Since January 2020 Elsevier has created a COVID-19 resource centre with free information in English and Mandarin on the novel coronavirus COVID-19. The COVID-19 resource centre is hosted on Elsevier Connect, the company's public news and information website.

Elsevier hereby grants permission to make all its COVID-19-related research that is available on the COVID-19 resource centre - including this research content - immediately available in PubMed Central and other publicly funded repositories, such as the WHO COVID database with rights for unrestricted research re-use and analyses in any form or by any means with acknowledgement of the original source. These permissions are granted for free by Elsevier for as long as the COVID-19 resource centre remains active.
Multizonal modeling of SARS-CoV-2 aerosol dispersion in a virtual office building

Prateek Shrestha a,*, Jason W. DeGraw a, Mingkan Zhang b, Xiaobing Liu c

a Integrated Building Performance Group, Oak Ridge National Laboratory, Oak Ridge, TN, USA
b Multifunctional Equipment Integration Group, Oak Ridge National Laboratory, Oak Ridge, TN, USA
c Building Equipment Research Group, Oak Ridge National Laboratory, Oak Ridge, TN, USA

ARTICLE INFO

Keywords:
Multizonal modeling
Aerosol
Ventilation
Airflow network
SARS-CoV-2

ABSTRACT

The dispersion of indoor airborne contaminants across different zones within a mechanically ventilated building is a complex phenomenon driven by multiple factors. In this study, we modeled the indoor dispersion of airborne SARS-CoV-2 aerosols within a US Department of Energy detailed medium office prototype building using CONTAM software. The aim of this study is to improve our understanding about how different parts of a building can experience varying concentrations of the airborne viruses under different circumstances of release and mitigation strategies. Results indicate that unventilated stairwells can have significantly higher concentrations of airborne viruses. The mitigation strategies of morning and evening flushing of conditioned zones were not found to be very effective. Instead, a constant high percentage of outdoor air in the supply mix, and the use of masks, portable HEPA air cleaners, MERV 13 or higher HVAC air filters, and ultraviolet germicidal irradiation disinfection were effective strategies to prevent airborne viral contamination in the majority of the simulated office building.

1. Introduction

The airborne route of COVID-19 disease transmission has received significant interest from researchers, along with close-contact and fomite transmission routes [1–19]. As buildings start to reopen after long periods of being closed because of the COVID-19 pandemic, knowing what parts of a building have a high risk of infection transmission remains crucial in developing infection control and prevention plans and strategies. Close-contact and fomite transmission controls are enforceable with policies such as social distancing, surface disinfection and handwashing. Conversely, the aerosol transmission route is much harder to characterize and mitigate in a mechanically ventilated building [20–24]. Availability of a whole-building depiction of the concentration distribution of airborne contaminants, potentially laden with infectious viruses, can be of great help in designing and enforcing preventative and mitigation strategies to minimize the risk of infection among building occupants.

Experimental sampling of active viral aerosols from indoor air in buildings can be challenging to execute in a real-world setting. Several studies have thus used computational modeling to better understand the dispersion patterns and driving forces of infection spread in various indoor environments [13,25–35]. Computational fluid dynamics (CFD) simulations have highlighted the role of certain factors such as persistent recirculation eddies inside closed, poorly ventilated indoor spaces [25, 30,33–35]. However, CFD simulations are generally limited to studying contaminant transport characteristics in a single zone of a building because of the immense computational resources required to reasonably capture most of the details involved in simulating airflow within indoor environments of buildings [36–43]. Simplified multizonal airflow and contaminant transport modeling is significantly faster and computationally less expensive than CFD. This is because in typical multizonal modeling, contaminant dispersion is simulated by treating the various zones as well-mixed nodes of an airflow network interconnected by airflow paths, taking into account only the conservation of mass without solving for momentum and energy equations such as in the Navier-Stokes equations [44–50]. However, careful application of the multizonal airflow network modeling technique can provide a useful way of analyzing contaminant dispersion patterns within a building, including the transport of contaminants due to the operation of the HVAC system.

