Computational fluid dynamics modelling of UR-UVGI lamp effectiveness to promote disinfection of airborne microorganisms

Mohammad Heidarinejad*

Department of Mechanical Engineering,
The Pennsylvania State University,
127 Reber Building,
University Park, PA 16802, USA
Fax: 814-863-4789
E-mail: muh182@psu.edu
*Corresponding author

Jelena Srebric

Department of Architectural Engineering,
The Pennsylvania State University,
104 Engineering Unit A,
University Park, PA 16802, USA
Fax: 814-863-4789
E-mail: jsrebric@engr.psu.edu

Abstract: This paper focuses on using computational fluid dynamics (CFD) modelling methods to study the effectiveness of upper-room ultraviolet germicidal irradiation (UR-UVGI) lamps in healthcare facilities. This work develops and uses simplifications for boundary conditions in CFD, while details of UR-UVGI lamps and microorganism characteristics were obtained from existing experimental studies. Three approximation methods were developed to implement the effects of UR-UVGI lamps on microorganism dispersion patterns represented with the Eulerian and the Lagrangian methods in CFD simulations. Then, a non-dimensional parameter, the UR-UVGI effectiveness, was introduced to study the effectiveness of UR-UVGI lamp(s) disinfection process with respect to the combined effect of UR-UVGI lamp(s) and ventilation systems. Although comparisons of results obtained from CFD simulations and experimental data show that local microorganism numbers/concentrations depend on boundary condition modelling methods, global variables such as the fraction of remaining microorganisms remain relatively unchanged and in a good agreement with the measured data.

Keywords: UR-UVGI lamps; UR-UVGI lamp effectiveness; computational fluid dynamic; CFD; airborne microorganism; healthcare facilities.

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Biographical notes: Mohammad Heidarinejad is currently a PhD candidate in Mechanical Engineering at The Pennsylvania State University (PSU). He received his Bachelor of Science from Sharif University of Technology, Iran, in Mechanical Engineering and his Master of Science from The Pennsylvania State University in Architectural Engineering. This paper is based on his Master thesis findings. He received ASHRAE Graduate Grant-in-Fellowship for 2009–2010. He published a dozen papers in international conferences and journals. He is also co-author of three books.

Jelena Srebric is a Professor of Architectural Engineering and Mechanical Engineering at The Pennsylvania State University. She holds a PhD from the Massachusetts Institute of Technology. She conducts research and teaches in the field of building science. Her work is sponsored by grants from NSF, NIH, DOE, ASHRAE and industry. She is a recipient of both NSF and NIOSH's career awards. She has received several research awards, including the Yaglou award from the International Academy of Indoor Air Sciences. She is an editorial board member of five international journals. Her work in ASHARE was recognised with an outstanding service award.

1 Introduction

Computational fluid dynamics (CFD) has been recently used to study the transport and dispersion of airborne microorganisms as well as to evaluate opportunities for the disinfection of healthcare facilities. CFD results have predicted potential exposure to contaminants in many healthcare facilities, such as patient rooms (Balocco, 2011). Not only have CFD results been used to predict potential exposure to contaminants, but they have also been used to establish a connection between the airborne transport of microorganisms and the outbreak of widespread diseases such as SARS (Yu et al., 2004).

The growing interest in the transport and dispersion of the airborne microorganisms has revealed a need to disinfect indoor environments within buildings. This disinfection process inside of buildings promotes the occupants' health due to decreased risk of occupants' exposure to microorganisms. A practical way to disinfect spaces with known presence of microorganisms, such as patient rooms, healthcare facilities environments, and microbiology laboratories, uses upper-room ultraviolet germicidal irradiation (UR-UVGI) lamps to reduce microorganism dispersion in indoor environments (Memarzadeh et al., 2004). It is believed that UVGI lamps damage the DNA of a wide range of microorganisms, killing them immediately or preventing their multiplication, which is a process called inactivation (Shechmeister, 1991; First et al., 1999; Bolashikov and Melikov, 2009). In the inactivation process, the UV-c emitted from the UVGI lamp renders the microorganisms harmless to the occupants' health (Brickner et al., 2003; CIE, 2003). On one hand, UR-UVGI lamps can be useful to disinfect patient rooms; on the other hand, the same radiation wavelength can be harmful to the occupants' health. Therefore, there is a need to experimentally and computationally study effectiveness of UR-UVGI lamps in more detail.

Effectiveness of air cleaning technologies is generally defined as a non-dimensional parameter that shows how successful a disinfection air cleaning technology can be. This parameter is the difference between the contaminant concentration when the air cleaning system is 'on' and when the system is 'off' divided by the contaminant concentration when the air cleaning system is ‘off’ (Nazaroff, 2000). This definition of the effectiveness of air cleaning systems enables a performance comparison of different air cleaning systems by modelling the system and contaminant of interest (Howard-Reed et al., 2008). However, in this definition, it is difficult to relate other non-dimensional parameters, such as ventilation efficiency, to the effectiveness of air cleaning systems. Therefore, there is a need to introduce a non-dimensional parameter that includes inherent variables in the definition of an air cleaning system effectiveness.

