Inhaled Mass and Particle Removal Dynamics in Commercial Buildings And Aircraft Cabins

BY STEPHEN TRENT; ANGELA DAVIS; TATEH WU, PH.D.; DANNY MENARD; JOSHUA J. CUMMINS, PH.D.; JOSHUA L. SANTARPIA, PH.D.; NELS OLSON, PH.D.

Computational fluid dynamics (CFD) models of an aircraft cabin and an indoor commercial space (ICS) were used to characterize the spread of aerosols generated by a coughing or breathing person suffering from a respiratory illness. Occupant exposure to these aerosols was then compared between the ICS and the aircraft cabin. The lifetime of the aerosols, system designs and airflow patterns that reduce their concentration over time were also examined. Differences between steady state and well-mixed conditions were identified and comparisons made between the model environments. The CFD analysis results were also compared to empirical data from a U.S. Transportation Command study that tracked particles introduced by simulated infectious individuals in an airplane cabin environment.

Stephen Trent is an engineer in the Cabin Environment/Air Quality group within Environmental Control Systems for Boeing Commercial Airplanes. He is the vice chair of ASHRAE Standard 161 and TC 9.3. Angela Davis is a materials and chemical engineer within the Chemical Technology group in Boeing Research and Technology. Tateh Wu, Ph.D., is an associate technical fellow of Boeing Commercial Airplanes in the Environmental Control Systems (ECS) organization. Danny Menard is a flight engineer in Boeing Defense, Space and Security. Josh Cummins, Ph.D., is the probabilistic analytics team lead and a senior manager in Boeing's Safety Management System for Boeing Global Services and Boeing Test and Evaluation. Joshua L. Santarpia, Ph.D., is the research director for Counter WMD programs at the National Strategic Research Institute, associate professor of microbiology and pathology and program director for Biodefense and Health Security Degree Program at the University of Nebraska Medical Center. Nels Olson, Ph.D., is an analytical chemist with over 43 years of experience working in engineering, biotechnology and aerospace industrial and academic environments.

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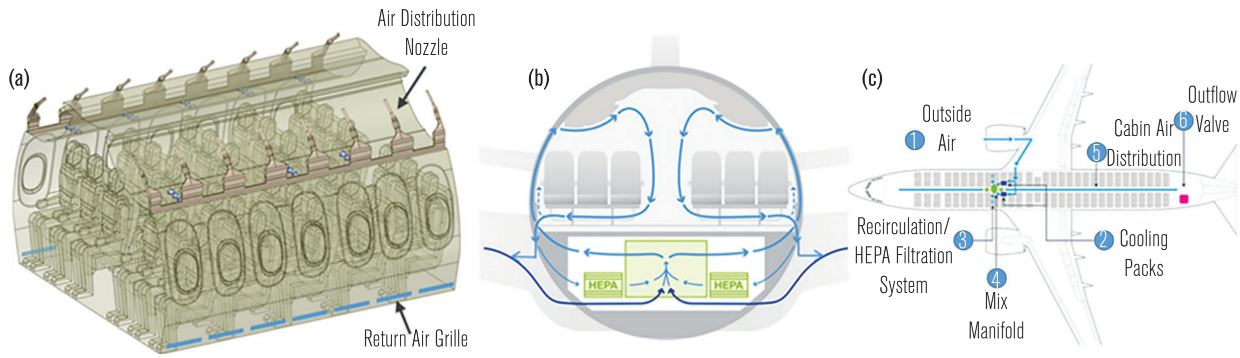
FIGURE 1 (a) Position of distributed air nozzle inlets throughout the aircaft cabin; (b) cross sectional diagram of intended airflow design for the aircraft cabin; (c) top-down view of environmental control system.



From March 2020 to October 2020, only 44 known cases of COVID-19 were transmitted in the air travel system while 1.2 billion passengers traveled by air worldwide.[1,2] While this transmission rate is certainly undercounted, other studies tracking cases in the air travel system also show very low transmission rates amongst occupants.[1] The low risk of transmission may be aided by the multilayered approach adopted by airlines, regulators and other organizations to keep passengers and flight crews healthy.[3] This approach includes physical distancing, masking, vaccinations, washing hands, avoiding travel for individuals feeling unwell and disinfecting the airplane cabin and flight deck.

