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Experimental evaluation of particle exposure at different seats in a single-aisle aircraft cabin

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ABSTRACT

During the COVID-19 pandemic, exposure to particles exhaled by infected passengers in commercial aircraft cabins has been a great concern. Currently, aircraft cabins adopt mixing ventilation. However, complete mixing may not be achieved, and thus the particle concentration in the respiratory zone may vary from seat to seat in a cabin. To evaluate the particle exposure in a typical single-aisle aircraft cabin, this investigation constructed an aircraft cabin mockup for experimental tests. Particles were released from a single source or dual sources at different seats to represent particles exhaled by infected passengers. The particle concentrations in the respiratory zones at various seats were measured and compared. The particle exposure was evaluated in both a cross section and a longitudinal section. Leaving the middle seat vacant to reduce particle exposure was also addressed. In addition, the velocity fields and air temperatures were measured to provide a better understanding of particle transport. It was found that the particle exposure at the window seat is always the lowest, regardless of the particle release locations. If the passenger seated in the middle does not release particles, his/her presence enhances the particle dispersion and thereby reduces the particle exposure for adjacent passengers. In the cabin mockup, the released particles can be transported across at least four rows of seats in the longitudinal direction.

1. Introduction

The entire world continues to suffer from the COVID-19 pandemic. Transmission of COVID-19 during air travel has been a significant concern. Probable transmission of the infection inside an aircraft cabin has been reported on several flights [1–4]. In the past, transmission of severe acute respiratory syndrome (SARS) [5], H1N1 influenza [6], tuberculosis [7], and norovirus [8] in aircraft cabins were documented. There are three transmission routes for infectious diseases, i.e., direct transmission or short-range transmission, surface contact transmission or fomite transmission, and aerosol transmission or long-range airborne transmission. Although any of these three routes of transmission can occur in aircraft cabins, the present investigation examined only the aerosol route. Indeed, aerosol transmission in aircraft cabins has been identified as the probable cause of some COVID-19 infection cases during air travel [2,4].

Mixing ventilation is currently used in commercial aircraft [9–11]. Conditioned air enters the cabin at a relatively high speed at ceiling level, circulates in the cabin, and finally leaves the cabin via exhaust outlets near the floor on both sides in the same row as the inlets [12]. This ventilation mode produces a uniform temperature distribution [13] with the goal of superior thermal comfort. However, cross transport of expired aerosols among passengers in the same row and even across several rows may exist [14], although the air supply and air exhaust span the whole fuselage. The air supply in a commercial aircraft cabin should not contain virus-laden particles, because the recirculated air

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passes through a high efficiency particulate air (HEPA) filter, and the outdoor air has been compressed to over 170 °C and then expanded and cooled [10]. The aerosol transmission of infection between infected and susceptible individuals is due to airflow circulation inside the aircraft cabin.

For the sake of safety, virus-laden particles have been replaced by innocuous particles during experimental tests of particle exposure in an aircraft cabin mockup [15]. A single particle source has commonly been used for simplicity. Particle tests have been carried out either in an aircraft cabin mockup [16] or on an actual aircraft [17], in which temporal particle concentrations [16] or steady-state particle concentrations [17] were measured. The simultaneous release of particles from two or more particulate sources is common, but it has been addressed in only a few experimental studies. A steady concentration of SF₆ gas from dual sources was measured in a seven-row aircraft cabin mockup [18]. The concentration of a non-reactive gas released from dual sources was determined as the superposition of gas concentrations from two independent single releases. The concentrations of talc powder particles were measured after the particles were released at seven positions in the same row in a B767 aircraft cabin mockup [19]. The above research indicates that released particulates can travel a considerable distance in a cross section, subject to the airflow pattern inside the cabin. It should be noted that although the air in the cabin is highly mixed, the particle exposure may still vary from seat to seat.