Several research studies have been focused on the usage of UR-UVGI lamps to disinfect indoor environments. First et al. (1999, 2007), Xu et al. (2003), as well as Rudnick and First (2007) experimentally studied and assessed the performance of UR-UVGI lamps in a patient room. Memarzadeh et al. (2004), Noakes et al. (2004, 2006), Sung et al. (2008, 2009), Sung and Kato (2010), as well as Li et al. (2009) used CFD to study the effectiveness of UR-UVGI lamps in different patient rooms. Experimental and computational studies have shown that both experimental and computational methods should be complementary used to predict the effectiveness of UR-UVGI lamps in a patient room. For instance, experimental studies can provide reliable results, yet depending on the situation, the measurements can be too expensive, or impossible to acquire. Computational studies are relatively cheap, but they can be unreliable, if not validated with measured data. Specifically, for computational studies, it is vital to select appropriate approximations for modelling and boundary conditions (Srebric and Chen 2001). This need creates uncertainties with regards to the UVGI lamp modelling methods used in CFD studies. For example, First et al. (1999) suggested relying on experimental methods until the CFD modelling methods became readily available. Overall, a comparison between existing studies shows that there is a need to use these experimental and computational methods together. Therefore, this paper uses and develops a new modelling method that uses the experimentally measured UV irradiance field and implements it into CFD simulations. The new modelling method provides reliable results that can be used to study the effectiveness of UR-UVGI lamps in patient rooms.

One of the main important parameters when considering the UR-UVGI lamps within CFD studies is related to the implementation of UV irradiance fields inside of the CFD simulation domain. A comparison between the UR-UVGI lamp CFD and experimental studies shows that implementation of the UR-UVGI lamp effects have not been done in the experimental studies. For example, experimental studies can be categorised into two groups:

1. research studies that only measure UV irradiance intensity values of UVGI lamps to assess resultant irradiance field and do not have a microorganism source(s)
2. research studies that use an environmental chamber with a known existing microorganism source(s) and installed UR-UVGI lamp(s) to measure the effectiveness of UR-UVGI lamps.

Table 1 Existing CFD research studies of microorganism transport in the presence of UR-UVGI lamps

Study	*Year*	*CFD approach*	*Room dimension*	*UV irradiance modelling*
Alani et al.	2001	Lagrangian	4.5 m × 3.5 m × 2.7 m ($42.5\ m^3$)	Analytical
Noakes et al.	2004	Eulerian	4.26 m × 3.35 m × 2.26 m ($32\ m^3$)	Analytical
Memarzadeh et al.	2004	Lagrangian	4.6 m × 2.97 m × 3.05 m ($41.7\ m^3$)	Analytical
Noakes et al.	2006	Eulerian	4.26 m × 3.35 m × 2.26 m ($32\ m^3$)	Analytical
Sung et al.	2008	Eulerian	5.4 m × 6.0 m × 2.7 m ($87.5\ m^3$)	Experimental
Sung et al.	2009	Eulerian	5.4 m × 6.0 m × 2.7 m ($87.5\ m^3$)	Experimental
Heidarinejad and Srebric	2009	Eulerian	4.6 m × 2.97 m × 3.05 m ($41.7\ m^3$)	Experimental
Li et al.	2009	Eulerian	4.26 m × 3.35 m × 2.26 m ($32\ m^3$)	Analytical
Sung and Kato	2010	Eulerian	5.4 m × 6.0 m × 2.7 m ($87.5\ m^3$)	Experimental
Heidarinejad and Srebric	2011	Eulerian + Lagrangian	4.6 m × 2.97 m × 3.05 m ($41.7\ m^3$)	Experimental

For the first group of studies, devices, such as actinometry, measure values of UV irradiance in discrete locations (Rahn 2004; Schaefer et al., 2007). For the second group of studies, microorganisms are typically sampled at the chamber exhaust for UVGI lamps ‘on’ and ‘off’, so the lamp performance can be directly measured. However, CFD studies usually do not use experimental data and typically derive UV irradiance field based on analytical methods, such as the view factor method (Kowalski, 2001). This method has been successfully used for in-duct UVGI lamps in air handling units (AHUs) where the geometry of the modelling domain is relatively simple and can be approximated as a two-dimensional problem. However, the view factor method has not been used for UR-UVGI lamps in patient rooms since the derivation of three-dimensional UV irradiance field is complex and can create erroneous results. With reference to past CFD studies, Sung et al. (2008) experimentally measured the UV irradiance field from a UVGI lamp in a dark room and then integrating the UV values into the CFD simulations. In addition, Sung et al. (2009) show that the distribution of the UV irradiance field in an indoor environment has significant effects on the inactivation process. Table 1 compares the UV modelling methods for existing CFD studies.

Throughout the literature review, two microorganism modelling methods including the Lagrangian and Eulerian methods have been employed. The Eulerian method successfully predicts the distribution of contaminant concentration in indoor environments (Zhao et al., 2004, 2005; Mui et al., 2009). On the other hand, Lagrangian method has been widely used to simulate coughing, inhaling, and exhaling process of human occupants (Zhang and Chen, 2006, 2007). However, only a few studies have used CFD to study the effectiveness of UR-UVGI lamps in indoor environments as shown in

Table 1. Therefore, the present study uses experimentally measured UV irradiance values in a model patient room to input them into CFD simulations. More specifically, this study develops and uses three different methods to implement the measured UV irradiance intensity values into both Eulerian and Lagrangian CFD simulation methods.

