METRICS FOR INTERZONAL DISPERSION ASSESSMENT OF AIRBORNE SARS-COV-2 WITHIN OFFICE BUILDINGS

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Abstract

High ventilation rate is increasingly considered as a mitigation strategy for the airborne spread of COVID-19 in existing buildings besides other options like UVGI and indoor air filtration. However, similar measures may also impact energy efficiency of buildings in which they are installed. A careful comparison is necessary in making informed decisions to optimize the building performance while minimizing the risk of indoor airborne virus dispersion. Concrete metrics representing overall building performance can help compare various mitigation strategies to each other. Multizone airflow and contaminant transport simulations using CONTAM software involving parameters such as infiltration rate, system configuration, and level of occupancy can provide critical information on relative risk distribution within a building. In this study, the U.S. Department of Energy's detailed medium office prototype building is modelled in CONTAM to simulate the spread of airborne SARS-CoV-2 aerosols within different zones of an office building and different mitigation strategies are compared to each other. The goal of this study is to generate a set of suitable metrics that will give a whole-building picture of airborne SARS-CoV-2 virus distributions across the different zones of the building under different conditions and scenarios.

Keywords: COVID-19, SARS-CoV-2, airborne, ventilation, CONTAM

1 Introduction

Many widely accepted COVID-19 prevention strategies like frequent hand-washing and social distancing are designed for larger droplets (>5 μm). However, risk assessment and mitigation efforts for airborne viruses (aerosols <5 μm) require a deeper level of understanding about airflow patterns and more stringent mitigation strategies (Klompas, Baker, & Rhee, 2020). In expanding understanding of how SARS-CoV-2 spreads in indoor environments, modelling of airflow and contaminant transport in various types of buildings under various scenarios and conditions is crucial to complement experimental measurements, which are almost exclusively limited to the settings of hospitals and laboratories. However, many parameters associated with SARS-CoV-2, including the dose-response characteristics, viability and critical viral load in droplets and aerosols, are still not well-enough defined to definitively and quantitatively model the health risk posed by the virus. While greater building ventilation rates are increasingly being considered as a mitigation strategy in buildings, filtration and ultraviolet germicidal irradiation (UVGI) are important as well, and simplified metrics to quantify the building performance in terms of exposure vulnerability will allow the comparison of different mitigation strategies to each other under different operating conditions and in combination with other mitigation strategies. Multizone airflow and contaminant transport simulations involving parameters such as infiltration rate, system configuration, and level of occupancy can provide critical information on relative risk distribution within a building. Vulnerability-based metrics derived from such simulations can be helpful in quantitative comparison of various scenarios of contaminant dispersion within a building even without the availability of agent-specific or receptor-specific information. In this study, a simplified multizone airflow network model of a medium office prototype building is used to simulate various conditions and scenarios to semi-quantitatively study the dispersion of airborne SARS-CoV-2 viruses across different zones of a medium-sized office building.

2 Methods

The U.S. Department of Energy supports the development of commercial building energy codes and standards based on the prototype building models that represent approximately 80% of the commercial buildings by floor area use in the United States for new and existing construction, including mid- to high-rise residential buildings, across all U.S. Climate Zones (Goel et al., 2014). The prototype detailed medium office (PDMO) model is a 3-story building constructed slab-on-grade with 4978.6 m^2 (49.9 m by 33.3 m) of conditioned floor area per floor. The height of each floor is 2.74 m, with a 1.26 m high plenum in between each floor. Each floor has a "ribbon window" 1.3 m high on all sides of each floor. The reader is referred to Im, New, & Bae (2019) for the detailed design and configuration of the PDMO building. Contaminant dispersion modelling on the PDMO was developed and simulated using the multizone airflow and contaminant transport analysis software CONTAM (Dols & Polidoro, 2015). A simplified steady-state simulation was conducted with a constant ambient wind conditions (4.3 m/s wind blowing at 290 degrees, yearly average mode values for Chicago, IL 2019 data) and a constant indoor temperature of 20°C.

After setting up and running simulations of the CONTAM model, the technique developed at the Pennsylvania State University (DeGraw & Bahnfleth, 2011) was used for the vulnerability-based (relative) metric computation from the simulation results. Following this technique, a graphical form is used in which the exposure dose is plotted as a function of the fraction of the total building area.

Several scenarios were simulated using the model in which a single index person releasing viruses at a rate of 0.001 kg/s was located at various zones of the building. SARS-CoV-2 virus was given properties similar to a water droplet of size 0.1 µm (Zhu et al., 2020) and UVGI susceptibility constant of 0.021 m^2/J (Wladyslaw J Kowalski, 2020). Note that minor deviations of physical properties of the hypothetical pathogen is not anticipated to affect our analysis as this is a relative metric irrespective of a specific pathogen type. Scenarios were also simulated with the index person wearing a mask which reduced the rate of pathogen release by a factor of 50%. Next, outdoor air (OA) percentage in the AHS were varied between 0% OA (worst case scenario), 31% (the minimum OA% required for the building to comply with ASHRAE 90.1-2013 ventilation requirements), 50% OA, and 100% OA to investigate the degree of impact of ventilation on the building vulnerability. Finally, the impact of high-efficiency filter and UVGI system used in the AHS was also simulated. Filtration efficiency curve was user-defined in CONTAM to match that of a 20×25×5 inch MERV 13 filter (W.J. Kowalski & Bahnfleth, n.d.) and UVGI system parameters were defined by the Penn State UVGI filter default data in CONTAM as a design survivability of 0.01, design velocity of 4 m/s, design mass flow rate of 0.5 kg/s, organism-specific rate constant of 0.021 m^2/J.