Our knowledge of many parameters associated with the SARS-CoV-2 and its COVID-19 disease is still very limited, including critical infectious viral load in droplets and aerosols, and dose-response
characteristics of the virus in humans [51–55]. However, the combination of simplified multizonal modeling along with vulnerability-based metrics can be helpful in generating a whole-building depiction of the airborne virus-laden aerosols. This combination will also play a vital role in comparing the estimated effectiveness of various mitigation strategies against one another.

2. Methods

In this study, we simulated the indoor dispersion of SARS-CoV-2 aerosols within the US Department of Energy’s updated detailed medium office prototype (DMOP) building (enhanced version) [56] under various scenarios of contaminant release inside the building, and the impact that various mitigation strategies have on the overall building. The DMOP building is one of several hypothetical building designs developed by Pacific Northwest National Laboratory under the US Department of Energy’s support of ANSI/ASHRAE/IES Standard 90.1 and IECC commercial building energy codes, which represent approximately 80% of the mid-to high-rise buildings across all US climate zones [57]. The DMOP model is a three-story building with a slab-on-grade construction and 4978.6 m$^2$ (49.9 × 33.3 m) conditioned floor area per floor. The height of each floor is 2.74 m, and plenums are above each floor at 1.26 m high. Each floor has “ribbon windows” 1.3 m high on exterior walls of all sides on each floor. Fig. 1 depicts the DMOP building design, and a previous study by Im et al. provides further details of the DMOP building [56].

2.1. Model description

Simplified airflow and contaminant dispersion modeling was performed in the DMOP building using CONTAM software Version 3.4 [58]. The CONTAM tool is a well-validated multizonal airflow network modeling tool [59]. It has been used in many previous studies to simulate the transport and dispersion of indoor air contaminants ranging from building fire smoke to biological and chemical agents including airborne infectious aerosols [60–69]. Fig. 2 depicts the CONTAM model developed for the DMOP building, along with the description of various icons (symbols) used in the graphical user interface feature of CONTAM (ContamW). The inputs to the model related to the wall leakages, HVAC system flow rates to each zone, and various schedules were based on a report by the National Institute for Standards and Technology (NIST TN-2072 report) [70].

The CONTAM model does not need to be drawn to scale because properties associated with each zone are specified as part of the model development process. The layouts (floor plans) of levels 2 and 3 are identical, and the layouts of all plenum spaces above each floor are also identical. The legend items depicted in Fig. 2 represent each unique item among many presented across different zones as viewed in the ContamW sketchpad view.

2.1.1. Source properties

To generate a whole-building map of high-aerosol concentration zones, a single source was introduced as an index person releasing virus-laden or pathogenic aerosols (referred to as “aerosols” or “pathogens” from here on) at a constant rate of 1 mg/s as an extremely simplified hypothetical case. It can be argued that in an actual scenario, the release rate of aerosols can happen either in a single burst or a series of

| Abbreviations |
|----------------|
| DMOP | Detailed Medium Office Prototype |
| EIS$^{10}$ | Exposure Improvement Score (decile-based) |
| NED-CAD | Normalized Exposure Dose – Cumulative Area Decile |

Fig. 1. (a) 3D model and (b) Floor plan layout of the DMOP Building.
randomly occurring bursts of varying concentrations and sizes of the released aerosols. However, in the present study, an agent-independent and simplified comparison is being made across different zones being affected by aerosols which can highlight the key characteristics of the aerosol build-up and decay across different zones and help build our initial understanding about the nature of dispersion patterns that can be expected across different zones of a building. Such a constant rate of release can be thought of as an average rate of release when an infected person is simply breathing. The actual rate of the release itself is not critical in the nature of analysis that we are performing in this study. The actual rates and sizes of the released aerosols can be highly variable depending upon the activity that produce the aerosols (such as breathing, coughing, sneezing, talking, shouting and singing), depends on factors such as age of the persons, and is also a matter of ongoing research [52, 71–73].