2 Research methodology

This research study simulates an environmental chamber located at the Harvard School of Public Health, which was designed and built to mimic a patient room with a microorganism source located in the centre of the room (First et al., 2007; Rudnick and First, 2007). In the CFD simulations, the environmental setup including supply, exhaust, microorganism source, visible lamps, and the UR-UVGI lamp(s) sizes and positions have been kept as close as possible to the real environment. However, there are discrepancies between the experimental setup and CFD simulations due to pieces of missing information. Thus, discrepancies between CFD and experimental results could have originated from assumptions that had to be introduced. Those assumptions are:

1 heat fluxes were assigned to the environmental chamber walls even though the environmental chamber was highly insulated

2 heat fluxes were assumed for visible lamps based on regular visible lamp heat dissipation

3 the microorganism source was modelled based on a regular nebuliser performance

4 supply and exhaust positions and velocities were selected based on other research studies that simulated the same chamber.

The Reynolds averaged Navier-Stokes equations along with RNG $k - \varepsilon$ were used to simulate turbulent indoor airflow. The room domain was discretised into more than 215,000 cells to ensure grid independency of simulations. All variables, except the pressure term, were discretised with the second-order upwind scheme. For the pressure term, PRESTO! scheme was used. For coupling pressure and velocity, this paper used the SIMPLE algorithm.

This research study shows that effects of UR-UVGI lamps and ventilation systems can be studied using CFD. A new scale, UR-UVGI lamp effectiveness, is derived based on definition of contaminant removal effectiveness to study combined effects of UR-UVGI lamp and ventilation systems. Furthermore, a new UV irradiance field modelling method for CFD studies was developed.

2.1 Definition of UR-UVGI effectiveness ($\eta_{UR\text{-}UVGI}$) as a new non-dimensional performance parameter

In the UR-UVGI studies, global parameters, such as a fraction of remaining microorganism, are mostly used to express the effect of UR-UVGI lamp(s) on the dispersed microorganisms. The fraction of remaining microorganism is defined as the microorganism concentration at the exhaust when the UVGI lamp is 'on', $C_{ex_{on}}$, divided by the microorganism concentration when the UR-UVGI lamp is 'off', $C_{ex_{off}}$. This non-dimensional parameter quantifies the total effect of UR-UVGI lamp(s) on the microorganisms. Equation (1) shows the fraction of remaining at the exhaust.

$$f_{ss} = \frac{C_{ex_{on}}}{C_{ex_{off}}} \tag{1}$$

This number is less than one, and it varies in the range of zero to one. Depending on the air exchange rate and the strength of UR-UVGI lamp, this value can vary. Results section discusses the effect of these variables on the fraction of remaining microorganism. This non-dimensional parameter inherently includes effects of both HVAC system and UR-UVGI lamp(s) system. However, to reorganise the effect of these two distinct systems, this study proposes a new non-dimensional parameter. This new parameter originates from the definition of the contaminant removal effectiveness (ε) in the literature (Novoselac and Srebric, 2003). This parameter provides assessment of contaminant removal with known position and generation rate. Equation (2) shows the original definition of this parameter:

$$\varepsilon = \frac{C_{ex} - C_s}{< C > - C_s} \tag{2}$$

In equation (2), C_{ex} is the contaminant concentration at exhaust, C_s is the contaminant concentration at supply, and $<C>$ is the room average concentration. This equation needs to be adopted for the UR-UVGI lamp(s) studies. The main source of contamination in the patients' room is the microorganisms generated from the patients. In the experimental studies the microorganisms generates from the nebulisers and mostly the supply does not disperse any microorganism concentration into the room. Consequently, equation (3) shows the revised form of contaminant removal effectiveness for the patient room with UR-UVGI lamp(s).

$$\varepsilon = \frac{C_{ex_{off}}}{< C >_{off}} \tag{3}$$

The value of ε is related to the ventilation effectiveness, and the approximate value of ε is available in the literature for popular ventilation systems. Moreover, the fraction of remaining can be rewritten into equation (4) representing the effectiveness of the UR-UVGI system:

$$\eta_{UR-UVGI} = 1 - f_{ss} = 1 - \frac{C_{ex_{on}}}{\varepsilon < C >_{off}} \tag{4}$$

This parameter can have values from zero to one. Perfect disinfection, or the case of this study perfect inactivation, occurs when the UR-UVGI lamp effectiveness is close to one, and it shows that the indoor space is completely disinfected. The lower limit of the UR-UVGI lamp effectiveness, zero, can be named as poor disinfection since the UR-UVGI lamp(s) does not have any influence in the microorganisms disinfection. Equation (4) enables different ventilation system effectiveness to be taken into account, so that the actual ventilation system can be accounted for rather than assuming that the ventilation system creates perfect mixing in a patient room. The perfect mixing assumption certainly does not hold for displacement ventilation or natural ventilation. In addition to accounting for real ventilation system, it is important to account for the real UV irradiance field.

