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Characterization of the indoor near-field aerosol transmission in a model commercial office building

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A R T I C L E   I N F O

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A B S T R A C T

To evaluate the exposure potential of infectious aerosols containing SARS-CoV-2 in an office building setting, synthetic test aerosols were used to experimental study airborne particle transmission in a multizone small office test building at the Oak Ridge National Laboratory. Nine measurement points in a single zone using active aerosol impactors report that the coefficient of variation of the time-averaged concentration is <10% in two campaigns and <15% in one campaign, so a nearly well-mixed condition was noted. To understand the effect of HVAC system operation on the dynamic concentration of aerosols in office spaces, an aerosol transport model that includes factors such as outside air (OA) ratio, filtration, return air fraction, transport loss in air ducts, and particle deposition has been developed. The results of model fitting demonstrate strong agreement with experimental data. Our investigation finds the return air fraction effects outweigh other mechanisms for the aerosol recirculation in this study, and the impact of air change rate (ACR) is more important than the small particle deposition for aerosol removal. Because ACR dominates the aerosol transport, the full model can be simplified to just one factor, the ACR, while maintaining an acceptable representation of the experimental data.

1. Introduction

The nature of SARS-CoV-2 transmission suggests that not only close contact and droplet transmission occur, but so does airborne transmission [1]. The detection of SARS-CoV-2 Ribonucleic Acid (RNA) in aerosols [2] and the discovery of viable SARS-CoV-2 in air [3] support the airborne transmission route of the virus. Epidemiology studies have also reported several aerosol transmission events. It was reported that the aerosol transmission event of SARS-CoV-2 in a Guangzhou restaurant was due to poor ventilation [4]. The superspreading event in a choir rehearsal in Skagit Valley Chorale is likely to have been due to inhalation of respiratory droplets in the indoor environment [5]. Airborne transmission of SARS-CoV-2 can be efficient under circumstances including prolonged exposure to respirable particles and inadequate ventilation or air handling [1].

Because the demand to reduce energy consumption of buildings has increased, the focus of heating, ventilating and air-conditioning (HVAC) system design has been on energy efficiency [6]. One strategy for building ventilation is to mix return air with fresh outside air (OA) and to filter the mixed air to maintain indoor air quality. The ratio of return air to outside air can significantly impact HVAC system energy consumption and the indoor air quality (IAQ). In winter, the minimum required OA for ventilation purposes is usually introduced into the building. As the amount of recirculated air dominates the mixed indoor air, respiratory aerosols from occupants can recirculate and accumulate within the building. Furthermore, as the percentage of recirculated air increases, more burden is placed on the recirculation filter as compared with replacing with uncontaminated OA in the air handling equipment. The ANSI/ASHRAE Standard 52.2–2017 [7] indicates that Minimum Efficiency Reporting Value (MERV) 5–8 filters are appropriate for
industrial workplaces. Unfortunately, MERV 5–8 filters have limited capacity to capture viral aerosols. For example, the efficiency of a MERV 8 filter for filtering 1 μm particles is approximately 30% while the efficiency of a MERV 6 filter is about 18%. Therefore, a rising concern is the health impacts of indoor aerosols in workplace buildings or other indoor environments with similar air handling and filtration equipment.

To slow SARS-CoV-2 spread, social distancing guidelines state that individuals must stay at least 6 ft (1.8 m) from others who are not from the same household in both indoor and outdoor spaces [1]. The effectiveness of the 6-ft guideline to slow respiratory aerosol spread is still under debate. The 6-ft guideline was based on an outdated dichotomous concept of respiratory droplet size [6], but droplets of all sizes are moved by the exhalation. The turbulent cloud from natural human forceful emissions such as a sneeze can reach over 26 ft. (8 m) [9], which is greatly beyond the 6-ft guideline.

In indoor zones with mixing ventilation, supply air could be quickly mixed in the zone. However, the mixing process can facilitate aerosol transmission in that zone. Thus, understanding the extent of the aerosol spatial concentration distribution, the dynamic concentration, and the mechanisms are important for the evaluation of human exposure to respiratory aerosols. Therefore, the specific goals of this study are to 1) experimentally characterize the 3-dimensional aerosol concentration distribution in the source zone, 2) experimentally characterize dynamic aerosol concentrations and apply a model for fitting, and 3) develop a hypothetical test case to predict aerosol concentration change under the effect of HVAC system operation.