To approximate the simulated aerosols as airborne SARS-CoV-2, the physical properties of simulated aerosols were defined to be similar to that of a droplet of water of 0.1 μm diameter [74, 75]. The virus itself will not likely suspend in air as a singular unit; it usually gets released in aerosols of much larger size than the individual virus itself. However, simulating the aerosols of the smallest diameter can help visualize an exaggerated worst-case scenario of the smallest size of the aerosols suspended in air and being transported to many other parts of the building. No decay of the released aerosols was modeled attributable to deposition or deactivation over time.

To analyze the steady-state simulations, the single source (index person) was placed in each of the 65 occupiable zones of the DMOP building, one at a time; each of those placements of the source in one of the zones is one “instance” of the source location. The aerosol concentrations induced by the source across different zones due to each of those instances were then aggregated by averaging the aerosol concentrations across all instances for each zone. The resulting overall building-integrated average concentration map provided a visual reference of the parts of the building with the expected airborne concentrations.

2.1.2. Mitigation strategies

Mitigation strategies simulated in the DMOP building included the following:

Fig. 2. Two-dimensional sketchpad view of the DMOP building CONTAM model.
• Mask-wearing by the simulated infected person (as a source control strategy),
• Distributed use of portable HEPA air cleaners in high-occupancy zones,
• Use of MERV 13 (minimum efficiency reporting value of 13) filters in the HVAC system’s air handling unit (AHU),
• Use of ultraviolet germicidal irradiation (UVGI) in the return air duct of the AHU,
• Combination of MERV 13 filter and UVGI in the AHU return air duct, and
• Increasing the outdoor air (OA) percentage of the air delivered by the HVAC system’s AHU.

To simulate the impact of mask-wearing, a mask filtration efficiency of 50% for the simulated 0.1-μm aerosols (assuming that it is a surgical mask) was used based on a previous study [76].

OA percentages in the supply air mix through the HVAC AHU were simulated to vary incrementally at 0%, 31%, 50%, and 100%. The 31% value was chosen as a minimum OA percentage required for the building to match the model developed by a prior study [56]. CONTAM treats the HVAC system as a constant air volume system. Although the 0% OA case is not expected in an actual building, analyses including 0% OA provide a reference for the worst-case scenario of an unnoticed OA damper failure.

A deposition rate sink model with a deposition rate of 0.003 s⁻¹ was used to simulate air cleaning with portable air cleaners using HEPA filters for a clean air delivery rate of 330 ft³/min (0.156 m³/s) based on a previous study [77]. Although the actual experimental conditions of a study cannot be directly and exactly replicated in our CONTAM model because of its lack of efficient size-resolved analysis, the filtration efficiency assumptions provide a basis to deduce a vulnerability-based semi-quantitative comparison with a baseline case. The actual clean air delivery rate, filtration efficiency, and deposition rates are hence bound to vary when comparing this study with empirical data.

Finally, for simulating the impact of in-duct UVGI treatment of air on the viruses, the built-in Penn State UVGI model in CONTAM [78,79] was used as an in-duct air disinfection system fitted to the return air side of the AHU. The UVGI susceptibility constant of 0.021 m²/J was used for a hypothetical mercury vapor system with 253.7 nm effective wavelength [80]. A combination of UVGI with MERV 13 filtration in the AHU, as well as MERV 13 filtration without the UVGI system, were also individually simulated. The choice of MERV 13 filtration was made according to the ASHRAE Epidemic Task Force guidance [81] on particulate matter filtration for COVID-19 risk reduction in indoor environments.

2.2. Simulation descriptions

Steady-state and transient simulations were performed to characterize contaminant dispersion patterns inside the building.

2.2.1. Steady-state simulation

The initial steady-state simulation allowed the evolution of the model in a systematic way and created a simplified baseline model on which further complexity could be added. The steady-state simulation helped to generate a whole-building picture, identifying zones that had a higher tendency for aerosol build-up under the simplistic assumption of a single source releasing viral aerosols. Zero ambient wind speed and a constant indoor temperature of 20 °C were used for the steady-state case.