The longitudinal transport of particulates is also of great concern. Ideally, cabin ventilation will minimize the longitudinal airflow. However, available studies reveal that a degree of longitudinal airflow exists in aircraft cabins [20,21], mainly due to the unevenness of air supply and/or exhaust. The particulates in a cabin were found to be transported across more than three rows of seats, and the particle concentration decayed by approximately one order of magnitude every three rows [22]. Meanwhile, a certain number of particles could still be detected in the eleventh row of a B767 aircraft cabin mockup when the particles were released in the second row, and the particle concentration decayed by about 37% every row [19]. Minimizing the airborne transmission risk of COVID-19 requires a better understanding of particle transport by the longitudinal airflow in the cabin.

Meanwhile, the passenger occupancy in the cabin may have an impact on the cabin airflow and thus on particulate transport. Early research [23] measured and simulated the airflow fields and particle concentrations in a cabin mockup with an occupation density of one half. Due to the uneven distribution of occupants, the cabin layout was not symmetric. In more recent studies [24,25], the cabin was fully occupied by thermal manikins, although the measured airflow and pollutant distribution were asymmetric. To lessen the infection transmission, many airlines have reduced the occupancy density by leaving the middle seats vacant. However, the impact of this measure on airborne particle exposure is still unclear.

To evaluate the exposure to exhaled particles for passengers in different seats, this investigation measured airflow, temperature, and concentrations of airborne particles with a diameter of 1 μm in a single-aisle aircraft cabin mockup. The following issues were examined: the particle exposure in the respiratory zones at different seats, the reduction in particle exposure when the middle seats were left vacant, and the particle transport in the longitudinal direction. In addition, the concentration of particles released by dual sources and the sum of the concentrations of particles released by two independent single sources were compared.

2. Methodology

2.1. Aircraft cabin mockup

A single-aisle aircraft cabin mockup, as shown in Fig. 1, was constructed for experimental tests. The mockup had a seven-row capacity, but only six rows of seats were employed in the tests. The dimensions of

![Aircraft cabin mockup for experimental tests: (a) photograph of the cabin interior, (b) schematic diagram of the airflow pattern, and (c) schematic diagram of the cabin layout (unit: mm).](image)
consistent with the ASHRAE161-2007 standard. Therefore, the total HEPA filtrated air supplied into the cabin was set to 1436.4 m$^3$/h. The recommended ventilation rate is no less than 9.4 l/s per person, which is also commercial aircraft uses approximately 50% recirculated air, the recommended air supply rate is no less than 0.55 lb/min per person. Since a commercial aircraft cabin at a rate of at least 0.55 lb/min per person. Since a commercial aircraft uses approximately 50% recirculated air, the recommended ventilation rate is no less than 9.4 l/s per person, which is also consistent with the ASHRAE161-2007 standard. Therefore, the total HEPA filtrated air supplied into the cabin was set to 1436.4 m$^3$/h, with an average ventilation rate of approximately 9.5 l/s per person. No recirculated air was used. The average air-supply temperature was 19.4 °C, and the exhaust air temperature was close to 25 °C. The exhaust outlets were located near the floor on both sides of the cabin, each with a width of 6.5 cm. The interior cabin walls and the surface temperature of the thermal manikins. These boundary conditions created a comfortable cabin environment as those on realistic flight.

### 2.2. Measurement of airflow and temperature fields

To elucidate the particle transport in the cabin mockup, the steady-state airflow and air temperature fields in the cross section across row 4 and the longitudinal section along the D seats were measured, as shown in Fig. 1(c). The instruments used to measure the velocity field were three ultrasonic anemometers (type: DA-650 with TR-92T; Kaijo, Japan). The velocity resolution was 0.005 m/s with an accuracy of 1%. Meanwhile, the air temperature was measured by T-type thermocouples. The resolution of the air temperature measurement was 0.02 °C with an accuracy of ±0.5 °C [26]. The anemometer probes and thermocouples were mounted on a three-dimensional guide rail, as shown in Fig. 2. The spatial resolution of each measurement was 150 mm. The guide rail only moved between the interval of two successive measurements to minimize its interruption to the thermoflow. Once moving the rail, the airflow was stabilized for at least 4 min before continuing the next measurements.