2.2 UV irradiance modelling Methods in CFD studies

This paper develops and uses UV irradiance modelling methods to integrate the UV irradiance field into CFD simulations. In general, irradiance is defined as the UV power received on a surface divided by the area of that surface. Several research studies have explored various methods to experimentally measuring of UV intensity emitted from UVGI lamp(s) (Rahn, 2004). The present study uses experimental measurements of UR-UVGI lamp irradiation in a model patient room to implement this UV irradiance field into CFD software packages (Rudnick et al., 2012). Moreover, depending on the lamp configurations and position of lamps, UV irradiance values were developed. The implementation of the UV irradiance field uses various modelling methods and simplifications that are presented in the order of simplest ones to most complex. These modelling methods and simplifications are:

1 using a single averaged intensity value for the UV irradiance field in the upper-zone region

2 using different configurations of multi-averaged UV irradiance intensity values in the upper-zone region

3 using local UV irradiance intensity values for each measured point in the upper-zone region.

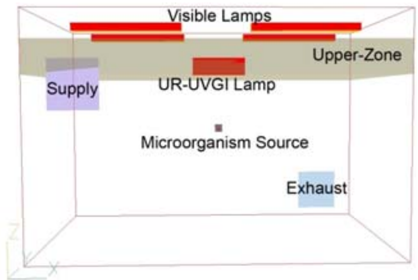
This paper used the Eulerian method to implement the first two UV modelling methods, and the Lagrangian method for the third method. Finally, this research study conducted sensitivity analyses for these three UV modelling methods in CFD simulations.

2.2.1 Single averaged UV intensity modelling

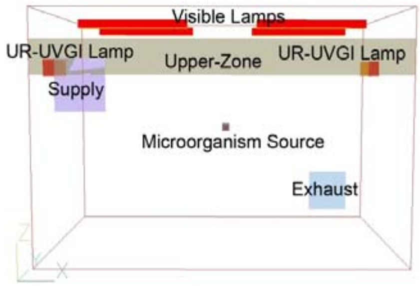
In this method, the entire upper-zone is associated with a single averaged UV intensity value. The upper-zone region represents the effects of UR-UVGI lamp(s) in the model patient room. First et al. (1999) measured UV intensity of UV lamps; this research study suggested that at a distance of up to 3 m from the louvered lamp fixtures, 95% of the emission is confined to a 30 cm band height. Therefore, this method is valid and applicable for the UV modelling method. More details about advantages and disadvantages will be discussed and compared with other methods at the end of this section. In Figure 1 the shaded zone, named the upper-zone region, shows the single averaged UV intensity value region as implemented into CFD simulations.

Table 2 shows several configurations for the selection of a single averaged UV irradiance intensity value depending on the three different volumes (heights) of the upper-zone region, which are based on their relative position to the UR-UVGI lamp from the lamp bottom elevation as shown in Figure 1 configurations. It is important to note that the selection of UV volumes needs careful consideration. This consideration should include tradeoffs between the height of the upper-zone region and its relative position to the lamp (Heidarinejad and Srebric, 2011).

Figure 1 Representation of the UV irradiance field with a single averaged value within the thin horizontal layer named upper-zone region of the room, (a) one UR-UVGI lamp installed on the long wall (b) two UR-UVGI lamps installed on the short walls (see online version for colours)



(a)



(b)

Table 2 Averaged values of the UV irradiance field based on experimental data for different volumes of the upper-zone region positioned at the bottom of the UR-UVGI lamps elevation

Configuration in Figure 1	*(a)*	*(b)*	*(a)*	*(b)*	*(a)*	*(b)*
Height of UV zone (cm)	67		41		10.6	
UV average value ($\mu W/cm^2$)	33.9	26.27	49.9	21.92	17.4	4.5

2.2.2 Multi-averaged UV intensity modelling

This research study has suggested and developed a more complex uniform UV irradiance modelling method that accounts for the height and position of UV lamp(s). In this UV irradiance modelling method, instead of using a uniform single averaged UV irradiance intensity value for the whole upper-zone of the room, several UV volumes with uniform averaged UV irradiance intensities were used to represent effects of UR-UVGI lamps on the microorganisms as shown in Figure 2. Similar to the single averaged method, implementation of this method needs careful consideration to take into account the position and height of UV volumes, in addition to the height of the upper-zone region and its relative position to the lamp. Figure 2 shows position and area of actual and approximated UV irradiance distribution. In this figure, solid lines represent an actual UV irradiance distribution and dashed lines represent volumes with approximated averaged values of the UV irradiance field.

2.2.3 Local UV irradiance intensity modelling

The local UV irradiance intensity modelling uses discrete UV intensity values in the upper-zone to represent the effects of UR-UVGI lamps. Discrete experimental UV intensities were used for 85 points in the upper-zone region of the model patient room (Rudnick et al., 2012). Then, based on these existing 85 points, a three dimensional interpolation and approximation was used to compute a local UV intensity distribution for the upper-zone region. In the present research study, the Lagrangian method uses this UV modelling method. Local UV intensities have been implemented into CFD control volumes during the post-processing stage. Then, based on the residence time of each particle and the susceptibility of the microorganisms, the local UV irradiance field can result in the inactivation of microorganisms. Figure 3 shows two samples of a horizontal cross-section of UV irradiance field distribution for the two UV lamp configurations outlined in Figure 1.