2. Methodology

2.1. Building and indoor air ventilation

The aerosol transmission experiments were conducted in a model commercial office building, the Flexible Research Platform (FRP), at the Oak Ridge National Laboratory from October 2020 to January 2021. The FRP was designed to represent a typical two-story small to medium sized building emulates occupant airflow at each level. In addition, the building emulates occupant’s sensible and latent heat generation using portable heaters and humidifiers that represents typical occupants’ behavior in an office setup.

Fig. 2 shows the HVAC system configuration and measurement points in the FRP. The dampers in the Rooftop Unit (RTU) allow the return air to mix with OA to reduce energy cost. When the OA temperature is between 45 and 55 °F (7 to 13 °C), the OA damper is opened because, from an energy standpoint, it is favorable to use the OA to condition the building zones. This mode of operation is known as “economizer” mode. The minimum position of the OA damper is 10%, even if the economizer is disabled to provide minimum ventilation to the building. Upstream of the cooling and heating coils, aerosols in mixed air are partially filtered by MERV 7 filters. After filtration, the mixed air is conditioned by cooling and/or heating coils, and then directly dispersed into each zone via the supply duct system. For this study, the thermostat of the HVAC system was set to maintain the temperature between 70 and 76 °F (21 to 24 °C). The minimum and maximum supply air flow rate for each zone varies depending on the size and orientation of the zone. The variable air volume (VAV) box in each zone modulates the airflow rate to meet the heating demand of the zone. The return air from each zone enters the plenum space of each zone through the return grille, and then travels to the return duct through the plenum. Finally, the total return air travels back to the RTU for another cycle.

2.2. Experimental method: Aerosol generation, collection, and measurement

Sodium Chloride (MW = 58.44 g mol⁻¹; NaCl; CAS#: 7647-14-5; Sigma Aldrich) was selected as the material for testing aerosol transmission in this study because of the safety concerns of using bioaerosols during indoor air experiments. The atomizer disintegrated the NaCl solution into airborne droplets, and the low-RH indoor environment can dry the NaCl droplets in a short time to form suspended solid particle in the air (i.e., aerosol). The size of these solid chloride aerosols does not change because the relative humidity (RH) in the building environment has been controlled to be lower than the deliquescence RH (75%). To positively identify NaCl aerosols against the background indoor or outdoor aerosols with the same size, the NaCl aerosol was tagged with uranine (Fluorescein sodium salt, MW = 376.27 g mol⁻¹; C₂₀H₂₄Na₂O₅S, CAS#: 518-47-8; Sigma Aldrich) to provide a unique fluorescent signal for aerosol characterization from the ambient environmental aerosol. Similar tagging technology has been used to understand indoor aerosol transmission in aircraft [12].

A TSI model 3076 nebulizer and a Collison nebulizer were used for particle generation. The TSI model 3076 can generate sufficient aerosol with constant output [13] The stable output allows for dynamic aerosol concentration analysis. However, the upper bound of aerosol size from TSI model 3076 nebulizer is limited to the submicron (<1 μm) range. To mimic the respiratory aerosols in the micron range (>1 μm), a Collison nebulizer was employed to generate larger size aerosols. For the TSI model 3076, the nebulization solution was prepared by dissolving 3 g NaCl and 1 g Urainine into 400 mL Nanopure water. To generate micron particles using the Collison nebulizer, the solution concentration was increased by dissolving 10 g NaCl and 1 g Urainine into 75 mL Nanopure water and 25 mL ethanol. Ethanol was added to the solutions in the Collison nebulizer to promote consistent aerosol generation and reduce potential co-generation of air bubbles which can disrupt aerosol generation. The discharge flow direction was upward for both generators. In summary, submicron aerosol transmission was reported using TSI model 3076, while both submicron and micron aerosol transmission were reported when the Collison nebulizer was used.