However, even with these additional precautions, an infectious person may still be onboard. Therefore, additional studies were undertaken to characterize the aircraft cabin airflow and understand why the risk of transmission was lower than might be expected for an indoor commercial space (ICS).

Comparing Ventilation Systems

Ventilation that provides acceptable indoor air quality (IAQ) and minimizes health risks is an important part of any indoor environment. ASHRAE Standard 62.1 defines ventilation air as that portion of supply air that is outdoor air plus any recirculated air that has been treated for the purposes of maintaining acceptable indoor air quality,[4] e.g., removal of viruses by HEPA filters.

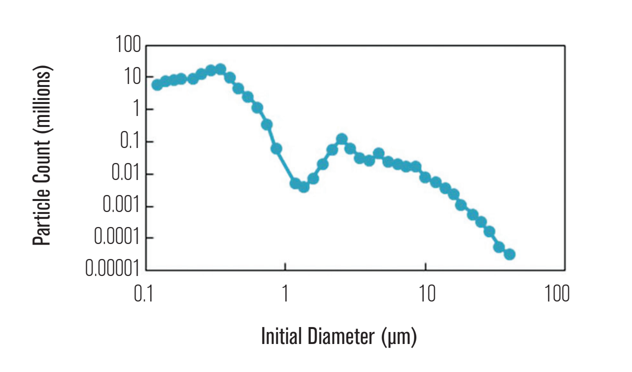
Aircraft typically provide 20 to 30 air changes per hour (ACH), with airflow rates of 15 cfm to 20 cfm (7 L/s to 9.4 L/s) of outdoor and recirculated air per occupant. The recirculated component of supply air is HEPA filtered (defined as 99.97% removal at most penetrating particle size of 0.3 µm)[5,6] and is mixed typically with 50% outdoor air. Since the outdoor air does not contain significant quantities of infectious agents, the resultant mixed outdoor and HEPA-filtered supply air has no significant viral contamination. Air then flows in a predominantly downward direction in the cabin and exits through return air grilles at floor level where it is again HEPA-filtered or expelled overboard (*Figure 1*). The seats act as additional physical barriers to help isolate passengers from each other and partially compartmentalize the airflow.

When compared to an aircraft, air exchange and filtration rates within an ICS are lower, typically between 2 ACH and 8 ACH. Prior to the current COVID-19 pandemic, ICSs had a MERV of 4 to 7 (mean 10.5% to 42.2% at 0.3 µm). Since the pandemic began, the filtration efficiency of some indoor environments has increased to MERV 13 (mean: 85.9% at 0.3 µm).[7] However, these factors, coupled with an overall lack of directional flow, allow a substantial percentage of expiratory particles to spend a longer time in an ICS than in an airplane.

Commonly Used ICS Model

The Wells-Riley model, first used by Wells[8] and Riley[9] to determine the spread of measles in a school environment, has been the basis for many retrospective studies modeling disease transmission in ICSs. This model assumes a space with a well-mixed air volume that instantaneously arrives at a steady state concentration. While necessary at the time, in hindsight, the assumption of a well-mixed environment

FIGURE 2 Cough particle size distribution on a semi-log scale. Adapted from Zayas.[14]



may not have been well represented even in the original studies.

Riley[9] discusses the mix of recirculated to outdoor airflow varying from 28.6% to 100% of total flow supplied to each room depending on the outdoor temperature for the school building studied. The ventilation in an ICS may also be on or off depending on airflow and temperature requirements. The filtration used for recirculated air was relatively ineffective for viruses—particularly measles. The filters in the study only had an efficiency between 12%–30% (depending on school wing). In addition, the Wells-Riley approach assumes a transmission from an index occupant to a susceptible occupant to have taken place in the school, while ignoring other potential transmission environments, such as the school bus, and is applied retrospectively.