Figure 2 A horizontal cross section at the lamp elevation for actual and approximate UV irradiance fields, (a) one UR-UVGI lamp installed on the long wall (b) two UR-UVGI lamps installed on the short walls

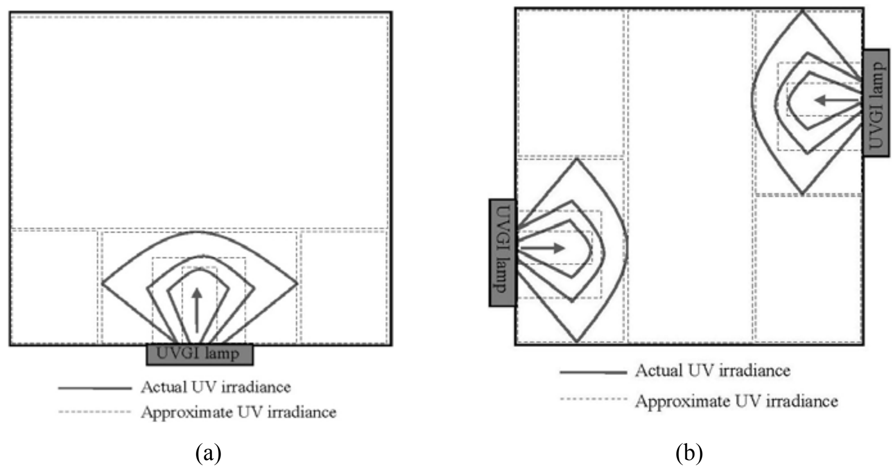
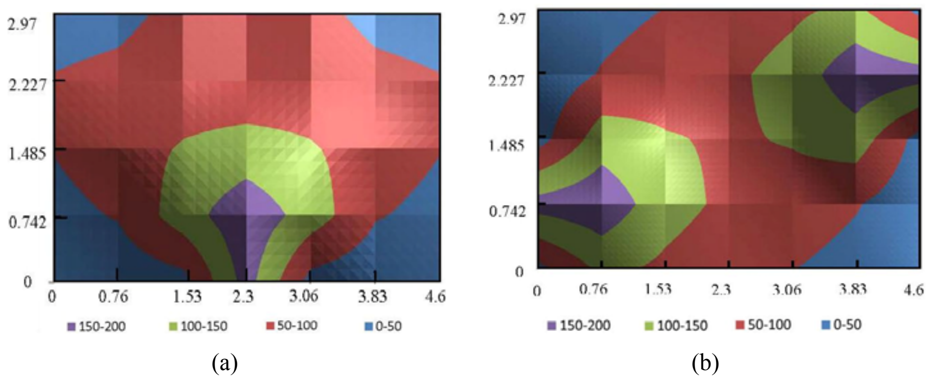


Figure 3 Local UV irradiance values (μW/cm^2) in a horizontal plane, 2.3 m from the floor, (a) one UR-UVGI lamp installed on the long wall (b) two UR-UVGI lamps installed on the short walls (see online version for colours)



2.2.4 Comparison of the three proposed methods for UV irradiance modelling

Each of the proposed three UV irradiance modelling methods has advantages and disadvantages that play a role when selecting an appropriate method for a particular study. Table 3 compares advantages and disadvantages of these three UV modelling methods.

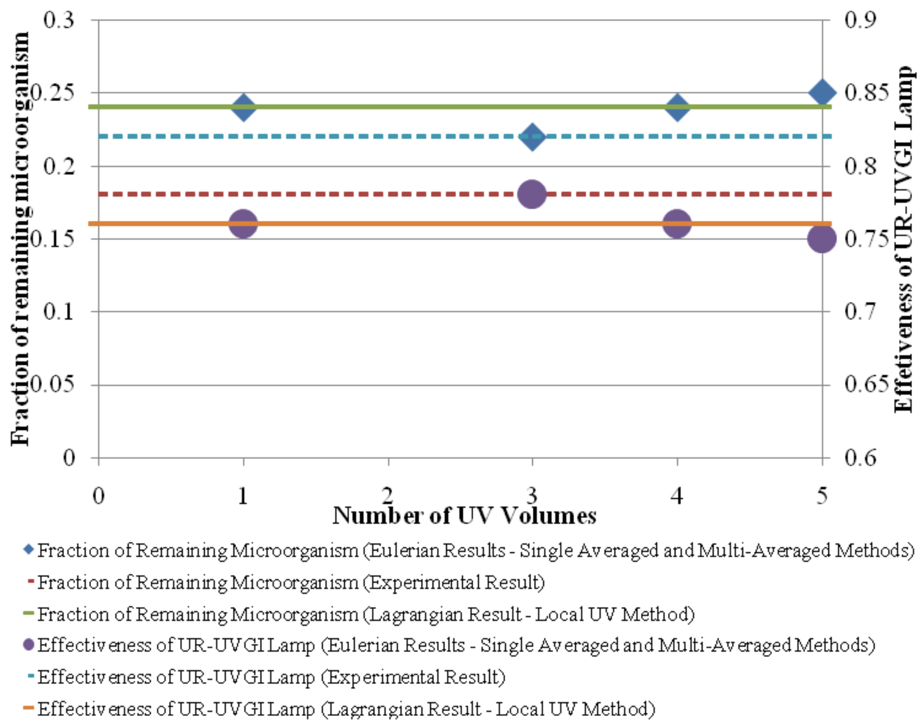
Table 3 UV irradiance implementation methods in CFD studies with installed UR-UVGI lamp(s)