Stoutas cascade impactors were used to collect fluorescent aerosols to map and quantify the near-field transmission under the influence of the centralized HVAC system. The high flow rate, 9 liters per minute (Lpm), of these impactors results in the collection of sufficient samples for mass analysis within a reasonable time. The cascade impactors classify aerosols into five stages based on their aerodynamic diameter,
ranging as follows: <0.25 μm, 0.25–0.5 μm, 0.5–1.0 μm, 1.0–2.5 μm, and > 2.5 μm [14]. Particles were collected on Polytetrafluoroethylene (PTFE) (25-mm, 0.5 μm pore size) substrates and a final PTFE filter (37-mm, 2.0 μm pore size). Several experiments concluded that at least one hour of sampling time was required to collect adequate particle mass for analysis.

Particles on filters were extracted after each campaign and dissolved in a cuvette with Nanopure water for fluorescent analysis. Water is a good extracting solution for aerosol tagged with Uranine on filters as the extraction efficiency is >99% [15]. The fluorescent signal of aerosol was detected by a custom-made fiber-optics coupled spectrometer with an LED excitation wavelength of 470 nm, and the fluorescent emission was detected at 525 nm with a high-resolution spectrometer (OceanInsight Model HR4000CG-UV-NIR). The spectral signal was recorded and processed by the OceanView software on a 64-bit Windows-based laptop. The quantification limit by this spectral system was determined prior to the campaigns to be approximately 0.3 μg, which was sufficient for the intended fieldwork.

In addition to the impact of HVAC system operation, the different particle releasing rates from different aerosol generators can contribute to variation of absolute aerosol concentration. To normalize the concentration variation, a normalized concentration (NC) was defined as follows [16]:

\[
\text{Normalized concentration (NC)} = \frac{C_i}{C_S}
\]

where \(C_i\) is the aerosol concentration at a location and \(C_S\) represents the concentration nearby the aerosol generator. NC serves as an indicator to evaluate the relative exposure level at any location in reference to the source. NC ranges from 0 to 1, and a value of 1 indicates that the concentration at a particular location is identical to the source concentration.

### 2.3. Experimental design

Experiments were conducted in the source zone with the interior door closed on the first floor of the FRP. The floor surface in the source zone is bare and the floor area is 312 ft² (29 m²). The height of the source zone is 8 ft. (2.43 m), and the resulting volume of the zone is 2496 ft³ (71 m³). Two four-way square ceiling diffusers and one return grille are situated on the suspended ceiling at 8 ft. above the floor as shown in Fig. 3. In addition to one ceramic fan-forced heater and humidifier that were set to emulate human occupancy, vacuum pumps were placed to introduce sample air while the compressor provided compressed air for the nebulizer. The building envelope includes four large fixed windows (i.e. non-operable windows) on the north and west sides.

To achieve the first goal of characterization of the 3-dimensional aerosol concentration distribution in the source zone, experiments were conducted during October 2020 through January 2021. Fluorescent particles in the submicron and micron range were generated and monitored at various locations throughout the campaign. Each experiment was conducted on different days, with sufficient time between experiments to minimize the influence of one test to the next. The nebulizer continuously generated aerosol in the source zone during the sampling period to mimic aerosol generation from an occupant. No aerosols were generated in other zones. Sampling was conducted in the source zone and continued until the aerosol concentration was stabilized. Experimental data showed that the HVAC system took about one hour to reach stable concentration. Three monitoring towers were placed 6 ft., 8 ft., and 10 ft. (1.83 m, 2.44 m, and 3.05 m) away from the aerosol source, and each tower was equipped with three cascade impactors at heights of 3 ft., 5 ft., and 7 ft. (0.91 m, 1.52 m, and 2.13 m) above the floor (Fig. 3). These impactors measured nine local concentrations (\(C_i\)). The 4th tower was 1 ft. (0.30 m) away from the aerosol source and equipped with the 10th cascade impactor at a height of 3 ft. (0.91 m) above the floor (Fig. 3). The 10th cascade impactor (i.e., source impactor, S in Fig. 3) measured the source concentration (\(C_S\)).

To achieve the second goal of characterizing the dynamic aerosol concentration, real-time aerosol measurement instruments including a Scanning Mobility Particle Sizer Spectrometer (SMPS, TSI Model 3080 L + 3025A) and an Aerodynamic Particle Sizer (APS, TSI Model 3320) were deployed in this zone to monitor the submicron and micron aerosol concentrations over time, respectively. The SMPS was placed 6 ft. (1.83 m) away from the source to evaluate the 6-ft guideline while the APS...
was located next to the nebulizer to monitor the source concentration change over time.