### 2.3. Particle release and measurement

A polydisperse aerosol generator (type: ATM 241; Topas, Germany) with two discharge outlets was used as the particle source and released the electrically neutral Di-ethyl-hexyl-sebacate (DEHS) particles, as shown in Fig. 3(a). Only those particles with a size of 1.0 µm were evaluated, for its good representation of most bioaerosols that lead infection. The particle generator could function as either a single particle source or dual sources. Each discharge outlet was connected to a floating flowmeter to ensure the desired flow rate of the particle-laden gas. The carrier gas was HEPA filtrated and dried pressure air. The flow rate at either discharge outlet was controlled at 26 l/min in the experiment, and the particle concentration was maintained at 1.1 × 10^3 particles/cm³. Fig. A.1 shows the recorded particle source concentration in the course of an hour at the two discharge outlets. The above parameters assured that the airborne particle concentrations inside the cabin were higher than the background concentration by two orders of magnitude, to minimize the interruption from the airborne particles in the background air.

The generated particles were released into the cabin by porous acrylic balls with a diameter of 10 cm, as shown in Fig. 3(a). The acrylic balls were positioned just above the heads of the manikins. This layout was somewhat similar to the release of particles through the gaps of a face mask or the leakage of particles from a mask. Fig. 3(b) provides a more precise schematic diagram of the balls used for particle release. The ball surface was evenly perforated with 400 small holes, each with a diameter of 3 mm. Each ball was filled with cotton to reduce the momentum of the particle-laden gas. Table 2 lists the measured speeds when the particle-laden gas was released in six directions. The release speed in the backward direction was the highest because of impedance by the cotton, while the downward and forward speeds were very low. The particle laden gas release directions and speeds were not purposely controlled. However, the low-momentum of the particle laden gas release was achieved.

For determination of particle exposure, the particle concentrations were evaluated in the inhalation zones at different seats. As shown in the right-hand photograph of Fig. 3(a), silica gel sampling tubes were mounted to the guide rail next to the manikins to extract air samples for particle concentration measurement. The guide rail was never moved when measuring particle concentrations. The guide rail to mount air-sampling tubes moved only when flushing the background particles inside the cabin between different test cases. Fig. 3(b) shows the exact locations at which cabin air was extracted for particle counting, i.e., the sampling points or entrances to the sampling tubes. Each sampling point was located 10 cm away from the trunk of the associated manikin and 116 cm above the floor. The sampling tubes were connected to a multipoint gas sampler for extraction of the air samples. Finally, the air samples were delivered to an aerodynamic particle size spectrometer (type: 3321; TSI, USA) for concentration measurement. All the sampling tubes had a length of 8 m, regardless of the sampling point location, which ensured similar particle transport loss during sampling. The flow rate of the particle spectrometer was 5 L/min, with 52 channels for counting particles of different sizes. The lower limit for particle counting was 0.001 particles/cm³, and the accuracy was ±10% of the reading value plus the statistical deviation. The air sampling time was determined from the length, diameter and flowrate of the sampling tubes. The sampling tubes had an inner diameter of 6 mm. Under the rated sampling flow rate, the transport time of the air sample in the tube was 2.71 s. The minimum sampling time for each concentration reading was 10 s.

| Table 1 Overview of basic thermo-flow boundary conditions. |
|-----------------|-----------------|-----------------|
| Parameter       | Value           | Parameter       | Value           |
| Total air supply rate | 1436.4 m$^3$/h | Right luggage rack temperature | 25.45 °C |
| Width of central air-supply opening | 40 mm | Left lighting temperature | 29.64 °C |
| Central air-supply speed | 0.63 m/s | Right lighting temperature | 29.09 °C |
| Central air-supply temperature | 19.3 °C | Temperature of upper left wall | 26.72 °C |
| Width of side air-supply opening | 20 mm | Temperature of upper right wall | 26.68 °C |
| Side air-supply speed | 1.45 m/s | Temperature of lower left wall | 26.97 °C |
| Left air-supply temperature | 19.4 °C | Temperature of lower right wall | 26.22 °C |
| Right air-supply temperature | 19.5 °C | Floor temperature | 25.42 °C |
| Width of bottom air-exhaust opening | 65 mm | Sectional surface temperature | 26.31 °C |
| Ceiling surface temperature | 22.04 °C | Door surface temperature | 25.51 °C |
| Left luggage rack temperature | 25.24 °C | Surface temperature of thermal manikin | 30 °C |

Fig. 2. Anemometer probes and thermocouples mounted on a guide rail for thermoflow measurement.
which was more than triple the transport time. The concentrations at a particular location was measured for at least 20 min.

