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

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ABSTRACT

As businesses gradually reopen and employees return to work, the potential spread of SARS-CoV-2 and its variants through airborne transmission via the heating, ventilation, and air-conditioning (HVAC) systems of commercial building raises concerns. Since the general practice in commercial buildings is to use low-efficiency air filters and given that indoor air is generally recycled, the degree to which cross-zone aerosol transmission occurs is of interest. To quantify the cross-zone aerosol transmission, experiments were conducted using a synthetic test aerosol in the five zones on the first floor of a model commercial office building at the Oak Ridge National Laboratory. Because the synthetic aerosol was tagged with fluorescent salt, the aerosol generated from the source zone can be distinguished from the background aerosols due to its unique fluorescent signal. Data from cross-zone campaigns showed that submicron-aerosol transmission was higher than the micron aerosols. In campaigns with doors closed, the submicron aerosol transmission was less than 16% and less than 11% for micron aerosol transmission. Opening the interior doors that connecting different zones can significantly enhance the aerosol transmission for zones at the close proximity to the source, but has less impact on those farther away.

1. Introduction

Aerosol transport within buildings is an important route for SARS-CoV-2 transmission. This has been justified by the detection of SARS-CoV-2 RNA in aerosols [1] and the discovery of viable SARS-CoV-2 in air [2]. Also, unexplained community spread events of SARS-CoV-2 cast doubt on the claimed insignificance of airborne transmission. For example, the aerosol transmission event of SARS-CoV-2 in a Guangzhou (China) restaurant is attributed to poor ventilation [3]. The super-spreading event at a choir rehearsal in Skagit County, Washington (USA) is likely due to inhalation of respiratory aerosol in the indoor environment [4]. Therefore, the Centers for Disease Control and Prevention (CDC) has stated that airborne transmission of SARS-CoV-2 can be viable under circumstances including prolonged exposure to respirable particles and inadequate ventilation or air handling [5].

Interczonal migration of infectious airborne aerosols in healthcare facilities has been studied [6–9]. Hang et al. studied the inter-cubicle airborne aerosol transmissions through a shared anteroom under the effects of hinged door swinging [7]. As the door is closed, the current negative-pressure design of an isolation cubicle can be effective for the containment of aerosols with an index patient. However, with the door opened, it was found that the flow differential, temperature difference, and the concentration gradient across the doorway between the cubicle and shared anteroom induced flow, and the aerosol migrated across the doorway. As the common isolation ward does not share space and is equipped with an independent anteroom, Leung et al. showed that aerosol migration still occurred in such negative pressure isolation wards under the effects of hinged door swing and human movement [6].

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When the cubicle was under negative pressure with respect to the anteroom, the aerosol migration was 0.06% from the cubicle to the anteroom with the door closed. The aerosol migration increased to 0.46% with door opening and human movement. On the other hand, the negative pressure design was in favor of the aerosol transmission from the corridor to the cubicles with the migration ratio of 20% as reported.

Another field study was conducted to investigate far aerosol transmission routes from a general patient room to an isolation cubicle through a nurse station in a hospital [8]. Aerosols were found to migrate 14.5 m from a general patient room to the entrance of the anteroom but the aerosol transmission is merely 0.1%. In summary, the interzonal migration of aerosol is low except for the transmission from the anteroom to the cubicle due to its lower pressure with respect to other zones.

The results of the interzonal aerosol migration studies in healthcare facilities do not warrant the low aerosol transmission in non-healthcare facilities such as office buildings or schools. Healthcare facilities are required to utilize high-performance air filtration and maintain a minimum of 12 air changes per hour (ACH) [10], which implies that the air volume in the zone should be replaced by fresh air 12 times per hour. Even though building ventilation typically mixes return air with fresh outside air (OA), most aerosols can be removed by high-performance filters. In contrast, the general practice in commercial buildings is to use low-efficiency air filters with a Minimum Efficiency Reporting Value (MERV) rating from 4 to 8 [11]. These filters do not efficiently remove micron or submicron aerosols, and the aerosols can recirculate in the building. Additionally, the air change rate per hour in commercial building is much lower than that of healthcare facilities. The air change rate (ACR) in schools and offices in Denver (USA) were reported as 1.3–3.4 (h⁻¹) and 3.3–5.5 (h⁻¹), respectively [12]. Therefore, aerosol migration cannot be ignored in the commercial building.