2.4. Model fitting

The mechanism of dynamic aerosol concentration in this study involves the inward and outward zone airflow as well as the interaction between the aerosol and the building environment. To be specific, OA introduced in the economizer, air filtration, transport loss in the ducts, and aerosol deposition impact the aerosol concentration in the inward and outward airflow. Although Computational Fluid Dynamics (CFD) modeling coupled with particle tracking can detail the instantaneous aerosol concentration at a specific time and location, the temporal and spatial aerosol concentration distributions in the simulation domain, including the zones and the HVAC system, are very difficult to be solved using CFD [17]. Additionally, the risk of exposure to respiratory aerosols such as SARS-CoV-2 is related to aerosol accumulation over time. Because the time step of interest is not instantaneous, a mass-balance model with the well-mixed assumption is appropriate in this study [18].

Considering the source zone as a large control volume, the dynamic aerosol concentration $C$ in this zone can be characterized with the differential equation

$$V \frac{dC}{dt} = C_l Q_l - C_r Q_r + E - V C k$$

(1)

where $C_l$ is concentration at the supply air inlet ($\mu g/m^3$), $E$ is aerosol emission rate ($\mu g/h$), $V$ is zone volume ($m^3$), $t$ is time (hr), $Q_l$ is supply air flow rate ($m^3/h$), $Q_r$ is return air flow rate ($m^3/h$), and $k$ is the first-order aerosol loss rate (hr$^{-1}$). $Q_r$ is assumed to equal $Q_l$ in this study. Aerosol emission, $E$, is independent of time. Moreover, the concentration at the supply air inlet, $C_0$, can be written as

$$C_0 = a C_{source} + (1 - a)(1 - \eta)(1 - r) C$$

(2)

where $a$ is the ratio of OA to supply air (i.e., 0 refers to full recirculation while 1 indicates a one-pass system), $\eta$ is the filter efficiency, $r$ is the transport loss, and $R$ is the return air fraction as the return air from the individual zone merges into one flow in the return duct (e.g., 0.1 means that the 10% of the zone air is recirculated and mixed with OA air). Because SARS-CoV-2 viral particles can be deactivated by UV irradiation [19] and quickly diluted in the outdoor environment, the outdoor aerosol concentration, $C_{out}$, is assumed as zero. The parameters in the second term of Eq. (2) represent the effect of recirculation, therefore $(1 - a)(1 - \eta)(1 - r)$ is combined into one recirculation parameter $R$. By combining Eqs. (1) and (2), a linear ordinary differential equation for $C(t)$ can be obtained. The analytical solution is

$$C(t) = C_l e^{(1 - R)\lambda t} + \frac{E}{(1 - R)\lambda V} (1 - e^{-(1 - R)\lambda t})$$

(3)

Note that the aerosol removal mechanism involves $Q/V$ (air change rate, ACR) and the first-order surface deposition loss rate ($k$). The aerosol surface deposition loss rate was based on data from Thatcher et al. [20]. The loss rate is 0.1 h$^{-1}$ on the bare room surface for submicron aerosol and 1 h$^{-1}$ for micron aerosol ($< 3 \mu m$), respectively. As these two parameters have the same units, it is convenient to lump them into $\lambda$ as a lump-sum first-order loss rate ($hr^{-1}$) in this study.