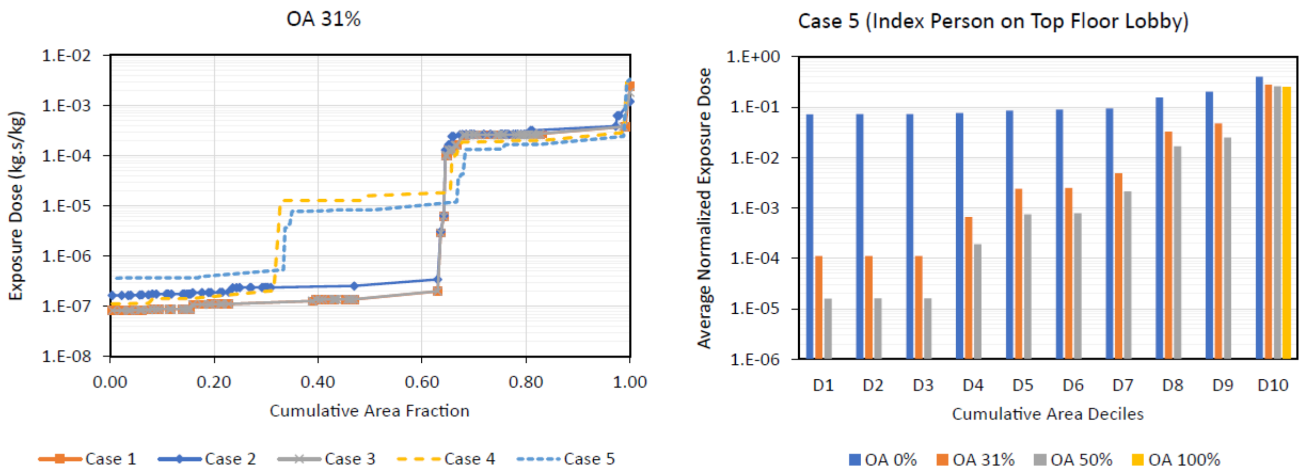
To make the comparisons concise in defining the degree of vulnerability of the building to pathogen, an exposure improvement score (EIS_{10}) was defined as:

$$EIS_{10} = \sum_{k=1}^{10} \alpha_k \frac{D_{\text{baseline},k} - D_k}{D_{\text{baseline},k}} \tag{1}$$

Where, the subscript 10 indicates that this is a decile-based score, α_k is the weight associated with each decile (equally distributed among all deciles in our case with α_k =10), $D_{\text{baseline},k}$ is the baseline result in decile k, and D_k is the candidate result in decile k. When the baseline case is taken as the release zone exposure dose, EIS_{10} gives an estimate of the degree to which the remainder of the building compares with the release zone exposure dose. A higher value of EIS_{10} implies that the overall building performance is good i.e. most of the building is less vulnerable.

3 Results

Figure 1 (a) compares the severity of exposure dose in the release zone (spike at the far right) compared to the cumulative whole building area fraction under the minimum required OA condition of 31%. First, the index person's location in the bottom floor was changed from one zone to another resulting in Cases 1 through 3. Case 4 represented the location of the index person in the middle floor lobby, and Case 5 represented the location of the index person in the top floor lobby. This display of the exposure dose indicates that the release zone experiences orders of magnitude higher exposure dose than the rest of the building, and moving away by each floor from the floor where the release zone is located results in a steep drop in exposure dose. Figure 1 (b) compares the normalized exposure doses for the whole building by binning all the zones (normalized by the highest exposure dose in the release zone) into ten cumulative area decile bins.



(a) ***(b)***

Figure 1. *(a) Ordered exposure dose as a function of cumulative area fraction, and (b) decile breakdown of exposure dose with varying OA ventilation rates.*

When varying OA percentages were simulated through the AHS (Figure 1 (b)), using 100% OA in the supply mix resulted in the least vulnerability of the building, as expected. But the drastic rate of decrease in overall building vulnerability was demonstrated even by the minimum required 31% OA compared to the worst case scenario of 0% OA. The exposure improvement scores calculated from Equation (1) are shown for individual simulation scenarios in Table 1. As seen from Table 1, the steep change in EIS_{10} values for cases in which there are no mitigation strategies available other than increasing OA% underlines the importance of increased ventilation rate for reducing potential exposure dose in most parts of the building.

Table 1. *Exposure improvement scores (EIS_{10} Values) for different simulation scenarios.*

S.N.	*Scenario*	*EIS_{10} Values*			
		0% OA	31% OA	50% OA	100% OA
1.	Index person in top floor lobby	67.02	86.72	88.25	90.00
2.	S.N. 1 with portable air purifiers in all high-occupancy zones *	88.20	88.95	89.30	90.00
3.	S.N. 1 with MERV 13 filter in each AHS	88.13	88.95	89.31	90.00
4.	S.N. 1 with UVGI system (only) in each AHS	85.96	88.51	89.24	90.00
5.	S.N. 3 with added UVGI system in each AHS	88.82	89.39	89.65	90.00
* High occupancy zones include open and enclosed office spaces, conference rooms and classroom (all floors)					

4 Conclusion

Metrics in graphical and quantitative forms were developed to compare various mitigation strategies for exposure risk reduction to airborne SARS-CoV-2 viruses being released by a hypothetical index person in a medium office prototype building. Based on the vulnerability metrics for several simulation scenarios studied in this study is evident that increasing ventilation rates in the building by increasing OA percentages at the AHS is very effective in reducing potential exposure dose in most zones of the building, even in absence or unavailability of other mitigation strategies. Other mitigation strategies including the use of a MERV 13 filter in the AHS and UVGI system showed drastic improvement in exposure dose reduction in majority of the building as well, but not as high as using 100% outdoor air supply through the air handling system.

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