As businesses gradually reopen and employees return to work, the asymptomatic spread of SARS-CoV-2 in office buildings raises concerns. Because supply air largely consists of recirculated air, in a building with multiple zones, it is possible that aerosols from the source zone can be transmitted to other zones through the centralized heating, ventilation and air-conditioning (HVAC) system. The degree to which such a far-field aerosol transmission occurs has not yet been reported. Also, the impact of opening doors on the aerosol transmission in the office building setting is unknown. To investigate these knowledge gaps, the specific goals of this study are to experimentally characterize cross-zone aerosol transmission in a model office building during scenarios with doors-opened and closed.

2. Methodology

The aerosol transmission experiments were conducted in five zones on the 1st floor of a model commercial office building, the Flexible Research Platform (FRP), at the Oak Ridge National Laboratory (ORNL). Sodium chloride aerosols were chosen as the preferred surrogate for respiratory aerosols because of the safety concerns of using bioaerosols during indoor air experiments. Sodium chloride aerosols tagged with uranine (fluorescent marker) were generated and collected in cascade impactors to map and quantify the far-field aerosol transmission under the influence of a centralized Variable Air Volume (VAV) HVAC system with open and closed-door scenarios. Details of the building, indoor air ventilation, aerosol generation and collection as well as measurement, and experimental design are further described below.

2.1. Building

Six aerosol transmission campaigns were conducted in ORNL’s model commercial office building, the Flexible Research Platform (FRP), from November 2020 to January 2021. The FRP was designed to represent a typical two-story small to medium sized office building which was built in the 1990s. The two-story FRP has a total floor area of 3200 ft² (297 m²) for investigating building energy efficiency and has been equipped with more than 500 sensors and instruments to monitor the building environment, such as relative humidity (RH) and temperature, and HVAC system and building performance (Fig. 1). This test platform has been used for multiple studies including empirical validation of building energy models and HVAC system performance analysis [13,14]. Hence, the building’s envelope and HVAC system properties such as the building’s air infiltration rate and HVAC system performance have been well characterized, which can be leveraged in this multizone aerosol transmission study. In addition, the occupants’ sensible and latent heat generation within the building is simulated using portable electric resistance heaters and humidifiers to represent typical occupant behavior in an office setup.

2.2. Indoor air ventilation

Fig. 2 shows the HVAC system configuration and measuring points in the FRP. The HVAC system is equipped with an air-side economizer, and the economizer modulates the OA damper to control the fresh air intake to maximize the energy efficiency of the system. In the existing control, the economizer is enabled when the OA temperature is between 45 and 55 °F (7 to 13 °C), where the outside air is favorable to be used to precool the return air. The minimum position of the OA damper is 10%, even if the economizer is disabled to provide adequate ventilation to the building. Before the cooling and heating coils, partial aerosols in mixed air are removed by MERV 7 filters, which are commonly used in centralized HVAC systems in office buildings. 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 airflow rate for each zone varies per size and orientation of the zone, and the VAV box in each zone modulates the airflow rate to meet the cooling demand of the zone. The measurement of inward airflow rate into individual zones during the sampling period is also shown in Fig. 2. The 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 Rooftop Unit (RTU) for another cycle.

2.3. Aerosol generation, collection, and measurement

In this study, synthetic test aerosols were selected rather than tracer gas. Compared to tracer gas as a surrogate for aerosols, the use of aerosol can represent the particle transport dynamics under the impact of the HVAC system. For example, tracer gas testing will not account for the aerosol deposition during transport and aerosol loss during filtration. Sodium Chloride (MW = 58.44 g mol⁻¹; NaCl; CAS#: 7647-14-5; Sigma...
Aldrich) was selected as the material for testing aerosol transmission. As the NaCl droplets initially leave the aerosol generator, the NaCl droplets evaporate and turn into solid aerosols in a short time. 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 generated aerosols (RH) in the building environment has been controlled to be lower than solid chloride aerosols does not change, because the relative humidity

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Similar tagging technology has been used to understand indoor aerosol transmission in aircraft [15].

An aerosol generator (TSI model 3076) and a Collison nebulizer were used for particle generation to meet the objectives of this study. The TSI model 3076 can generate sufficient aerosols with constant output [16]. However, the upper bound of aerosol size from the TSI model 3076 nebulizer is limited to the submicron range. To mimic the respiratory aerosols in the micron range, 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 uranine 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 uranine into 75 mL Nanopure water and 25 mL ethanol.