Parameters of $\alpha$, $\eta$, $I$, and $r$ are determined by the following. Because the outside temperature was unfavorable for the economizer during the sampling time, a reasonable $\alpha$ of 0.1 was assumed. The filtration efficiency for MERV 7 filters ranges from 10% - 50% for 0.5–3 μm particles [21], so an efficiency of 20% was applied for submicron aerosons and an efficiency of 40% for micron particles in this study. Transport loss $I$ includes aerosol deposition in the HVAC heat exchanger and in the ventilation ducts. The loss in the HVAC heat exchanger is <10% for 1–10 μm particles for air velocities ranging from 1 to 4 m/s for a film spacing of 4.7 fin per centimeter [22]. The loss in the ventilation ducts is negligible for submicron particles [23]. For micron aerosol, loss in the supply duct is higher than in the return duct duct runs because of the internal insulation surface in the supply ducts. It was reported that a 10% loss for particle size at 8.7 and 17.2 μm in the supply and return ducts, respectively. Accordingly, the lump-sum transport loss in the heat exchanger and the ducts was assumed to be negligible for submicron particles and 10% for micron particles. As mentioned earlier that $Q_r$ is assumed to equal $Q_l$, the $Q_l$ measured in each zone as shown in Fig. 2 can be applied to calculate the return air fraction $r$ as 0.1. In summary, $R$ are calculated to be 0.072 and 0.0486 for submicron and micron particles, respectively.

3. Results and discussion

The first section below reports the experimental results of 3-D aerosol concentration distribution and applies these results to provide insights on the 6-ft physical distancing rule in the indoor setting. In the
scenario, we simulate an occupant emitting respiratory aerosols in a zone to measure the dynamic changes in aerosol concentration under the influences of the HVAC system and the indoor environment. The second section reports the experimental results of the dynamic aerosol concentration for a constant emission, and the third section presents the dynamic aerosol concentration after the emission stops. Also, the model described is applied to fit the experimental results and the mechanism of how the air flow rate influences the dynamic aerosol concentration is quantified and discussed.

3.1 3-D aerosol concentration distribution

Three campaigns were conducted in this study. The TSI model 3076 generated submicron aerosols during Campaign A, which was conducted from 10:00 am to 2:00 pm on October 27, 2020. As mentioned previously in the experimental method, both submicron and micron size aerosols can be generated using the Collison nebulizer in the Campaigns B and C, which were conducted from 1:15 pm to 3:15 pm on December 152,020, and from 1:30 pm to 3:30 pm on January 142,021, respectively. Table 1 displays the building and outdoor temperature and RH during the three campaigns. The weather in Campaign A was warmer. Outdoor RH in Campaigns B and C were lower than Campaign A, and indoor RH was less than 30%. The inward airflow rates through the VAV box were similar, approximately 320 CFM (151 L/s) in Campaigns A and B, while the airflow rate in Campaign C was set to be lower, about 275 CFM (130 L/s), to achieve a different HVAC system operating condition.

The aerosol concentration distribution measured using the 10 impacters is shown in Fig. 4. The size distribution is associated with the aerosol generation method. When aerosols are generated by the TSI model 3076 generator, aerosols were collected in the last three stages in the impactor, especially the last stage with cut-size 0.25 μm. Figs. 4[a]-[d] show that the size distributions are dominated by submicron particles. When the Collison nebulizer was utilized in the Campaigns B and C, Figs. 4[e]-[l] show that the aerosols were collected in all five stages of the impactor, which proves this method can generate aerosols in a broad range from <0.25 μm to >2.5 μm. Fig. 4(a) indicates that the time-averaged total mass source concentration in Campaign A is approximately 60 μg/m³, which is less than the time-averaged total mass source concentrations of approximately 800 μg/m³ in Campaigns B and C (Figs. 4(e) and 4(i)). This is because Campaign A is dominated by submicron particles and the mass scales with the cubic of the particle size. Although the mass concentration in Campaign A was lower, the mass measurement is still sensitive because the mass collection is higher than the quantification limit of 0.3 μg.

Fig. 5 displays the normalized concentrations in the submicron or micron range, distributed in the source zone during the three campaigns. The coefficient of variation (CV), the ratio of standard deviation to the average of sample concentrations, was used as an indicator to quantify the concentration variation at all nine measuring points, in the vertical direction, and on the horizontal plane [24,25]. The CV at the nine measuring points is 10% for the submicron normalized concentration in Campaign A, and the CV is 8% and 10% for the submicron and micron normalized concentrations, respectively in Campaign B. Although overall concentration variation is insignificant (<10%), the measurements at the 7 ft. (2.1 m) height and 6 ft. (1.8 m) away from the source show a significantly lower concentration in both campaigns. When the impactors are located below the diffusers, the aerosol concentration decreases as the height increases. This indicates the aerosol concentration in the supply air is lower than the indoor environment, and the less-contaminated supply air dilutes the aerosol concentration. On the other hand, at 10 ft. (3.0 m) and 8 ft. (2.4 m) away from the source in the horizontal direction, the low variation in the vertical direction shows that the local aerosol concentrations are less susceptible to the jet flow from the diffuser. In addition, the effect of sampling location being farther from the return can contribute to the low variation in the vertical direction.