In this study, for evaluation of the particle transport in the cross section, a single particle source was placed successively at each of three positions, I (4F), II (4E) and III (4D), as shown in Fig. 4, or single sources were placed simultaneously at two of the above positions to constitute dual-sources particle release. For evaluation of the longitudinal transport of particles along the D seats, only a single particle source was placed at position IV (2D). Table 3 provides an overview of the particle measurement tasks. More detailed descriptions of the measurement tasks can be found in A.2 of the appendix.

### Table 2
Measured discharge speeds of the particle-laden gas in different directions from the porous ball.

| Direction  | Forward (m/s) | Upward (m/s) | Downward (m/s) | Left (m/s) | Right (m/s) | Backward (m/s) |
|------------|---------------|--------------|----------------|------------|-------------|----------------|
|            | 0.04          | 0.12         | 0.01           | 0.12       | 0.18        | 0.28           |

![Fig. 3. Particle sources and particle sampling points: (a) photographs of particle sources and sampling tubes, and (b) illustrations of particle sources and sampling points (unit: mm).](image)

![Fig. 4. Planar view of the particle release sources.](image)

### Table 3
Overview of particle measurement tasks.

| Experimental test task | Release source type | Release source location | Seats at which particle concentration is measured in the respiratory zone |
|------------------------|---------------------|-------------------------|------------------------------------------------------------------------|
| Single-source release in the cross section | Single source | 4D, 4E, 4F | 4A, 4B, 4C, 4D, 4E, 4F |
| Dual-source release in the cross section | Dual sources | 4D & 4E, 4D & 4F, 4E & 4F | 4A, 4B, 4C, 4D, 4E, 4F |
| Both source types released in the cross section when the middle seat is vacant | Single source and dual sources | 4D & 4E, 4D & 4F | 4D, 4E, 4F |
| Single source release in the longitudinal section | Single source | 2D | 1D, 2D, 3D, 4D, 5D, 6D |

### 2.4. Measurement procedure and concentration normalization

Prior to the particle experiment, the steady-state velocity and temperature fields were measured. The air-conditioning systems for both the cabin mockup and the room accommodating the mockup were operated for at least 4 h to ensure that the air-supply and air-exhaust temperatures in the cabin were stable. The anemometer probes and thermocouples were then mounted on the guide rail in appropriate positions for velocity and temperature recording. The measurement time at each point was 4 min. After the guide rail was moved, the airflow was allowed to stabilize for at least 3 min before the next measurement was conducted.

Before release of the particles for the tests, the air-conditioning systems were again operated for at least 4 h to stabilize the thermoflow conditions. Next, each measurement task as shown in Table 3 was carried out. Once the particle concentration reached a stable level
and remained there for a sufficient time to obtain the required particle concentration at a given sampling point, the particle measurement was switched to the next point, and the process was repeated until all the experimental measurements were completed.

For easy comparison, dimensionless particle concentrations were reported. The dimensionless concentration \(C^*\) was calculated by Eq. (1):

\[
C^* = \frac{C_{\text{local}} - C_0}{C_{\text{out}} - C_0}
\]

where \(C_{\text{local}}\) is the particle number concentration at a sampling point, particles/cm\(^3\); \(C_0\) is the particle number concentration in the air supply, which varied in each test but was usually less than 5 particles/cm\(^3\); and \(C_{\text{out}}\) is the nominal exhaust particle concentration without considering particle transmission loss, particles/cm\(^3\), whose calculation was based on Eq. (2):

\[
C_{\text{out}} = \frac{Q_{\text{source}} \times C_{\text{source}}}{Q_{\text{ventilation}}}
\]

Here, \(Q_{\text{source}}\) is the particle-laden gas flow rate from a single release source, 26 L/min; \(C_{\text{source}}\) is the number concentration of the particle source, which was \(1.1 \times 10^5\) particles/cm\(^3\) in this investigation; and \(Q_{\text{ventilation}}\) is the total air-supply rate into the cabin, which was 1436.4 m\(^3\)/h. The calculated nominal exhaust concentration of 1 \(\mu\)m particles was 123.13 particles/cm\(^3\) in this investigation.