Ethanol was added to the solutions in the Collison nebulizer to stabilize aerosol generation and reduce potential co-generation of air bubbles which can disrupt aerosol generation. In summary, submicron aerosol transmission was reported using the TSI model 3076, while both submicron and micron aerosol transmission (< 0.25 μm to >2.5 μm) were reported when the Collison nebulizer was utilized.

Sioutas cascade impactors were used to collect fluorescent aerosols, since the high flow rate, 9 Lpm, results in the collection of sufficient samples for mass analysis within a reasonable time period. 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 [17]. Particles are collected on Polytetrafluoroethylene (PTFE) (25-mm, 0.5 μm pore size) substrates and a final PTFE filter (37-mm, 2.0 μm pore size). The sampling time depends on the source concentration, zone dimensions, ventilation conditions, and analytical quantification limit. 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 aerosols tagged with uranine on filters, as the extraction efficiency is >99% [18]. The fluorescent signal of the aerosols 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 fieldworks.

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

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

where \( C_i \) is the aerosol concentration at a zone and \( C_g \) 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 the same as the source concentration.

2.4. Experimental design

Experiments were conducted in five zones on the first floor of the FRP. The floor surface is bare. The height of the five zones is 8 ft. (2.43 m) and the floor areas are 136 ft² (12.2 m²), 196 ft² (18.2 m²), 312 ft² (29.0 m²), 312 ft² (29.0 m²), and 312 ft² (29.0 m²) for zones R102, R103, R104, R105, and R106, respectively. Two four-way square ceiling
diffusers and one return grilles are situated on the suspended ceiling at 8 ft. (2.43 m) above the floor in the perimeter zones as shown in Fig. 3. The mean values of the inward airflow into each zone during the sampling period were calculated, as shown in Fig. 3. In the inward ACR is higher in R104, R105, and R106, while lower in R102 and R103 (core zone), with 6.5 and 5.4 ACH, respectively. In addition to a diffuser and a return, an exhaust fan directly extracted air from the core zone at approximately 250 CFM (118 L/s), which is equivalent to 9.6 ACH. Therefore, the outward airflow rate was greater than the inward airflow rate in the core zone, and the core zone was under negative pressure with respect to the perimeter zones including the source zone.

Zone R104 was selected as the source zone, and the aerosol generator was placed in the center of the source zone. One source impactor was 1 ft. (0.3 m) horizontally away from the source and at a height of 3 ft. (0.9 m) above the floor, and the monitoring data represented the source concentration. In the other four zones R103, R102, R105, and R106, four impactors were placed at a height of 3 ft. (0.9 m) above the floor and 5 ft. (1.5 m) away from the door. Because the ventilation strategy in the FRP is mechanical mixing ventilation, the measurement represented the aerosol concentration under diffusers. The remaining five impactors were deployed at a height of 7 ft. (2.1 m) and located under the four-way square ceiling diffusers by 1 ft. (0.3 m), and the measurement represented the aerosol concentration under diffusers. Several real-time instruments were deployed in the source zone to monitor the aerosol concentrations for quality assurance (QA) and quality control (QC) purposes. Finally, open- and closed-door scenarios were tested. Closed-door scenarios represent an office setting in which aerosols are expected to be majorly trans and closed-door scenarios were tested. Closed-door scenarios represent quality assurance (QA) and quality control (QC) purposes. Finally, open-
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A mass-balance model with the well-mixed assumption is applied to estimate the recirculation rate. Detailed aerosol mass balance calculations are described in near field study; see reference [19].

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

$$V \frac{dC}{dt} = C_l Q_l - C_R Q_R + E - VC_k$$

(2)

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 airflow rate ($m^3/h$), $Q_R$ is return airflow rate ($m^3/h$), $k$ is the first-order aerosol loss rate ($hr^{-1}$). $Q_l$ is assumed to equal $Q_R$ in this study. Aerosol emission, $E$, is independent of time, $t$. Moreover, the concentration at the supply air inlet, $C_s$, can be written as

$$C_s = \alpha C_{sa} + (1 - \alpha)(1 - \eta)(1 - l)C$$

(3)

where $\alpha$ 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, $l$ 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 [20] and quickly diluted in the outdoor environment, the outdoor aerosol concentration, $C_{out}$, is assumed as zero. The parameters in the second term of the eq. (3) represent the effect of recirculation, therefore $(1 - \alpha)(1 - \eta)(1 - l)r$ is combined into one recirculation rate $R$.