In Campaign C, the CV of the submicron concentrations are 5%, 6%, and 7% for the samples in the sampling towers 6 ft., 8 ft., and 10 ft. away horizontally from the source; as well as 6%, 6%, and 3% for the micron concentrations. Unlike Campaigns A and B, the vertical variation is insignificant. Table 1 shows the supply air flowrate in Campaign C is about 14% lower than Campaigns A and B. Therefore, the weaker jet flow from the diffuser is likely to result in a more uniform distribution in the vertical direction. Note that the concentrations in the sampling towers 6 ft. away from the source is slightly higher than the other towers. Despite the minor concentration difference on the horizontal plane, the overall CV of the submicron and micron normalized concentrations at all nine measuring points is 12% and 15%, respectively. The above measurements suggest that, in the condition of the sampling time scale of one hour, the time-averaged concentration is uniformly distributed throughout the zone.

The thermal conditions noted in this study would be favorable to promote relatively rapid mixing. The experimental study from Baughman et al. [24] showed, when a 500 W electrical heater was applied or the incoming solar radiation was introduced, the mixing time for a point-source pollutant by natural convection in an unoccupied 1095 ft³ (31 m³) room was reduced to 13–15 min and 7–10 min, respectively. In this study, the zone experienced both solar radiation and the heat from a ceramic fan-forced heater. Moreover, the exhaust airflow and the heat from vacuum pumps and the compressor contribute to both mechanical and thermal air movement in the zone. Therefore, a fast mixing could be expected. At the measuring point 6 ft. (1.83 m) away from the source in the zone with a volume of 2496 ft³ (71 m³), Fig. 6 shows the aerosol concentration reached a steady state within 30 min after the start of aerosol generation. This observation is in agreement with the time scale in the experimental study from Baughman et al. [24]. Because the characteristic mixing time is shorter than the exposure timescale, it is appropriate to treat the indoor air as well-mixed in this study.

In summary, the mean of normalized concentration in the three campaigns is 0.59 ± 0.11 and 0.59 ± 0.15 for submicron and micron aerosol, respectively. Regardless of the distance of the cascade impactors from the source, the time-averaged concentration is still significantly high. Fig. 6 shows the plateau concentration is reached within 30 min. Therefore, even if occupants are in compliance with the 6-ft spacing guideline or even when occupants are spatially greater than 6 ft apart with the exposure time scale in hours and under the same HVAC system operation, the exposure risk is still high when occupants share the same zone with a contagious occupant.

3.2 Dynamic concentrations for constant continuous emission

Three campaigns were conducted to investigate the dynamic concentrations. Campaigns D, E, and F were conducted on September 52,020, October 272,020, and November 102,020, respectively. The TSI model 3076 generated constant output of submicron aerosol, and TSI SMPS monitored concentration with a 5-min time resolution.

As the source continuously emits aerosol at a constant rate, the first term of Eq. (3) is omitted due to the zero-initial concentration C₀. By keeping the second term, Eq. (3) is reduced to:
\[ C(t) = \frac{E}{(1 - R)\lambda V} (1 - e^{-(1 - R)\lambda t}) \]  

In essence, this equation shows the dynamic concentration follows “1 minus exponential decay”, and the coefficient \( \frac{E}{(1 - R)\lambda V} \) represents the steady state concentration \( C_{ss} \), provided that the emission is constant. According to the parameters given in Section 2.4, \( R \) is calculated as 0.072 for submicron aerosol, and the lump-sum first-order loss rate was calculated as 7.8 h\(^{-1}\) including ventilation of 7.7 ACH and submicron particle deposition of 0.1 h\(^{-1}\) in Campaigns D, E, and F.

