

Bacteria transport and UV inactivation

The Eulerian approach is used to simulate the transport of airborne bacteria. The deposition and gravitational settling of droplet nuclei are neglected. The developed CFD model is meant to solve the following transport equation:

$$\nabla \cdot (UC) - \nabla \cdot [(D + D_t)\nabla C] - E.Z.C = 0 \qquad (2)$$

where U is the air velocity field, C is the bacterial concentration, D is the Brownian diffusivity, and D_t is the particle Eddy diffusivity. The last term, $E.Z.C$, in Eq. (2) is a spatial sink term that represents the rate of inactivation due to the UV field where E is the UV irradiance at the centroid of a grid cell and Z is the microorganism susceptibility to UV light. The value of Z = 0.35 m^2/J is used for *S. aureus* [21].

The UV fields are determined using the published model of Wu et al. [22]. This model was reported to be more precise in predicting the UV irradiance in the proximity of the UV lamp, with error less than 0.1 W/m^2, than in the remote region (more than 2 m away from the lamp). A user-defined function (udf) is developed in programming language C++ and is used to incorporate the UV irradiance model into the CFD code. A similar CFD-UV model was developed and experimentally validated in [23].

Table 1. Simulation parameters for the three ventilation systems

	Cell count	Boundary conditions
Mixing ventilation	832,605	Velocity inlet, 2.3 m/s, Turbulence intensity: 5%, Hydraulic diameter: 0.145 m, Temperature: 18°C. Pressure outlet, pressure: 0 Pa
Downward ventilation	831,530	Velocity inlet, 2.3 m/s, Turbulence intensity: 5%, Hydraulic diameter 0.08 m, Temperature: 18°C. Pressure outlet, pressure: 0 Pa
Displacement ventilation	838,278	Velocity inlet, 0.335 m/s, Turbulence intensity: 5%, Hydraulic diameter 0.33 m, Temperature: 18°C. Pressure outlet, pressure: 0 Pa

Convergence of the solution is obtained when the scaled residuals reach 5×10^{-5}, the mass and heat imbalances become less than 1% of the minimal reported flux, and the value of bacteria concentration at the room exhaust is stabilized.

CFD Methods

A tetrahedral mesh ensuring the solution grid independence is generated for the simulated room in each of the three ventilation cases with refinement around openings. The mesh quality is ensured with maximal skewness less than 0.9. The geometry is divided into two zones: an occupied zone that extends from the floor to the height of 1.2 m (height of a seated adult) and an upper zone. The realizable k-epsilon turbulence model is used to simulate the air flow. This model was found to predict the indoor airflows, especially air recirculation, more accurately than the standard k-epsilon model [24]. The Boussinesq approximation is used for buoyancy modeling. Second-order schemes are used for discretizing the governing equations and the implicit SIMPLE algorithm is adopted for coupling pressure and velocity. Standard wall functions are used without special treatment as the focus of this study is on the bulk airflow and the deposition of droplet nuclei onto walls is negligible. The inlet parameters used for mixing ventilation and downward ventilation are practical and consistent with literature [25]. For the case of displacement ventilation a lower velocity is used as required to obtain air stratification and thermal comfort [26-27]. The settings and boundary conditions used in the simulations are summarized in Table 1.

RESULTS AND DISCUSSION

Air flow patterns

Figure 2 shows a comparison of airflow patterns on the midplane (y-z) in the three ventilation systems. For mixing ventilation (Fig. 2.a), the supply jet moves horizontally toward the opposite wall and then is directed downward which promotes air mixing within the room. Similar mixing effect is produced in the case of downward ventilation (Fig. 2.b) where the descending supply jet hits the floor and then moves toward the adjacent wall. In the displacement ventilation system (Fig. 2.c), the cool air supplied at relatively low velocity extends on the floor, warms up, and then moves upward by buoyancy. Air recirculation in the upper zone is observed as well.

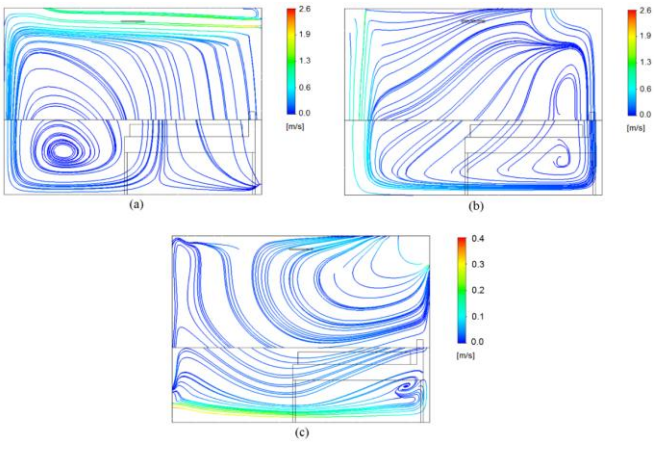

Figure 2. Air flow patterns in the room with (a) mixing ventilation, (b) downward ventilation, and (c) displacement ventilation

Bacteria concentration fields without UVGI

A comparative plot of *S. aureus* distribution on a sampling plane (x-z) without the use of UR-UVGI for the three

ventilation systems is shown in Fig. 3. In all cases, the exhaled particles are immediately entrained by the upward thermal plumes. For both mixing and downward ventilation, the exhaled jets spread to the ambient room air and are diluted by ventilation air. More dilution is achieved in the case of mixed ventilation since the exhaust opening is right above the bacteria sources, then a large number of particles are immediately vented out of the room. With displacement ventilation, the exhaled jets only spread and mix in the upper zone. These results are consistent with the findings of [28].