Parameters of $\alpha, \eta, l,$ and $r$ were estimated in the following. When the outside temperature was unfavorable to be used for the economizer, damper position remained at 10% and $\alpha$ of 0.1 was assumed. The filtration efficiency for MERV 7 filters ranges from 10% - 50% for 0.5-3 $\mu m$ particles [21], so 20% was applied for submicron and 40% for micro particles in this study. Transport loss $l$ includes aerosol deposition in the HVAC heat exchanger and in the ventilation duct. The loss in HVAC heat exchanger is $<10\%$ for 1–10 $\mu m$ particles for air velocities ranging from 1 to 4 m/s for fin spacing of 4.7 fin per centimeter [22]. The loss in ventilation ducts is negligible for submicron particles [23]. For micron aerosol, loss in supply duct is higher than in return duct runs because of internal insulation surface in the portion of supply ducts. It was reported the 10% loss for particle size at 8.7 and 17.2 $\mu m$ in supply and return ducts, respectively. Accordingly, the lump-sum transport loss in heating coil and ducts was assumed to be negligible for submicron and 10% for

![Fig. 3. Ventilation and sampler deployment on the first floor.](image-url)
micron particles. Because \( Q_i \) is assumed to equal \( Q_s \), the \( Q_i \) measured in each zone as shown in Fig. 2 can be applied to calculate the return air fraction \( r \) as 0.1 in the source zone. Therefore, \( R \) are calculated for 0.072 and 0.049 for submicron and micron particles, respectively.

3. Results and discussion

3.1. Building environment: closed-door vs. open-door

Three closed-door and three open-door campaigns were conducted in this study. The TSI model 3076 generated submicron aerosols in Campaign A and D, which were conducted from 9:00 am to 1:00 pm on November 3 and November 10, 2020, respectively. As mentioned previously in the experimental methods section, both submicron and micron size aerosols can be generated using the Collison nebulizer; the four Campaigns B, C, E, and F were conducted from 1:55 pm to 3:55 pm on December 22, 020, from 1:10 pm to 2:50 pm on December 31,020, from 1:30 pm to 3:00 pm on December 23,020, and from 12:00 pm to 1:30 pm on January 12,021, respectively. Note that the shorter sampling period in Campaigns B, C, E, and F is due to higher aerosol output from the Collison nebulizer.

Table 1 displays the building and outdoor environments for the closed-door campaigns. The outdoor condition would be favorable to be used when OA temperature is between 45 and 55 °F (7 to 13 °C) in FRP. The OA in the three campaigns was unfavorable to be used based on OA temperature. Since the HVAC system was normally operated, the indoor environment including temperature was generally consistent. The weather in Campaign B and C were cold and the heater warmed up the indoor air, resulting in lower RHs compared to Campaign A. The inward airflow rate was also consistent with little variation except for R105 and R106 in Campaign A. The higher standard deviation of the airflow rate in the two zones were due to the increase of the incoming solar radiation. The increasing airflow rate also enhanced inward air change rate. A special operation was conducted in Campaign C and the inward airflow rate in R104 and R103 was lower by 12% and 14%, respectively, while the airflow rate remained similar in R 105 and R 106.

Table 2 displays the building and outdoor environments for the open-door campaigns. The OA in Campaign D and F was favorable to be used due to the suitable OA temperature. Note that the exact percentages of OA in the two campaigns were not available. Although the monitoring data of building environment in Campaign E is missing, inward air change rate in each zone was believed to be similar with Campaigns D and F because the operational settings of the HVAC system were not changed. In general, the inward air change rate in three perimeter zones (R104, R105, and R106) were higher at 7.6 h⁻¹, 8.5 h⁻¹, and 7.4 h⁻¹, respectively. The air change rate in perimeter zone R102 was lower as 6.5 h⁻¹. The inbound air change rate in the core zone was the lowest at 5.4 h⁻¹; however, as motioned in the Experimental Design section, the high extraction flow was equivalent to 9.6 h⁻¹, and the flow differential can induce a negative pressure environment.

3.2. Compare supply aerosol concentration to the aerosol concentration under the diffuser

The aerosol concentration measurement under the diffusers was compared to a theoretical value to determine the aerosol concentration in the supply air. Fig. 4 shows the normalized aerosol concentrations measured under the supply diffusers in the five zones. The results show the aerosol concentrations under the diffusers varied in the different zones. Although the measurement was conducted under the diffusers, some measured concentrations were unexpectedly high, especially in source zone.