After the concentration was normalized by the steady state concentration \( C_{ss} \), the experimental data was compared with Eq. 4, as shown in Fig. 7. The experimental data agree well with the model except for a few outliers. The outliers could be associated with the unstable output due to co-generation of aerosol and air bubbles. As mentioned in Section 2.2, the unwanted air bubbles from the nebulization solution containing NaCl and Uranine can lead to unstable output. We observed that the solution level in the container was higher in Campaign F. In other words, the space between the solution level and the aerosol outlet was shorter, and it was more likely to co-generate aerosol and air bubbles before the air bubbles dissipate.

The low OA ratio (\( \alpha = 0.1 \)), low filtration efficiency (\( \eta = 20\% \)), and negligible submicron transport loss create an effect of more aerosols to be recirculated, but the low return air fraction (\( r = 0.1 \)) outweighs other factors and dominated the estimation of recirculation in this study. In Section 2.4, the recirculation parameter \( R \) for submicron aerosol was calculated as 7\%, indicating the extent of aerosol recirculation is low. If we assume the recirculation parameter \( R \) and the surface deposition are less important than ACR, Eq. (3) can be simplified as

\[ C(t) = \frac{E}{Q} (1 - e^{-ACR t}) \]  

Fig. 7 shows the insignificant difference between the full model and the simple model. Because the simple model still agrees well with the experimental data, it is concluded that the air change rate dominates the mechanism of the dynamic aerosol concentration in this study.

3.3. Dynamic concentrations after the end of emission

Two campaigns were conducted to investigate the dynamic concentrations. Campaigns G and H were conducted on January 14, 2021, and January 12, 2021, respectively. The Collison nebulizer generated both submicron and micron aerosol, and TSI SMPS and TSI APS monitored submicron and micron concentration over time, respectively.

When the aerosol emission stops, the second term of Eq. (3) can be omitted and the dynamic aerosol concentration can be characterized as

\[ C(t) = C_0 e^{-(1 - R)\lambda t} \]  

Eq. (6) shows the aerosol concentration exponentially decays and the decay rate is influenced by \( R \) and \( \lambda \). \( R \) is calculated as 0.072 and 0.0486 for submicron and micron aerosol, respectively. Submicron \( \lambda \) is calculated as 6.7 h\(^{-1}\) including ventilation of 6.6 ACH and submicron particle transport.
deposition of 0.1 h⁻¹, while micron λ is 7.7 h⁻¹ due to higher micron particle deposition rate of 1 h⁻¹ [20] in Campaigns G and H. Because the emission is independent of the exponential decay in Eq. (6), the Collison nebulizer with less-constant output can still be used to conduct experiments. As the Collison nebulizer can generate both submicron and micron size aerosol, the experimental data in both ranges are shown in Fig. 8. In general, the model agrees well with the experimental data in both size ranges. As shown in Fig. 8 b, particles in the micron range fluctuated more from the model prediction during Campaign H. During Campaign H, researchers walked through the test space to attend to the operation of experiments. The deposition of aerosol particles on the closing of the moving human [26] and the human-induced wakes [27,28] may have led to some degree of fluctuation of the micron aerosol concentration.

With the same approximation strategy in Section 3.2, Eq. (6) can be simplified by considering only ACR as

\[ C(t) = C_{0}e^{-ACR t} \]  

Fig. 8 also shows the simple model is almost identical to the full model, and the simple model also fits the experimental data well. The difference between the simple and full models is less than 3% for submicron and micron particles. It is important to note that both simple models, given in Eqs. (5, 7), are sufficient, provided that the contribution from the recirculation parameter and particle deposition can be omitted. First, when aerosol emission occurs in multiple zones, more aerosols will be recirculated. It is expected the aerosol concentration in the supply becomes substantial and more time will be required by the HVAC system to remove the aerosol from the zones. Second, in this study, the low particle deposition rate is due to the fact of the bare surfaces and small aerosol size. However, the deposition rate can
enhance for large particles due to gravitational force. It is reported that the deposition rate can be up to 5.45 h\(^{-1}\) for particle size at 8.66 \(\mu m\) [20]. For such a scenario, the approximation is invalid, and the full model should be considered.