3. Results

3.1. Thermo-flow fields

Fig. 5 depicts the measured airflow field in the cross section across row 4 and in the longitudinal section along the D seats. Two vortices were formed on the two sides of the cabin, with the vortex centers above the middle passengers on each side. The velocity in the jet regions and outside the vortices was larger, while the velocity in the vortex center was smaller, which indicates that the velocity distribution was not uniform. The passengers near the aisle were in the downward flow of the circulation pattern, while the passengers near the window were in the upward flow. The lower torso of the middle passenger was in the outward flow of the circulation, and the upper torso was in the inward flow. With the downward air supply from the ceiling above the aisle, the airflow in the aisle was not vertical, but was shifted to seat 4C. In the longitudinal section, as shown in Fig. 5(b), most of the airflow was downward because of the circulation pattern. The velocity near the manikins’ heads was small because the upward thermal plume counteracted the downward general flow. The velocity distribution was not exactly the same in front of all the manikins.

Fig. 6 presents the air temperature distribution in the same two sections. The distribution in both sections was relatively uniform. The air temperature was slightly higher above the manikins because of the thermal plume created by the heat released from the manikins. The air temperature in the aisle was slightly lower due to the downward jets, which had a lower temperature. The thermal plumes above the manikins

![Fig. 5. Measured average airflow field: (a) in the cross section across row 4, and (b) in the longitudinal section along the D seats.](image-url)
in different seats varied slightly in the longitudinal section, as shown in Fig. 6(b), which indicates the turbulent nature of the flows in these regions.

3.2. Particle concentrations for full occupancy in the cross section

Fig. 7(a) shows the temporal particle concentrations in the respiratory zones of seats 4D, 4E, and 4F respectively, when the particle source was placed on the head of the manikin seated in 4D. Starting from the release of particles at the source, the concentration at each measurement point rose gradually. After approximately 5 min, the concentrations fluctuated within a certain interval, in a manner similar to that of test results in the literature [17]. Because seat 4D was close to the aisle, this region was at the intersection of the circulation flows on the left and right sides of the cabin, as demonstrated by the velocity field in the cross section shown in Fig. 5(a). Thus, the concentration in the respiratory zone of 4D fluctuated greatly. Fig. 7(b) and (c) present the particle concentrations in the respiratory zones of 4D, 4E, and 4F when the particles were released from the heads of the manikins seated in 4E and 4F, respectively. No matter where the release source was, the concentrations in the respiratory zones of 4D and 4E were relatively close, and they were higher than the concentration in the respiratory zone of 4F.

For easy comparison of the particle concentrations at the three seats, Fig. 8 displays the average concentration and standard deviation in the respiratory zone of the fourth row when the particle source was located on the heads of the 4D, 4E, and 4F manikins, respectively. The average particle concentrations were measured 5 min after the start of the particle release, to assure that steady-state concentrations were reported. As shown in Fig. 8, when the particle source was at either 4D or 4E, the concentration in the respiratory zone of the release source was the highest, while the 4F concentration was the lowest. Meanwhile, when the release source was at 4F, the concentration measured in the respiratory zone of 4F was the lowest among the three seats, while the 4E concentration was the highest. According to the velocity field shown in Fig. 5(a), the particle source at 4F was located outside the circulation flow, and there was significant airflow toward the center of the cabin ceiling. Moreover, the particle source at 4F was near the air-supply jet, and the jet carried the released particles to the middle of the cabin, resulting in the highest concentration in the respiratory zone of 4E and the lowest concentration at 4F. Therefore, no matter where the release sources were located, the measured concentration was similar in the respiratory zones of 4D and 4E, and the respiratory zone concentration at the window seat, 4F, was always the lowest.