In Section 2.5, the recirculation rate in the HVAC system is estimated as 7.2% and 4.9% for submicron and micron aerosol, respectively, in Campaign A-C. Note that OA condition is unfavorable to be used in Campaign A-C, but the OA condition is favorable to be used in Campaign D-F. Although the exact ratio of OA to supply air was unavailable, more fresh air was introduced into zones in Campaign D-F than Campaign A-C, and then the ratio is estimated to be >0.1. It is inferred that the recirculation rate in Campaign D-F is <7.2% and <4.9% for submicron and micron aerosol, respectively. Based on our previous near-field study, the mean of normalized concentration in the source zone is measured as 0.59 [19]. Accordingly, the normalized concentration at the supply inlet was calculated as 0.042 and 0.029 for submicron and micron aerosol, respectively, for Campaign A-C; the normalized concentration would be less in Campaign D-F. 0.042 and 0.029 were set as the maximum of the theoretical values of normalized aerosol concentration in the supply.

After comparing the measurement to the theoretical values of 0.042 and 0.029, the aerosol concentrations in R104, R103, and R102 were found to be higher than the theoretical values. So, it is likely that these measured concentrations were “contaminated”, and the measured values do not represent the aerosol concentration in the supply. The contamination could be attributed to aerosols entering the impactors’ sampling zone from other routes. The other routes could be primary aerosol transport from the source in R104 and secondary aerosol transport through door gaps from R104 to other zones. Therefore, the theoretical value is a better choice to represent aerosol concentration in the supply.

3.3. Cross-zone aerosol transmission: closed-door vs. open-door

Fig. 5 displays the aerosol transmission from the source zone to the other four zone in the closed-door and open-door scenarios. The submicron normalized concentration (NC) was higher than the micron NC in all zones. In other words, submicron aerosol transmission is greater than micron aerosol transmission. The lower transmission of micron particles is due to the large particles being susceptible to particle loss by deposition or impaction during transport. With doors closed, NC is less than 0.16 and 0.11 for submicron and micron aerosols, respectively. The lowest aerosol transmission occurred in perimeter zones R105 and R106. Comparing the theoretical value of 0.042 and 0.029 for submicron and micron aerosol, respectively, to the measurement shown in Fig. 5, it is likely that the transmission into the perimeter zones R105

Table 1 Building environment for the closed-door campaigns.

| Space | R104 (source) | R103 (core) | R102 (perimeter) | R105 (perimeter) | R106 (perimeter) | Outdoor |
|-------|---------------|-------------|-----------------|-----------------|-----------------|---------|
|       | A | B | C | A | B | C | A | B | C | A | B | C | A | B | C | A | B | C |
| Temperature (°F) | 71 ± 0 | 70 ± 0 | 70 ± 0 | 74 ± 71 ± 71 ± 71 ± 71 | 71 ± 71 ± 72 | 75 ± 70 ± 71 ± 71 | 76 ± 70 ± 71 ± 72 | 72 ± 58 ± 39 | 308 ± 306 | 52 |
| RH (%)     | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 2 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 2 ± 1 | ± 5 ± 2 ± 1 |
| VAV Airflow rate (CFM) | 316 | 317 | 299 | 142 | 140 | 120 | 117 | 117 | NA | 385 | 352 | 352 | 370 | 308 | 306 | NA | NA | NA |
| Inward Air Change Rate (h⁻¹) | 7.6 | 7.6 | 6.7 | 5.4 | 5.4 | 4.6 | 6.5 | 6.4 | NA | 9.3 | 9.5 | 8.5 | 8.9 | 7.4 | 7.4 | NA | NA | NA |
and R106 mainly through the HVAC ducts. The NC in R102 and R103 (the core zone) are higher than in R105 and R106. It is noted that higher NC in the perimeter zone R102 is most likely due to lower inward ACR. The negative pressure in the core zone provides a favorable condition to transport aerosol through door gap from the source to the core zone, and contributions to the observed higher core zone aerosol concentration.

Fig. 5 shows that opening interior doors can significantly enhance the aerosol transmission from the source zone to the core zone, but opening doors has less impact on the other perimeter zones. Fig. 5 also shows the submicron and micron aerosol transmission can double to 0.27 and 0.12 in the core zone, respectively. In line with the finding in the hospital isolation units [6,9], flow differential may explain the enhanced transmission in the zone under negative pressure (i.e. core zone) as the door was opened. As perimeter zones are under positive pressure with respect to the core zone, the aerosol transmission through doorways from one perimeter zone to another perimeter zone is unfavorable.