UV irradiance modelling method		*Advantage(s)*		*Disadvantages(s)*
Single averaged UV irradiance modelling	1	This method is applicable in the limited resources area where there is not enough information about the UR-UVGI lamp(s) configuration and sizes. This method of UR-UVGI lamp modelling method in the CFD simulations can be used to implement effects of UR-UVGI lamp	1	This method is a rough estimation of UV irradiance intensities in the upper-zone of the room. Consequently, effects of UR-UVGI lamp(s) on microorganisms are not modelled accurately.
	2	This method is simple. Simplicity of this method in the implementation stage of UV field into the CFD software (or code) is one of the main advantages of this method.	2	Selection of Upper room UV zone has an effect on the results. Selection of upper room UV height and position somehow depends on the user that works with the CFD software.
Multi-averaged UV irradiance modelling	1	This method still is computationally easier than the local UV irradiance intensity value method while still keeping simplicity of the single averaged UV irradiance intensity value method.	1	This method still uses a rough estimation to model UR-UVGI lamps in the upper- zone of the room.
			2	Similar to the single averaged method, selection of uniform averaged UV intensity volumes depends on the CFD users.
Local UV irradiance intensity modelling	1	This method contains details of UV irradiance field in the upper-zone.	1	The implementation of this method is computationally more intense than the two other methods.
	2	This method is suitable for comparison of local variables.	2	This method needs detailed UV irradiance intensity values in the upper-zone region. The UV intensity values could be either measured experimentally or derived theoretically. Thus, initial measurements or calculations of local UV irradiance intensity values are crucial for this method
	3	There is no assumption for UV intensity values in the upper-zone. Therefore, this method assumes no simplification in the implementation of UV field into the CFD software.		

3 Results and discussions

This study implemented three UV modelling methods into the CFD simulations. More specifically, a sensitivity analysis used a single averaged and multi-averaged UV irradiance intensity value method for predictions of the microorganism inactivation process. The sensitivity analysis used 1, 3, 4, and 5 volumes to represent a distribution of the UV irradiance field. To understand sensitivity of global variables, such as the fraction of remaining and the effectiveness of UR-UVGI lamp(s), to number of averaging UV volumes, Figure 4 presents the global variables for the single averaged, multi-averaged, and local UV intensity value methods. The results vary with the number of UV irradiance averaged volumes. An increase in the number of UV volumes was expected to produce an asymptotic trend. However, the results do not show an asymptotic trend, so this analysis does not include the results for six, seven, eight, and nine averaged volumes.

Figure 4 The simulated fraction of remaining microorganisms and UR-UVGI effectiveness for a different number of UV irradiance averaging volumes with the Eulerian and Lagrangian methods (air changes per hour (ACH) = 2) (see online version for colours)



For the single averaged and multi-averaged methods, the implementation of UV irradiance field effects into CFD needs careful consideration to account for the position and height of the UV volumes. The selection of UV volumes for these two methods can be done by the proposed UV approximations described in Section 2.2.1 and Section 2.2.2. The present study suggested these UV approximations by comparisons of the experimental results and CFD simulation results for the fraction of remaining microorganisms obtained with the local UV irradiance intensity value method. Based on the comparisons, a guideline was considered to interpret the results of the single averaged and multi-averaged UV irradiance intensity methods. This guideline has helped this research study and hopefully could help future research studies to determine reasonable UV volume selections for the single averaged and multi-averaged method.

Based on the developed guidelines, the position and height of UV volumes were changed in the CFD simulations to explore the influence of these parameters on the accuracy of the simulated fraction of remaining microorganisms. Finally, 3, 4, and 5 volumes were selected for the multi-averaged methods in the Lagrangian representation of microorganisms. The three selected configurations of the multi-averaged UV irradiance field are the best configurations that have reasonable tradeoffs between the computational time of simulations and result accuracy. Furthermore, averaged UV irradiance intensity values were added as a sink term into the selected UV volumes to simulate the distribution of microorganism concentrations. These three configurations of 3, 4, and 5 volumes also can be implemented in the Eulerian method. Figure 5 shows the simulated global variables for both the Lagrangian and Eulerian methods. The single averaged and multi-averaged UV irradiance methods can be easily implemented in the Lagrangian method. In Figure 5, besides the local UV irradiance intensity values, for the inactivation process for each microorganism, a uniform UV irradiance field is applied to groups of particles depending upon their locations in the Lagrangian method.