For evaluation of the particle concentrations in the respiratory zones of seats 4A to 4C, a single particle source was placed on the manikin seated in either 4D or 4F. It can be seen in Fig. 8 that the particle concentration in the respiratory zones of 4A to 4C was not zero, but it was much smaller than in the respiratory zones of 4D to 4F. It can be seen in Fig. 8 that the particle concentration in the respiratory zones of 4A to 4C was not zero, but it was much smaller than in the respiratory zones of 4D to 4F. Thus, the particles could be transported across the aisle to the other half of the cabin, which implies that the air-supply jet in the aisle was not sufficient to prevent the particles from spreading across the aisle. In addition, the airflow in the aisle shown in Fig. 5(a) was shifted to seat 4C. When the release source was at 4D, the concentration in seats 4A to 4C was higher than when the source was at 4F, because 4D was closer to the half row of
Fig. 7. Temporal particle concentrations in the respiratory zones of three seats in row 4 when particles were released from a single source on the manikin’s head at different positions successively: (a) III (4D), (b) II (4E), and (c) I (4F).
from the last 5 min of the measurement. The superposed particle concentration was highest in the respiratory zone of 4D and lowest in the respiratory zone of 4A (near the window) was still the lowest. Meanwhile, the concentrations in the respiratory zones of seats 4D to 4F were quite similar and were much lower than those in the respiratory zones of 4D to 4F. The superposed concentrations from two independent single source releases were close to the concentrations from the simultaneous dual sources, except in the respiratory zones of 4D and 4E. This was because seat 4D was close to the aisle, and the airflow near the aisle was at the intersection of the circulation flows on the left and right sides of the cabin. Seat 4E was in the center of the vortex flow, where the airflow was highly unstable.

3.3. Particle concentrations in the cross section when the middle seat is vacant

In a single-aisle aircraft cabin, it is common practice to leave the middle seat vacant when the occupant density is not high. Fig. 10 compares the average particle concentration in the respiratory zones of seats 4D to 4F when seat 4E was either vacant or occupied. For the single-source release at 4D, as shown in Fig. 10(a), the concentration in the respiratory zone of 4D when 4E was vacant was higher than when 4E was occupied; the concentration in 4E was nearly unchanged; and the concentration in 4F was slightly higher. This was because seat 4E was located in the circulation flow zone, as shown in Fig. 5(a). When 4E was occupied, the upward thermal plume drew the particles released from 4D upwards, and thus the concentrations in the respiratory zones of both 4D and 4F were reduced. When the source was at 4F, as shown in Fig. 10(b), the concentrations in the respiratory zones of both 4D and 4F were higher when 4E was vacant than when it was occupied, again due to the upward plume airflow. This shows that if the passenger in seat 4E does not release particles, the passenger’s presence facilitates the dispersion of the particles released by neighboring passengers. However, if the 4E passenger releases particles, the situation is quite different.

Fig. 11 compares the concentrations in respiratory zones when the middle seat was vacant or occupied, to constitute four different particle release scenarios. When 4E was vacant, only single-source particles were released from the head of the manikin in seat 4D or 4F; when 4E was occupied, dual-source particles were released from 4E and either 4D or 4F. Regardless of whether 4E was vacant or occupied, the particle concentration in the respiratory zone of 4E is provided, because the particle sampling did not require the presence of a manikin. A comparison of the concentrations in the respiratory zone of 4D in Fig. 11 shows that the concentration from dual sources at 4E and 4F was more than twice that from a single source at 4F when 4E was vacant; the same was true for dual sources at 4D and 4F and a single source at 4D while 4E was vacant. The concentration in the respiratory zone of 4F for dual sources at 4E and 4F was also more than twice that for a single source at 4F when 4F was vacant; and such was the case for dual sources at 4D and 4E and a single source at 4D when 4E was vacant. Thus, the particle concentrations in the respiratory zones of 4D and 4F were much lower when 4E was vacant than when 4E was occupied as a particle source.