4. A hypothetical test case study

By applying the model developed in the previous section, a hypothetical test case was conducted to predict the aerosol concentration changes over time under various air flow rates controlled by a VAV box, provided that an asymptomatic contagious occupant exhales \(10^6\) viral gene copies per hour [29] in the source zone and the expiratory particles are typically about 1 \(\mu m\) [30]. As the difference between the full and simple models is less than 3%, the simple model was used in the analysis presented in this section. Fig. 9 displays the dynamic aerosol concentrations predicted by the simple under various airflow rates from 50 to 400 CFM (24 to 189 L/s). ACR determines how quickly the steady state concentration is achieved. When the air flow rate is 100 CFM (47 L/s) or ACR is 2.4 h\(^{-1}\), the concentration can reach 90% of the steady state concentration within 60 min; only 20 min is needed to reach 95% of the steady state concentration at 300 CFM (142 L/s) or 7.1 ACH.

The steady state aerosol concentration can be determined by \(E, \lambda,\) and \(V\). As the air flow rate increases, the steady state concentration is inversely proportional to the flow rate as shown in Fig. 10. When the VAV box produces an airflow rate of 300 CFM (142 L/s) or 7.1 ACH, the steady state aerosol concentration is 1993 gene copies/m\(^3\). As a definitive infective dose for COVID-19 has not been established [30], assuming that the infective dose was 100 gene copies and the human breathing rate is 0.5 m\(^3\)/h, the critical time period to meet the exposure target in this case is calculated as only 6 min and 0.6 min, respectively. The analysis here points out the time scale to reach the infective dose targets is short. Therefore, to reduce the steady state concentration, techniques to mitigate the emission rates, such as wearing face masks, should be effective.

Fig. 10 shows the influence of the airflow rate on the steady state concentration 30 and 60 min after the aerosol emission stops. At 300 CFM (142 L/s) or 7.1 ACH, the respiratory aerosol concentration decreases from 1993 gene copies/m\(^3\) to 57 gene copies/m\(^3\) in 30 min and down to 2 gene copies/m\(^3\) after one hour. If the target infective dose was 100 gene copies, one-hour ventilation at 7.1 ACH is sufficient to mitigate the risk. Fig. 10 can serve as a tool to determine the sufficient time to mitigate the risk of exposure to respiratory aerosols such as SARS-CoV-2 in an office building environment.

5. Conclusions

To simulate the exposure potential of infectious aerosols such as SARS-CoV-2 in an office building setting, experimental studies for airborne particle transmission were conducted in a model commercial office building. When the synthetic test aerosol was generated in a building zone, three near-field aerosol transmission campaigns were conducted to measure the three-dimensional aerosol concentration and the dynamic aerosol concentration. The time scale of the measurements is similar to the human exposure time in an indoor office setting. The coefficient of variation of the nine measuring points used in this study is <10% in two campaigns and <15% in one campaign. Thus, the results indicate that the time-averaged aerosol concentrations are uniformly distributed throughout the zone. Regardless of the distance of the aerosol measurement impactors from the source, the mean of the normalized aerosol concentration is 0.59. In addition to the experimental data of dynamic aerosol concentration, a model was developed...
under the framework of a mass balance and a well-mixed condition to estimate the indoor aerosol concentration accounting for aerosol recirculation and particle deposition. The model has been validated and agrees well with the experimental data. Because aerosols were generated in only one out of ten zones in the model office building, we found that the return air fraction outweighs the filtration efficiency and OA ratio in this study, resulting in insignificant aerosol recirculation. Also, the impact of particle deposition rate is relatively minor compared to ACR for the particles <3 μm. Considering both conditions, the full aerosol concentration model can be simplified, in which only the ACR is involved. The simple model is sufficient and agrees well with the experimental data. Finally, provided that the airflow rate in a VAV box was adjustable, a hypothetical test case was evaluated to predict the concentration changes under continuous generation of one million viral gene copies per hour within one source zone. Our case study indicates the steady state concentration is inversely proportional to the airflow rate, and enhanced mixing can be achieved with increasing airflow rate or air change rate. When the aerosol emission stopped, a higher airflow rate or air change rate can enhance the exponential decay rate. At 300 CFM (142 L/s) or 7.1 ACH, only 20 min is required to reach 95% of the steady state concentration in the single zone setting. After aerosol emission stops, the HVAC system operating at the same condition (300 CFM or 7.1 ACH) can remove 99.9% of aerosols in one hour.

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.

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