Figure 5 The simulated fraction of remaining microorganisms and UR-UVGI effectiveness for a different number of UV irradiance averaging volumes with the Eulerian and Lagrangian methods (ACH = 6) (see online version for colours)

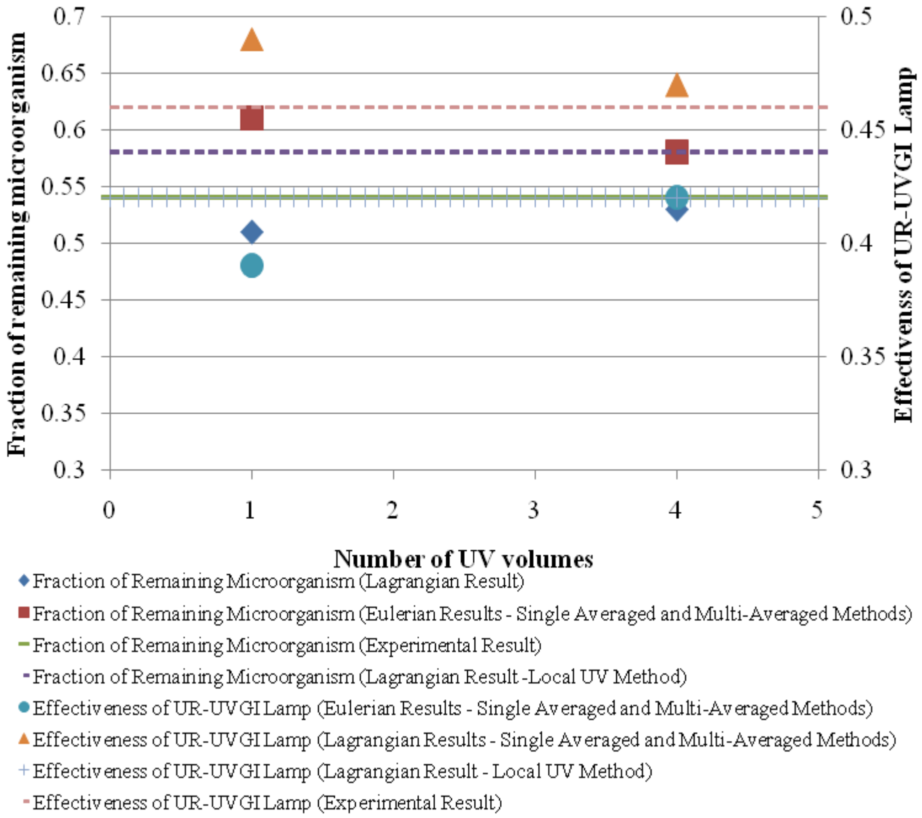
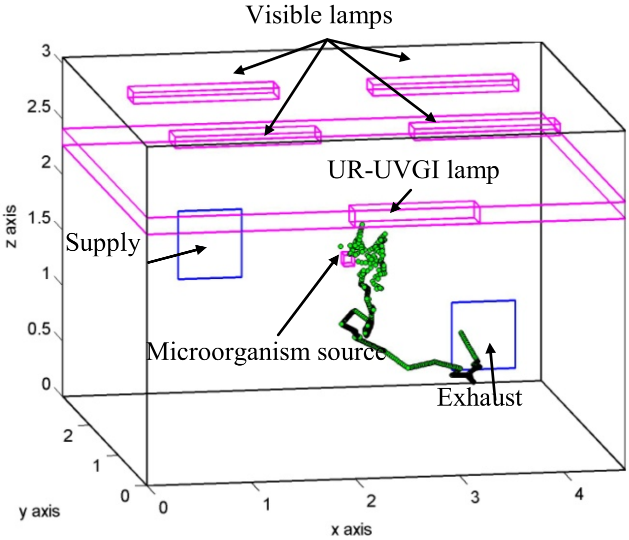
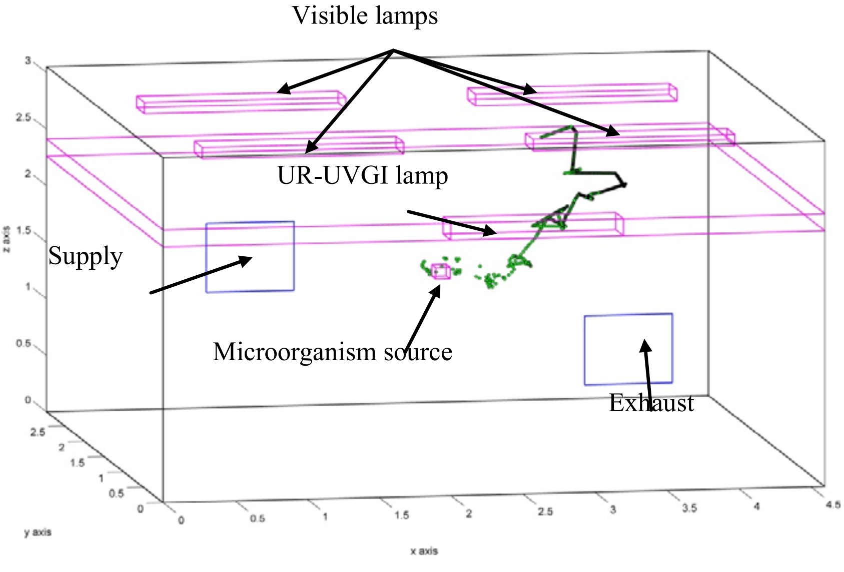


Figure 6 The trajectories for two different particles simulated with the single averaged UV irradiance intensity value method (ACH = 6), (a) a microorganism that has not been inactivated (b) a microorganism that has been inactivated in the upper-zone region (see online version for colours)



(a)



(b)

For the Eulerian method, the simulated fraction of remaining microorganism was calculated as the concentration of microorganism at the exhaust when the lamp was 'on' divided by the concentration of microorganism at the exhaust when the lamp was 'off'. For the Lagrangian method, the calculation of the fraction of remaining microorganism is a bit more complex. In this method, 10,000 particles were tracked in the simulations. Then, supplementary programs were developed to

1 draw trajectory of particles

2 implement derived UV irradiance modelling methods

3 couple the particle trajectories to UV irradiance modelling methods.