The initial steady-state runs of the model simulated the presence of one infected person (index person) releasing virus-laden aerosols in specific zones of the DMOP building, and the impacts on the release zones and the rest of the zones of the building were studied. These cases are referred to as “unitary test cases” in this paper. The unitary test cases provided a first-hand depiction of the dispersion characteristics of the viral aerosols throughout the building and provided some basic qualitative and quantitative information on the effectiveness of various mitigation strategies deployed in the DMOP building as mentioned in Section 2.1.2.

The DMOP building has 65 occupiable zones, so the single source was placed in each of those 65 zones, one at a time. This generated 65 instances of different aerosol concentrations in different zones of the DMOP building. The integrated impact in each zone due to these 65 different instances was then evaluated by averaging the aerosol concentrations across all 65 instances as

\[ D_i = \left( \frac{\sum_{j=1}^{N} C_{ij}}{N} \right) , (i = 1, 2, \ldots, N), \]

where.

\[ D_i \] is the mean exposure dose (equivalent to concentration for steady-state case) for zone \( i \),
\[ C_{ij} \] is the aerosol concentration in zone \( i \) due to source location in zone \( j \) (\( kg/\text{kg}_{\text{aer}} \)), and
\[ N \] is the total number of occupiable zones (65 for the DMOP building).

2.2.2. Transient simulation

Following the simplistic steady-state simulation, transient simulation cases enabled the investigation of temporal variation patterns of aerosol concentrations in different zones during different times of a day. For simplicity in analysis, all zones in the DMOP building were simulated to have no other occupants releasing aerosols, other than the single infected (index) person occupying a single zone (bottom floor lounge).

Although the index person’s location in other zones might yield slightly different results, this simplistic case can highlight some key characteristics of the temporal nature of indoor aerosol concentrations. A few neighboring zones relative to the location of the index person were also studied for comparison.

Occupancy and HVAC operation schedules were assigned to the building based on a report by the National Institute for Standards and Technology (NIST TN-2072 report) [70]. These schedules are shown in Fig. 3 (a) and (b). The occupancy schedule of the index person is shown in Fig. 3 (a). A normal HVAC operation schedule was simulated to run from 6 a.m. to 10 p.m. for weekdays, 6 a.m. to 6 p.m. for Saturdays, and the HVAC system was off for Sundays and holidays. Fig. 3 (c) and (d) show the schedules for 1-h “flushing” of indoor air with a 100% OA supply in the morning and evening, respectively, to study the impact of flushing as potential mitigation strategies. HVAC system OA setting was kept at 50% at other times. This hypothetical scenario assumed that the HVAC OA fraction was increased beyond the minimum required 31% OA value as a mitigation measure to dilute the indoor aerosols, but not increased fully to 100% due to the lack of the installed system capacity or other practical challenges. The morning and evening flushing were simulated as two separate and independent events not happening in the same day (i.e., only morning flushing or evening flushing simulation at a time). The morning or pre-flushing was done 1 h after beginning the normal HVAC operation schedule (i.e., 6 a.m.–7 a.m.), and the evening or post-flushing was done 1 h before the end of the normal HVAC operation schedule (i.e., 9 p.m.–10 p.m.).

Besides the morning and evening flushing effects, sensitivity of indoor air aerosol concentrations to weather variables and HVAC operation was also studied.

A constant set-point temperature of 20 °C was used for the transient case, as well. The transient simulation was run for the duration of a whole year. Specific characteristics of the year-long simulation were also investigated for shorter durations. To account for the variability in weather conditions, a weather file corresponding to weather data from the Chicago O’Hare International Airport was downloaded from the EnergyPlus weather data repository [82] and used in the transient
2.3. Performance assessment metrics

Performances of the various steady-state simulation cases were assessed using the quantitative and semi-quantitative vulnerability-based metrics based on the previous work of DeGraw and Bahnfleth [83]. These metrics were chosen to generate a vulnerability picture of the whole building on a relative scale because limited agent-specific information is currently available to confidently quantify infection risk specific to SARS-CoV-2. The chosen vulnerability metrics make no specific assumptions about any specific agent, and they only provide a comparative assessment regarding the presence of any zone of a building relative to the zone in which the viral aerosols were released (release zone).