**Table 2**

| Space          | R104 (source) | R103 (core) | R102 (perimeter) | R105 (perimeter) | R106 (perimeter) | Outdoor |
|----------------|---------------|-------------|-------------------|-------------------|-------------------|---------|
| **Temperature (°F)** | D 70 ± NA     | E 70 ± NA   | F 71 ± NA         | D 71 ± NA         | E 71 ± NA         | F 73 ± NA |
|                | 0 70 ± 1      | 0 70 ± 1    | 0 71 ± 1          | 0 71 ± 1          | 0 73 ± 1          | 0 74 ± 1 |
| **RH (%)**     | D 23 ± NA     | E 47 ± NA   | F 21 ± NA         | D 44 ± NA         | E 21 ± NA         | F 23 ± 1 |
|                | 1 23 ± NA     | 1 44 ± NA   | 1 21 ± NA         | 1 44 ± NA         | 1 23 ± 1          | 1 23 ± 2 |
| **VAV Airflow rate (CFM)** | D 317 ± 3 | E 318 ± 1 | F 140 ± 2 | D 117 ± 0 | E 119 ± 1 | F 352 ± 3 |
|                | ± 3           | ± 1         | ± 2               | ± 0               | ± 1               | ± 4     |
| **Inward Air Change Rate (h⁻¹)** | D 7.6 NA     | E 7.6 NA    | F 5.3 NA          | D 5.4 NA          | E 5.4 NA          | F 6.5 NA |
|                | 6.5 NA        | 5.4 NA      | 6.5 NA            | 6.5 NA            | 8.5 NA            | 8.5 NA  |

**Fig. 4.** Aerosol concentration measurement under diffusers in five zones.

**Fig. 5.** Comparison of cross-zone aerosol transmission: closed door vs. open door.
3.4. Special event: the effect of decreased inward airflow rate in source and core zone on the aerosol transmission

Operating under a special event in Campaign C, where the interior doors were closed, the inward airflow rate was reduced in R104 and R103 by 12% and 14%, respectively, while the airflow rates were maintained in the other zones. Changing the airflow rates in the source and core zones only had impacts on the aerosol transmission to the core zone, but changes in concentration in the other perimeter zones were not observed. The normalized concentration in the core zone was measured as 0.43 and 0.26 for the submicron and micron aerosols, respectively, which is significantly higher than the mean values of closed-door submicron and micron NC of 0.13 and 0.06, and even higher than the measurements in the open-door scenarios in Fig. 5.

The observed increased concentration is the results of less dilution and the airflow differential. First, as the inward airflow rate decreased in the source and core zones, the less dilution enhances the aerosol concentrations in both the source and core zones. Second, the induced flow caused by the negative pressure could introduce more-contaminated air in the source zone to the core zone through the door gap.

4. Conclusions

Far-field experiments were conducted in five zones on the first floor of ORNL’s Flexible Research Platform (FRP) to investigate the cross-zone aerosol transmission in open-door and closed-door scenarios. The measurement of aerosol concentration under the air supply diffusers showed a high variability in different zones. The measurement concentrations were generally higher than the theoretical concentration at the supply inlet contributed by recirculation, indicating these measured concentrations were “contaminated”. Therefore, the theoretical value is a better choice to represent aerosol concentration in the supply. The measurements in the source zone indicated the highest concentrations, while the lowest concentrations of 0.07 and 0.03 for submicron and micron aerosols, respectively, occurred in perimeter zone (R106). The results of cross-zone aerosol transmission indicated that submicron aerosol transmission was higher than the micron aerosol transmission. In door closed campaigns, submicron aerosol transmission was less than 16% and 11% for micron aerosols. The lowest aerosol transmission occurred in perimeter zones R105 and R106. The concentrations in R103 and R102 were higher than the aerosol concentration in the supply and implies additional aerosol transmission routes other than HVAC transport. The addition aerosol transmission could include the primary aerosol transport in the source zone and the secondary cross-zone aerosol transport through door gaps. Opening interior doors almost doubled the aerosol transmission from the source zone to the core zone, but the concentration difference in the other perimeter zones was less pronounced. The negative pressure in core zone might explain the observation of enhanced transmission in the core zone.

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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