While studies have attempted to use the Wells-Riley model, there are a few issues with the applicability of any well-mixed model assumption for the airplane environment, particularly with respect to airflow and filtration. Since the airflow in an aircraft is predominantly downward, with each row of seats having multiple air inlets near the ceiling, and multiple air outlets near the floor, as seen in *Figure 1*, the aircraft is more representative of a mixed-flow, advection-dispersion model (advection: airflow driven; dispersion: concentration gradient-driven) than a well-mixed model. In a typical commercial building environment, where people are present and aerosols are not driven in an overall downward direction, an instantaneous and well-mixed assumption is more reasonable than in the airplane cabin environment, but still an imperfect assumption due to stagnation points.

An example advection-dispersion model is below, where D is the dispersion coefficient, v = velocity and C = concentration:

$$\frac{\partial C}{\partial t} = \left(D_x \frac{\partial^2 C}{\partial x^2} - v_x \frac{\partial C}{\partial x}\right) + \left(D_y \frac{\partial^2 C}{\partial y^2} - v_y \frac{\partial C}{\partial y}\right) + \left(D_z \frac{\partial^2 C}{\partial z^2} - v_z \frac{\partial C}{\partial z}\right)$$

For an airplane cabin, the deterministic term is the velocity in the z direction.

The assumptions for outdoor and recirculated air studied by Riley cannot be applied to the outdoor and recirculated air in an aircraft due to effective filtration in an aircraft. In an ICS, air recirculated through low MERV-rated filters can spread contaminants throughout the indoor space. In an aircraft, the effectiveness of the HEPA filters prevents the recirculation of particulate contaminants such as viruses.[10] As a result, the lower an indoor space's filtration efficiency, the more a well-mixed model assumption might apply as the ventilation systems, designed to maintain even temperature distribution, recirculate particulates not filtered out.

Commonly Used Models for Aircrafts

In all environments, but especially the aircraft cabin environment, there is a significant difference between the behaviors of gases and particulates. HEPA filters provide essentially particulate-free air, while gases (e.g., CO_2) pass directly through the HEPA filter to be recirculated into the cabin. In addition, airflow does not separate gases. The study of the behavior of gases in the aircraft interior are thus not applicable to the study of particles. The concentrations of gases emitted by passengers may be higher than those of particulates because gases are not removed by HEPA filters. The continuous downward airflow gradient (unlike the intermittent airflow in some buildings) keeps the time required to remove particles within the breathing zone of aircraft passengers short, and consequently there is no long-lasting, high concentration of aerosol particles in that zone.

Methods

CFD Overview

To compare the lifespan and movement of particles within an airplane cabin[11] to an ICS, computational fluid dynamics (CFD) studies were performed tracking particles released from a single cough and from sinusoidal tidal breathing. Both the cough and breathing were modeled for the airplane environment, but only the cough was modeled for the ICS.

In general, aerosols were tracked within each environment. Airborne particles were removed from the environments by deposition onto surfaces or exiting through return air grilles. The mass of particles that entered the breathing zone of occupants was monitored, and the nonvolatile mass of particles (in other words, the mass of droplet nuclei) inhaled by each occupant, except the index individual, was calculated following the methodology in Davis and Zee, et al.[11] The results demonstrated the difference in exposure between an aircraft and ICS, the difference in exposure between a cough and breathing-generated aerosols, and validated the model through comparison to experimental U.S. Transportation Command (TRANSCOM)[12] data.

Particle Release

A cough was simulated, as described in Davis and Zee, et al.[11] A total of 106 million particles were released over 0.4 seconds using a time-dependent flow rate and a particle size distribution including sizes down to 0.1 µm (*Figure 2,* page 12).