In summary, if the passenger in seat 4E does not release particles, this passenger helps to reduce particle exposure for the passengers in seats 4D and 4F. However, when passenger 4E definitely releases particles, the adjacent passengers are demonstrably exposed to particles, which can also be seen in Fig. 8 for the single-source release at seat 4E. Furthermore, Fig. 11 shows that when 4E is occupied, the passenger in that seat experiences significant particle exposure. Therefore, when it is not clear whether a passenger in seat 4E will release virus particles or not, leaving that seat vacant is an effective way to reduce the potential exposure.

3.4. Particle concentrations in the longitudinal section

Fig. 12 shows the average particle concentrations in the respiratory zones of the D seats in the longitudinal direction when a single particle source was released from seat 2D (position IV). Fig. A.3 in the appendix presents the measured temporal particle concentrations without normalization of the data. It can be seen that the concentration was the highest in the respiratory zone of 2D, where the release source was located. In the rows immediately in front of and behind the source, the concentrations gradually decreased. The concentration decay from 5D to 6D was weaker than in the front rows. The nonzero particle concentration at seat 6D indicates that the particles could be transported across at least four rows. The aircraft cabin in this study contained only six rows of seats. For a more accurate understanding of the transport range of the particles along the longitudinal direction, a longer cabin mockup is needed.

4. Discussion

This investigation released particles with a nearly constant rate from porous balls on the heads of manikins. Such release may not exactly represent the dynamical viral shedding from the human respiratory tract. As for COVID-19, an infected person releases the virus particles mainly by coughing, talking, and exhalation. If the person is not wearing a face mask, the virus release is accompanied by strong momentum from the mouth or nose. The low-momentum particle release employed in this
The diameter of COVID-19 particles is commonly less than 0.1 μm, but the virus may be contained in droplets or droplet nuclei. Hence, this investigation evaluated particles with a diameter of 1 μm. It is known that the dispersion of particles smaller than 1 μm resembles that of gases. Our other measurements showed that the difference in dispersion between 1 μm and 5 μm particles was not substantial, but with slightly better diffusion for the 1 μm particles.

For measurements of particle concentration, a multi-point sampler was used. This approach facilitated the switching of sampling tubes among the respiratory zones of different seats. The connection to the sampler, switching of the sampling tubes, and long transport length may have caused particle transport loss when air was drawn to the particle spectrometer. Thus, the reported particle concentrations would be slightly less than the actual concentrations in the respiratory zones. However, since this investigation maintained the same sampling tube length and similar routes for all particle sampling, the particle transport loss and under-measured particle concentrations did not affect the comparison of concentrations or the overall findings in this paper.

As shown in Fig. 7, the recorded temporal particle concentrations fluctuated greatly. This was mainly due to the turbulence of the airflow and the small surface area of the particle release source, which made the particle concentration at the sampling points particularly sensitive to the stability of the airflow. The concentration fluctuation at seat 4F was weaker than the fluctuation at seats 4D and 4E, which was consistent with the turbulence intensity inside the cabin. In addition, the particle-laden gas flow rate and the particle concentrations of the release sources were not completely stable, as shown in Fig. A.1 in the appendix, which also contributed to fluctuation of the concentrations at the monitoring points.

The measured results show that the particle exposure was the lowest in the respiratory zones of the window seats. This difference in exposure arose simply from the flow pattern created by the two side-wall air supply jets, and the results might vary if different air supply modes were adopted. It should be noted that most current commercial aircrafts employ ventilation modes that are similar to the one in this investigation. The central downward air supply and the created jet cannot prevent released particles from crossing the aisle to the other half of the cabin. This movement of particles can be ascribed to the diffusion of particles by mainly turbulent mixing and also to molecular diffusion.