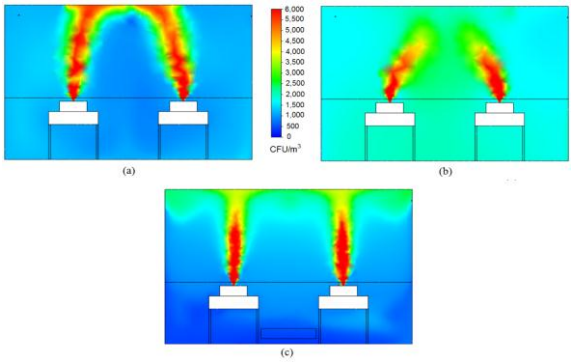

Figure 3. *S.aureus* distribution without UVGI on sampling plane (x-z) for (a) mixing ventilation, (b) downward ventilation, and (c) displacement ventilation

Bacteria concentration fields without UVGI

Figure 4 shows the *S. aureus* concentration fields on the same sampling plane (x-z) in the three ventilation systems when the two UV lamps are on. For the cases of mixing and downward ventilation (Fig. 4.a,b), significant reduction in bacterial concentrations is achieved because of perfect mixing of indoor air and interaction between the upper irradiated zone and lower zone. Figure 4 (c) shows that in the displacement ventilation system the bacteria concentration is reduced noticeably in the recirculation (upper) zone only. This can be explained by the buoyant behavior of displacement flow that transports air contaminants upward to the upper zone and often leaves the uni-directional (lower) zone with healthy air quality without the need for UVGI.

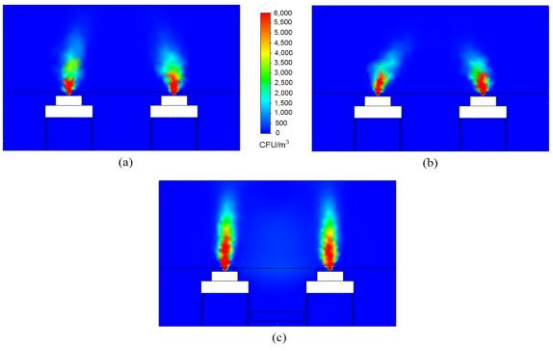

Figure 4. *S.aureus* distribution with UVGI on sampling plane (x-z) for (a) mixing ventilation, (b) downward ventilation, and (c) displacement ventilation

Table 2 shows the volume-averaged *S. aureus* concentrations in the occupied and upper zones of the patient room for each ventilation system with and without the use of UVGI. The corresponding disinfection rates achieved in each zone are also presented.

Table 2. Volume-averaged bacteria concentrations in the occupied and upper zonewith and without the use of UVGI and corresponding disinfection rates

		S. aureus concentration (cfu/m^3)		Disinfection rate (%)
		Without UVGI	With UVGI	
Mixing ventilation	Occupied zone	886	0	100
	Upper zone	1,202	2	99.8
Downward ventilation	Occupied zone	1,632	0	100
	Upper zone	1,650	3	99.8
Displacement ventilation	Occupied zone	500	110	78
	Upper zone	1,040	121	88

CONCLUSIONS

A steady-state three-dimensional CFD model was developed to investigate the effectiveness of UR-UVG in reducing the concentration of *S. aureus* in a two-bed patient room with three different ventilation systems: mixing, downward, and displacement ventilation. The Eulerian approach was used in the simulations to determine the bacteria concentration fields by predicting the dispersion patterns of the exhaled pathogen-carrying particles with and without the presence of UVGI. The deposition onto solid surfaces and gravitational settling of the particles are neglected since the study addresses the airborne part of cross-infection where pathogens are carried by droplet nuclei (1-5µm) that remain suspended in the air for prolonged periods of time. The UR-UVGI system consisting of two 18 W UVC lamps can achieve disinfection rates as high as 99.8%-100% with mixing and downward ventilation. In these cases, the infectious microorganisms will have a large number of passes in the UV zone and then receive sufficiently high UV dose. Lower disinfection rates are obtained in the case of displacement ventilation i.e. 78% in the occupied zone where the air flow is unidirectional and 88% in the upper zone where the pathogens likely receive lower UV dose than in the cases of mixing and downward ventilation.

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