Tidal breathing was modeled using the methodology of Gupta, et al.[13] Breathing was performed through the nose with a nostril area of 0.11 in.^{2} (0.71 cm^2). For each breathing passenger, the tidal breathing curve was calculated as:

$$V_{tidal}(t) = A \sin(Bt + C) \qquad (1)$$

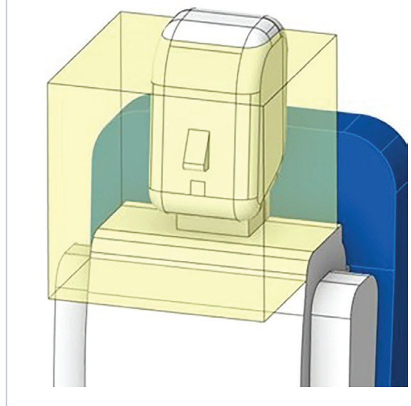
Random values of A (amplitude) and C (phase shift) were generated for all occupants, with A ranging from 0.72 cfm to 0.89 cfm (0.34 L/s to 0.42 L/s) and C ranging from 0 seconds to 5.8 seconds. As a consequence of the random phase shift, passengers were out of phase in their breathing activities. The same sinusoidal period with $B = 0.45\ \pi\ s^{-1}$ was used for all passengers.

Breathing passengers exhaled 88°F (31°C) air at 100% relative humidity,[13] and inhalation was modeled to disrupt airflow. Particles were released by the index passenger only. Exhaled particles were 0.4 µm, 0.75 µm and 3 µm in diameter, with 367, 92, and 66 particles, respectively per breath.[13] Each index passenger's exhalation released 9.7×10^{-5} µg of nonvolatile mass over 2.22 seconds, followed by 2.22 seconds of inhalation.

Aircraft Simulations

Within an aircraft cabin, a five-row section of a single-aisle cabin was modeled with periodic front and back interfaces, as shown in *Figure 1*. Air distribution nozzles were located above each row on either side of the aisle, and return air grilles were located at every window seat position below the window near the floor. Breathing zones were defined in front of the face of each occupant with an air volume of 0.8 ft^3 (0.02 m^3) (*Figure 3*). All 30 seats within the cabin were occupied, as shown in *Figure 4* (left), and susceptible passengers were simulated without the use of masks.

FIGURE 3 Occupant breathing zone marked in yellow, 0.8 ft^3 in volume.



Exposure to particles from a single cough in an aircraft cabin was modeled following the methods found in Davis and Zee, et al.[11]

For the aircraft, exposure to particles from breathing by a single infected passenger was modeled at cruise conditions following the methods described in Davis and Zee, et al.,[11] except as follows. Six simulations were performed, including three different index positions with and without all passengers breathing to disrupt airflow.

Respiration was simulated for eight minutes, with 0.05 second time steps. The nonvolatile mass of particles that entered an occupant's breathing zone between minute three and eight were used to calculate individual exposure at steady state. The total mass inhaled over five minutes was then scaled to eight hours of exposure to represent the longest regularly scheduled 737 flight.

Commercial Building Simulations

The ICS was selected for its similarities to an aircraft cabin—a relatively confined space with all occupants in seated positions, a ceiling air inlet and a ground level air outlet. The dimensions of the ICS shown in the middle and right panes of *Figure 4* were 25 ft × 20.5 ft × by 10 ft (7.6 m × 6.2 m × 3 m). An air outlet with dimensions of 2 in. × 36 in. (51 mm × 914 mm) was placed in the corner of the room behind Seat 1 to

FIGURE 4 (Left) Layout of aircraft cabin CFD model with inlets at ceiling above windows and return air grilles at floor level; (Center) layout of ICS CFD model; (Right) isometric of ICS CFD model.