An exposure dose (or dose factor) $D$ for a time-varying contaminant concentration $C$ for an exposure duration of $T$ can be defined as

$$D = \int_0^T C^n(t)dt,$$

where $n$ is a toxic load exponent that represents the dose-response characteristics of a particular agent [84]. For a steady-state simulation, the exposure dose can simply be substituted by the exposure concentration of the airborne aerosols in a well-mixed zone.

The two main metrics used for assessing the performance of the simulated conditions were normalized exposure dose distribution by cumulative area deciles (NED-CAD plots), and exposure improvement score ($EIS_{10}$).

2.3.1. NED-CAD plots

NED-CAD plots are semi-quantitative in nature and provide a graphical metric for the steady-state simulations to compare two scenarios by identifying the portion of the building affected by a single-zone release of airborne agents such as viral aerosols. First, the well-mixed occupiable zones of the building are divided into 10 deciles of the cumulative area of all the zones. The aerosol concentrations are then normalized by the maximum concentration value and arranged in ascending order of the cumulative area deciles. The 10th decile then becomes the decile with the highest normalized exposure dose, and hence contains the aerosol release zone.

2.3.2. $EIS_{10}$

Another metric to represent the steady-state whole-building exposure is the $EIS_{10}$. The subscript 10 signifies that this is a decile-based metric. $EIS_{10}$ can be computed as

$$EIS_{10} = \sum_{k=1}^{10} \left[ a_k \left( D_{baseline,k} - D_k \right) / D_{baseline,k} \right],$$

where, $a_k$ is the decile weight (10 used in this study for equally weighting all deciles), $D_{baseline,k}$ is the baseline result in the decile $k$, and $D_k$ is the candidate result in decile $k$.

The $EIS_{10}$ score provides a single-number quantification of the overall building performance in terms of improvement in the exposure by any receptor as the receptor moves away from the release zone.

3. Results and discussions

The various unitary test cases for the initial steady-state simulations were first analyzed with the vulnerability-based comparative metrics.
Next, the transient simulation cases were analyzed for a simplified scenario similar to Case 1 of the unitary test cases.

### 3.1. Steady-state simulation results

Eleven different unitary test cases were simulated for steady-state conditions. Table 1 describes all the unitary test cases and the corresponding mitigation strategies applied. Fig. 4 illustrates the overall impact on the building from the scenarios simulated in all 11 test cases in terms of the discrete EIS\(_{10}\) score values joined by straight lines. Fig. 4 shows that the first five unitary test cases illustrate a baseline situation of the index person being located in different zones of the DMOP building without wearing a face mask. For these cases, the rate of improvement of the EIS\(_{10}\) score is rapid from 0% OA up to just under 40% OA. From 50% OA onward, the EIS\(_{10}\) score improvement curve has a smaller slope. For unitary test cases 6 and 7, the mitigation strategies offer significant improvement to the building’s overall exposure compared with the previous five cases. Finally, cases 8 through 11 offer the best improvement (i.e., minimum exposure to the remainder of the building other than the release zone) to the overall building for all OA percentages. The marginal change in EIS\(_{10}\) scores for cases 8 through 11 indicate that these active mitigation strategies can drastically reduce the exposure of the majority of the building even for under-ventilated buildings, whereas ventilation with OA plays a more significant role to mitigate exposure in most zones in other cases. In practice, one would expect an operating office building to comply with the ASHRAE 62.1 minimum ventilation requirements, so there would already be a significant contribution to protecting the majority of the building with some fraction of OA (typically more than 25%) in the supply air mix [85].