Furthermore, based on the residence time and UV irradiance exposure, the amount of dose was calculated for each microorganism. Figure 6 shows two actual scenarios for microorganisms' dispersion inside of indoor environments with installed UR-UVGI lamps on the long side wall of the model patient room. On one hand, Figure 6(a) shows a sample microorganism that did not have a chance to reach the upper room space. Consequently, for this microorganism, there is no need to implement UV irradiance modelling methods in the upper-zone region. On the other hand, Figure 6(b) shows another microorganism with a completely different trajectory. This microorganism reached to the upper-zone region of the room and based on the UV irradiance field and residence time values, it received sufficient dose to be inactivated. This individual tracking feature is one of the main advantages for the Lagrangian method over the Eulerian method.

It is important to consider computational time of simulations. In the initial stage of this research study, a commercial software package installed on a single desktop computer was used to determine the effectiveness of UR-UVGI lamp based on the Eulerian method (CHAM, 2009). In the next stage of this research study, a parallel version of this commercial software package was used to decrease computational time of simulations with the Eulerian method. For the Lagrangian method, simulations were submitted and analysed in high performance computer (HPC) nodes because this method is much more computationally demanding than the Eulerian method (Fluent 12, 2010). These nodes in the Lagrangian method utilised Intel Xeon 3160 Dual-Core 3.0 GHz CPU, but computers in the Eulerian method had Dual-Core 3.2 GHz CPU. Therefore, it was not completely possible for this study to directly compare computational time of simulations for these two methods. Table 4 compares the difference between computation times and number of computational nodes for these two methods for the same simulation domain.

Table 4 Comparison between the Eulerian and the Lagrangian method computational costs[1]

CFD method	*Computational time (hours)*	*Number of nodes*
The Eulerian method	~ O* (14)	8
The Lagrangian method	~O* (30)	16

Note: *Stands for order of magnitude

Table 4 shows that the computation time for the Lagrangian method is roughly twice the computation time for the Eulerian method. Other particle tracking simulation studies for indoor environments confirmed that the Lagrangian method can provide more details about microorganism trajectories, yet simulations are more computationally intense (Zhang and Chen, 2006; Zhao et al., 2004). For the Lagrangian method, besides the primary commercial CFD software package, supplementary computer programs were developed in the Matlab to implement the UV field and compute the inactivation of microorganisms (Mathworks, 2010). The Eulerian method does not require additional post processing, other than the simple display of results. Therefore, the Lagrangian method is also much more demanding than the Eulerian method in the post processing of results. Table 4 only compares computational time for the primary CFD simulation of particles. The results confirm that selection of UV implementation and CFD modelling method is vital to save the computational cost and post processing efforts. Thus, the proposed UV modelling methods, summarised in Table 3, provide a guideline for CFD studies to model the effectiveness of UR-UVGI lamp in patient rooms.

4 Conclusions

The study results show the importance of CFD approximations on the accuracy of calculated UR-UVGI effectiveness. Three irradiance UV modelling methods were suggested and deployed to explore tradeoffs between accuracy and computational efforts for the calculated global variables, the fraction of remaining microorganisms and the UR-UVGI effectiveness. For the single averaged UV irradiance intensity modelling method, a uniform UV intensity value is applied to all microorganisms in the upper-room region. In one hand, this method can simply represent the UV field effect on all microorganisms. On the other hand, this simplification could create erroneous results due to oversimplification of the real UV irradiance field. For the multi-averaged UV irradiance intensity modelling, depending on the location of microorganism source and UR-UVGI lamp(s), different averaged UV irradiance values was applied to microorganisms. Finally, in the third proposed method, there is no simplification for the UV irradiance intensity values in the upper-zone region. Therefore, this method used the interpolated local UV irradiance intensities based on experimental measurements. The results show that the global parameters, such as the fraction of remaining at the exhaust, are not very sensitive to the UV intensity simplifications, while the individual microorganism inactivation process is dependent on these simplifications. Furthermore, this study discussed effects of the UV irradiance field implementation methods in CFD simulations and developed a table that could help future UR-UVGI studies to find out the advantages and disadvantages of UV modelling methods in advance. Finally, a new non-dimensional parameter, the UR-UVGI effectiveness, was derived to assess performance of the UV lamp system together with the ventilation systems in the microorganism inactivation process.

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Notes

1 It would be more efficient comparison if we could compare the CFD simulations in the Table 4 with the same number of nodes. Unfortunately, due to the licensing issue, it was not possible to install the Fluent and PHOENICS software packages on the same HPCs that have the same number of nodes (Fluent 12, 2010; CHAM, 2009). Although the comparisons did not use the same number of computational nodes, simulation scenarios mentioned in the Table 4 could provide useful information about the computational cost of the Eulerian and Lagrangian simulations for future CFD studies. In Table 4, the Lagrangian simulations used a larger number of nodes and could not be performed with much smaller computational capacity. This comparison confirms that Lagrangian simulations are computationally much more expensive than the Eulerian simulations.