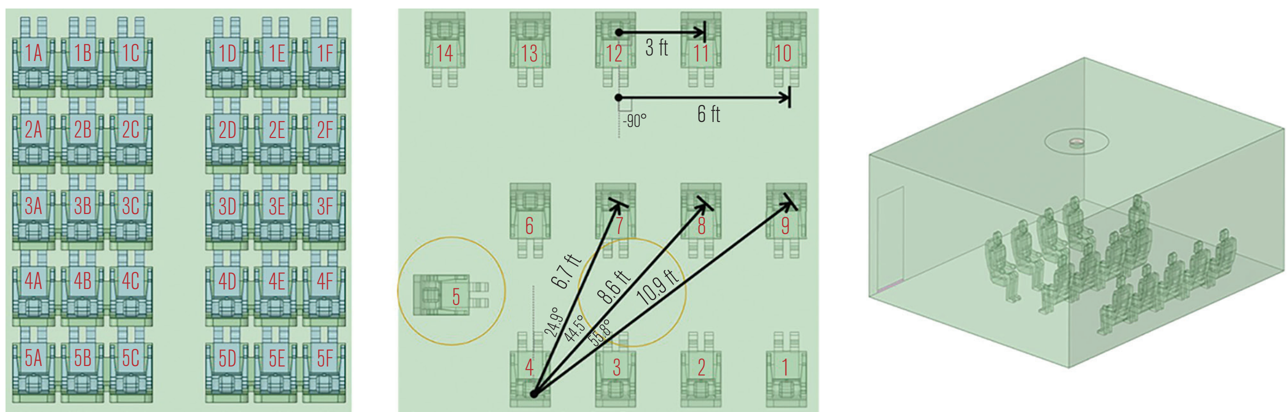


TABLE 1 Airflow and thermal boundary conditions used for CFD simulations

	737 AIRCRAFT COUGH	737 AIRCRAFT BREATHING	INDOOR COMMERCIAL SPACE COUGH
SUPPLY FLOW RATE (ACTUAL cfm)	323 – 588	588	171 – 683
RETURN FLOW RATE (ACTUAL cfm)	Same as supply	Same as supply	Same as supply
AIR CHANGES PER HOUR	24.7 – 44.9	44.9	2 – 8
RELATIVE HUMIDITY (%)	0 – 20	0	50
OCCUPANT HEAT GENERATION (W)	70/person	70/person	70/person
WALLS (°F)	55 – 65	65	Adiabatic
CEILING, FLOOR, STOWAGE BINS	Adiabatic	Adiabatic	Adiabatic
FRONT AND BACK INTERFACES	Periodic	Periodic	Non-periodic
SUPPLY AIR TEMPERATURE (°F)	62 – 67	65	65
ENVIRONMENT AVERAGE TEMPERATURE (°F)	75 – 77	75	70 – 80
ALL OCCUPANTS INHALING/ EXHALING?	Yes for simulations with relative humidity > 0%	Both	No
RECIRCULATION?	Yes	Yes	No

represent a gap under a door or a return air grille. To accurately model the relatively small but geometrically complex ceiling air supply diffuser in the room and to accelerate the simulation, a validated simplified method by Mohammed[15] was adopted for this study. Seven simulations were performed, including three inlet airflow rates, three index positions and two air inlet positions, and the same cough as used in the aircraft simulation. Simulations were performed with an air inlet placed either in the center of the room, or above the head of Seat 5 (*Figure 4*, circled in center pane). The air supplied to the ICS was entirely outdoor air with no recirculation.

Exposure from particles released by a single cough within an ICS followed the same methodology as in an aircraft cabin,[11] except the aircraft CFD models were simulated until 1% or less of the particles remained in the air, but ICS simulations were simulated for 15 minutes regardless of airflow rate. Overall, mass remaining airborne in the ICS simulations should lead to a slight underestimation of the inhaled mass in the ICS when compared to an aircraft.

A summary of boundary conditions used for the CFD models are shown in *Table 1*.