Fig. 5 depicts the zonal distribution of mean exposure doses under various OA percentages in the air supply mix through the AHU. Whereas 0% OA had a significant impact on the majority of the building with elevated aerosol exposure doses, 31%, 50%, and 100% OA cases had almost identical spatial distribution patterns, or a “whole-building map” of mean exposure doses, across all zones. Therefore, only one such whole-building map is shown for the 31% OA case in Fig. 5 (b). Fig. 5 (a) and (b) show that the stairwells experienced higher mean exposure doses of aerosol concentrations because these zones do not have supply and return grilles. These two zones are among the 65 occupiable zones in the DMOP building, although they are not occupied with a permanent scheduled occupancy. The International Building Code (Section 403) [86] and the National Fire Protection Associate Life Safety Code (NFPA 101) [87] require stairwells for high-rise buildings greater than 75 ft tall, measured from the ground level access to the highest floor level intended for occupant use [88]. However, buildings under 75 ft tall have no such requirement of stairwell pressurization. This study does highlight a potential of unconditioned and unpressurized stairwells of three-story medium office buildings to have lingering aerosol concentrations due to their release in the stairwells. Noting the fact that stairwells are mostly unoccupied zones in a building, additional simulations were conducted without the index person releasing aerosols in the stairwells.

![Fig. 4. EIS\(_{10}\) scores for the unitary test cases in the DMOP building.](https://example.com/fig4.png)

The mean exposure doses experienced by all zones excluding the stairwells as aerosol release zones are shown in Appendix for 31% OA, 50% OA and 100% OA in the HVAC air supply mix. In addition, Appendix also illustrates the mean exposure doses for all zones excluding release events in additional unoccupied zones like storage and mechanical rooms.

Fig. 6 shows the NED-CAD plots, showing the impact on the overall building under various scenarios.

Similar to the mean exposure dose calculations described in Eq. (1), the results in Fig. 6 show normalized exposure doses averaged across all 65 source locations. Each of those 65 realizations would individually correspond to a unitary test case, and the 10th decile in the NED-CAD plots would typically correspond to the decile containing the release zone. However, the plots shown in Fig. 6 are the overall average values and there is no such attribute of source location associated with the 10th decile. However, the comparison between the 10th decile and the remaining deciles can provide a quantitative comparison of the proportion of the total building area being affected by different degrees of aerosol contamination.

In the baseline case (Fig. 6 (a)), the whole building was balanced in terms of supply and return flow rates for each conditioned zone, and no intervention strategy was implemented. In the whole-building pressurization scenario (Fig. 6 (b)), return flow rates at the return grilles were reduced by 10% compared with the supply diffuser flow rates in each conditioned zone. Once again, no intervention strategy was implemented. When compared with the balanced baseline case (Fig. 6(a)), it can be seen from Fig. 6 (b) that the whole building pressurization, which is commonly practiced for real commercial buildings, has comparatively higher normalized exposure doses for all the cumulative area deciles. Even the 100% OA case shows that a significantly larger portion of the building gets affected by the viral aerosols due to pressurization. This can be attributed to the mass balance of the aerosols as the return rates in the pressurization case are lower than the supply, the viral aerosols released in any zone will try to find their way out of that zone through various leakage pathways in addition to the HVAC return pathway.

Fig. 6 (c) represents the use of portable air cleaners in all high-occupancy zones that include enclosed and open office spaces, classrooms, and conference rooms. It is to be noted that in real application of portable air cleaners, proper sizing of the air cleaners is recommended by selecting the air cleaners of suitable clean air delivery rate (CADR) based on the size or dimensions of the room in which they are installed. Fig. 6 (d) shows the NED-CAD plot for the use of a MERV 13 particulate filter in the AHU, which is closely comparable to Fig. 6 (c) except for the 100% OA condition in which the MERV 13 AHU filtration performance was superior to the distributed portable HEPA air cleaner use. Fig. 6 (e)

| Case number | Description |
|-------------|-------------|
| 1 | Index person located in bottom floor (level 1) lounge |
| 2 | Index person located in bottom floor east side open office |
| 3 | Index person located in bottom floor east side enclosed office |
| 4 | Index person located in middle floor (level 2) lobby |
| 5 | Index person located in top floor (level 3) lobby |
| 6 | Case 5 + index person wearing mask |
| 7 | Case 5 + single air cleaners used in one of the enclosed offices |
| 8 | Case 5 + use of portable air cleaners in all high-occupancy zones |
| 9 | Case 5 + MERV 13 filter in the AHU |
| 10 | Case 5 + in-duct UVGI in the return stream of the AHU |
| 11 | Case 5 + MERV 13 filter + UVGI in the AHU |
and (f) demonstrate that although the use of an AHU UVGI system alone is almost as significant as the use of a MERV 13 filter alone in the AHU, the combination of the two is the most effective mitigation measure among all cases.