Leaving the middle seats vacant throughout the cabin results in a two-thirds occupant density, dramatically reducing the virus release load from the level that would exist if the middle seats were occupied by infected individuals. However, vacating the middle seats also slows down particle dispersion, because the presence of the middle passenger creates upward thermal plume flow, which facilitates both the dispersion and exhaust of particles out of the cabin. Thus, there are pros and cons to leaving the middle seat vacant. In particular, wearing of a facial mask by middle-seat passengers should be more strictly enforced during a pandemic.
Longitudinal airflow should be minimized. The measured particle concentrations revealed that particles could be transported across at least four rows, and longitudinal particle transport is caused mainly by longitudinal airflow. Both uneven air supply and uneven air exhaust contributed to the longitudinal airflow. In addition, thermal plumes from the manikins, flow impedance by the seats and manikins, and diffusion by turbulence and molecular motion contributed to the longitudinal transport of particles. Further research is needed for a better understanding of longitudinal airflow and pollutant transport.

5. Conclusions

This investigation evaluated particle exposure in the respiratory zones of different seats in a single-aisle aircraft cabin. The particles were released from a single source or dual sources. The concentrations of 1 μm particles were evaluated, and the following conclusions can be drawn.

1. The measured particle concentration varies with the locations of particle sources and the seats at which the respiratory-zone measurements were conducted. In the current single-aisle aircraft cabin, the particle concentration in the respiratory zone of the window seat is the lowest, while the concentration is higher at the middle and aisle seats. The current mixing ventilation is not sufficient to retain the released particles in the half of the cabin where the particle sources are located.

2. Leaving the middle seat vacant has pros and cons in terms of particle exposure. If the passenger seated in the middle does not release particles, his/her presence enhances the particle dispersion and thus reduces the particle exposure for adjacent passengers. However, if the middle passenger releases particles, these particles together with those from any of the adjacent passengers result in a particle concentration in the respiratory zone that is more than twice that of a single-source release when the middle seat is left vacant. Therefore, the wearing of a face mask by middle-seat passengers should be more strictly enforced during a pandemic.

3. In the studied cabin, released particles can be transported across at least four rows of seats in the longitudinal direction. The particle concentration decreases with distance from the particle release source. For a more accurate understanding of the transport range of particles in the longitudinal direction, a longer cabin mockup for experimental testing is needed.

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.

Appendix

A.1 Supplemental results

![Fig. A.1. Measured temporal particle concentrations (1 μm) at the dual particle sources](#)

![Fig. A.2. Size spectrum of the generated poly-disperse particles at the source](#)
A.2 Particle measurement tasks and brief procedure

Table 3 summarizes the tasks of particle measurement in this investigation. The brief measurement procedure and purpose are:

1. Particle transport in a cross section of the cabin with a single particle source
   (a) Place a single particle source at positions I, II, and III, successively, as shown in Fig. 4.
   (b) Starting from the release of particles at the source, measure the temporal particle concentration in the respiratory zones of the seats in row 4, one by one.
   (c) Compare the measured concentrations in the respiratory zones of seats 4D, 4E, 4F, and 4C, 4B, and 4A, and rank the exposure risks at these seats.

2. Particle transport in the cross section for dual particle sources
   (a) Place dual particle sources at positions I (4F) and II (4E), positions I (4F) and III (4D), and positions II (4E) and III (4D), successively, pair by pair.
   (b) Starting from the release of particles at the sources, measure the temporal particle concentrations in the respiratory zones of the seats in row 4, one by one.
   (c) Rank the measured concentrations in the respiratory zones of the seats in row 4.
   (d) Compare the concentrations for the pairs of dual sources and the superposed particle concentrations from the corresponding single-source releases in test (1).

3. Particle transport in the cross section when the middle seat is left vacant
   (a) Remove the manikin in seat 4E and place a single particle source at positions I (4F) and III (4D) successively, and then a dual source at the two positions simultaneously.
   (b) Starting from the release of particles at the source(s), measure the temporal concentrations in the respiratory zones of seats 4D, 4E and 4F, one by one.
   (c) Comparing the results from tests (1), (2), and (3), evaluate the impact of leaving seat 4E vacant on the particle concentrations in the respiratory zones of seats 4D to 4F, one by one.

4. Particle transport in the longitudinal section when particles are released from a single source
   (a) Place a single particle source at position IV (2D).
   (b) Starting from the release of particles from the source, measure the temporal concentrations in the respiratory zones of the D seats in different rows, one by one.
   (c) Evaluate the particle transport range along the longitudinal direction.

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