3.2. Transient simulation results

The time-dependent concentrations of virus-laden aerosols were studied using various time-series plots for CONTAM simulations performed with 1-min resolution. Fig. 7 shows a 1 week-long aerosol concentration starting at the beginning of a calendar year. The shaded areas in Fig. 7 show the times when the HVAC system was operational. The spikes can be noted in the aerosol concentrations during the time durations with low (but nonzero) occupancy, and the HVAC system turning off during its scheduled operation (see Fig. 3). The first spike rose to a maximum value of $2.5 \times 10^{-9}$ kg/kg for the time duration in which the occupancy was nonzero. The aerosol concentration then declined exponentially when the occupancy and HVAC operation were zero. This decline is attributable to the dilution of aerosols due to air infiltration because of the building envelope leakage. For the remainder of the times, the aerosol concentrations followed the periodic patterns proportional to the occupancy schedule, reaching a peak concentration of approximately $2.3 \times 10^{-9}$ kg/kg at the release zone. In the neighboring zone (including the plenum space immediately above the release zone, where the return grilles are located), the peak concentrations were at least an order of magnitude lower than at the release zone. To enhance the visualization of aerosol concentration profiles in the neighboring zones, Fig. 8 illustrates the profiles in logarithmic y-axis scales. Fig. 8 also shows the sensitivity of the time-dependent aerosol concentration profiles on seasonality, as well as HVAC operation status. 50% OA in the supply mix was assumed for this case for the reason described in Section 2.2.2. Fig. 8 shows that HVAC operation significantly reduced the peak concentration for all zones. In addition, the peak concentrations of the aerosols were also significantly reduced for all zones when the HVAC fan was operational even when there was 0% OA in the supply mix. The indoor aerosol concentration

Fig. 5. Mean exposure dose ($D_i$) distribution across all zones of the DMOP building for (a) 0% OA and (b) 31% OA in the supply mix from the AHU.
Fig. 6. NED-CAD plots for various intervention strategies with varying OA percentages in the AHU supply mix. The color legends shown in Fig. 6(f) are consistent across all sub-figures. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)
temporal profiles were also found to be nonstationary and affected by seasonality throughout the year. This sensitivity was more pronounced when the HVAC system was nonoperational.

Fig. 9 depicts the effects of pre- and post-flushing strategies. Fig. 9 shows that the pre- and post-flushing strategies significantly affected the daily minimum concentration values, but these strategies did not affect the daily maximum concentrations. Because the maximum daily concentrations correspond to the peak exposure doses, these strategies also did not significantly reduce exposures to the airborne aerosols.

4. Study limitations

Through the very simplistic simulations conducted in this study, a few key characteristics and tendencies of the airborne viral aerosol dispersion patterns can be highlighted. However, additional complexities caused by a number of factors cannot be captured by the approaches used in this study.

First, this study assumes perfectly well-mixed conditions for the simplified multizonal contaminant dispersion and airflow network modeling. The simulation runs were also conducted in a virtual prototype building, which cannot be easily validated with experimental measurements. All the simulated zones and the HVAC system AHUs were greatly simplified, which can increase the deposition and decay rates of airborne viruses. We also did not consider fomite and large droplet transmission routes of infection in this study.

Additionally, a single source was used in all simulation cases to provide a clear idea about the generation of airborne viral aerosol distribution patterns. In reality, the overall concept can be obscured if there are multiple infected individuals inside a building, many of whom can
also be asymptomatic or pre-symptomatic infection spreaders. Simulating each scenario in such cases is not practically possible.

5. Conclusions

In this study, we showed that simplified multizonal contaminant dispersion and airflow network modeling can provide some basic answers regarding the dispersion patterns of indoor airborne viral aerosols such as the ones containing SARS-CoV-2. The simplified analysis conducted using steady-state simulations showed that unconditioned stairwells can potentially experience relatively high aerosol concentrations compared with other conditioned zones of an office building. Also, intervention strategies such as mask-wearing, using portable HEPA air cleaners, increasing OA percentages at the HVAC AHU supply mix, and using MERV 13 (or higher rating) HVAC air filters and in-duct UVGI disinfection mitigation strategies are all effective strategies in significantly reducing the risk of COVID-19 infection transmission in most parts of an office building. We also showed that the indoor aerosol concentrations can significantly build up even with minimal occupancy when the HVAC system is nonoperational. When the HVAC system is operational, even 50% OA in the AHU supply mix can significantly reduce the peak daily aerosol concentrations by as much as an order of magnitude. We also demonstrated that the morning and evening flushing strategies with 100% OA in the AHU supply mix were not effective in reducing the peak daily maximum concentrations of the indoor aerosols. The findings from our study bolster the guidance from the ASHRAE Epidemic Task Force regarding the airborne transmission of COVID-19 and the suggested mitigation strategies under various scenarios.

Funding

This work was funded by the US Department of Energy, Energy Efficiency and Renewable Energy, Building Technology Office under contract number DE-AC05-00OR22725.

Conflicts of interest

All authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

The authors would like to thank Carl Shapiro (DOE), Prof. Zheng O’Neill (Texas A&M University), and Piljae Im (ORNL) for providing comments and technical support, and Olivia Shafer (ORNL) and Heather Buckberry (ORNL) for technical editing and proofreading the article.
Appendix

The following figures illustrate the results of the sensitivity analyses showing mean exposure doses in various zones omitting release scenarios in certain zones.

Figure A1 Mean exposure doses in various zones when only the staircases were excluded as viral aerosol release zones. (a) 31% OA (b) 50% OA (c) 100% OA
Figure A. Mean exposure doses in various zones when the staircases, storage rooms, and mechanical rooms were excluded as viral aerosol release zones. (a) 31% OA (b) 50% OA (c) 100% OA.

References

[1] H. Ueki, Y. Furuaswa, K. Iwatsuki-Horimoto, M. Imai, H. Kabata, H. Nishimura, Y. Kawaoka, Effectiveness of face masks in preventing airborne transmission of SARS-CoV-2, msphere 5 (2020), https://doi.org/10.1128/msphere.00637-20.

[2] K. Razzini, M. Castrica, L. Menchetti, L. Maggi, L. Negroni, N.V. Orfeo, A. Pizzoccheri, M. Sacco, S. Muttini, C.M. Balzaretti, SARS-CoV-2 RNA detection in the air and on surfaces in the COVID-19 ward of a hospital in Milan, Italy, Sci. Total Environ. 742 (2020) 140540, https://doi.org/10.1016/j.scitotenv.2020.140540.

[3] A. Ahlawat, A. Wiedensohler, S.K. Mishra, in: An overview on the role of relative humidity in airborne transmission of SARS-CoV-2 in Indoor Environments, 20, 2020, pp. 1856–1861, https://doi.org/10.4209/aaqr.2020.06.0302.

[4] S. Faridi, S. Niazi, K. Sadeghi, K. Naddafi, J. Yavarian, M. Shamsipour, N.Z. S. Jandaghi, K. Sadeghniazi, R. Nabizadeh, M. Yunesian, F. Momenha, A. Mokamel, M.S. Hassanvand, T. MokhtariAzad, A field indoor air measurement of SARS-CoV-2 in the patient rooms of the largest hospital in Iran, Sci. Total Environ. 725 (2020) 138401, https://doi.org/10.1016/j.scitotenv.2020.138401.

[5] G. Buonanno, L. Stabile, L. Morawska, Estimation of airborne viral emission quanta emission rate of SARS-CoV-2 for infection risk assessment, Environ. Int. 141 (2020) 105794, https://doi.org/10.1016/j.envint.2020.105794.