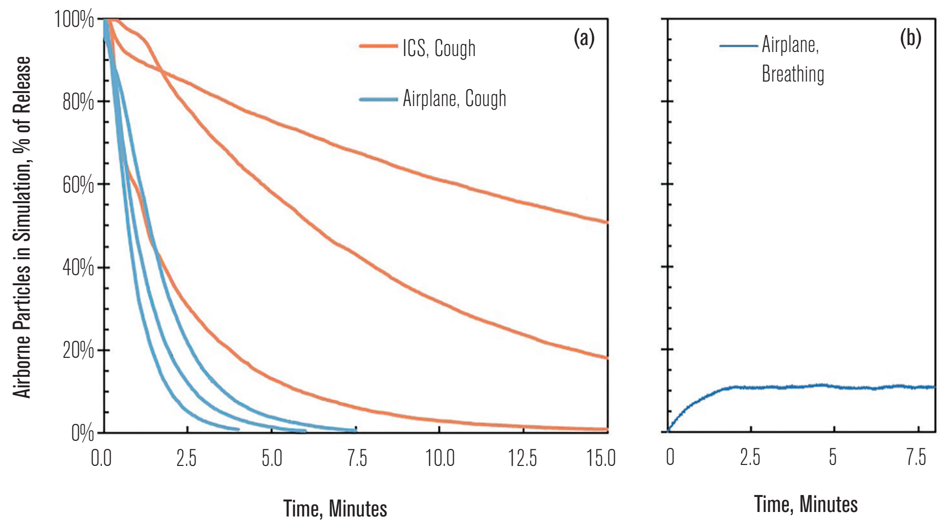
Results

Comparisons Between Commercial Building and Aircraft

The total airborne particles within the airplane and ICS environments were tracked throughout the simulations. The set of simulation conditions presented allow us to see the time-based performance of both the aircraft and the ICS. The longer the period required to lower the total number of particles, the more opportunity for a susceptible person to breathe in those particles.

Figure 5 shows the total number of airborne particles versus time, displayed as a percent of particles released during the simulation of a cough or breathing. It should be noted that this is the percentage of total particles present in the simulated release, not the percentage in the breathing zone of susceptible persons in the environment.

FIGURE 5 Airborne particles within the CFD simulations as a percent of total particles relased during the simulation for (a) a single cough within the airplane and ICS at various airflow rates, where airplane flow rates represent cruise (100% and 77% flow) and a on-ground (e.g., airport) condition (55% flow); and (b) breathing within the airplane at 100% flow rate.



The lifespan of airborne particles after a single cough are presented in *Figure 5a* for three airplane flow rates with an index in Seat 3D (where 100% and 77% flow represent cruise conditions, and 55% flow represents a ground condition), and three ICS flow rates (2 ACH, 4 ACH and 8 ACH) with an index in Seat 4 and an air inlet in the center of the room. Cough particles were introduced for a single cough and were then continuously removed from each environment. For a single cough, 80% of airborne particles released were removed five to 12 times more rapidly (1 to 2.5 minutes total) from the aircraft environment than the ICS, depending on airflow rate. The airborne particles were removed from both environments more rapidly as the airflow rate increased. The airborne cough particles did not reach steady state and were also not well-mixed in either simulated space.

Figure 5b shows the data for breathing in an aircraft cabin. Quasi-steady state, due to tidal breathing, is achieved within two to three minutes of breathing onset reaching particle concentrations of 9% to 12% of the total particles released during the simulation. Note that a steady state percentage of airborne particles emitted by a passenger in the aircraft cannot be equated with a well-mixed condition. When particles are removed quickly due to the high-flow compartmental nature of the flow pattern, particles never achieve a well-mixed state. Breathing simulations in the ICS were not performed, but it is expected that quasi-steady state would also be achieved within that environment as well.

Figure 6 summarizes the exposure seat maps for the CFD simulations, with a single cough in the ICS (left), the single cough in the airplane (middle) and the tidal breathing in the airplane (right). Each bubble represents the position of an occupant, and the size of the bubble represents the nonvolatile mass inhaled as either a percentage of the mass released (top row) or the total mass inhaled in µg (bottom row). In the cough studies, the occupants directly exposed to the cough plume from the index passenger had the highest exposures. This is particularly evident in the ICS, where the results demonstrate a seven times higher exposure than the airplane for a single cough.

In the aircraft simulation, with passengers facing forward, in high-backed seats, and with a downward airflow, the effect of the cough plume is less evident. For the airplane, the percentage of particles released that were then inhaled from both breathing and coughing were similar, as shown in *Figure 6*. However, breathing released significantly less mass than coughing, so the total mass inhaled for exposure to eight hours of breath-aerosols from an index passenger was considerably less than the mass inhaled for a single cough from the same source. The nonvolatile mass from a cough inhaled by other occupants as a function of distance away is shown in *Figure 7*.

Within an airplane, occupants within the same row and side of the airplane as the index passenger consistently experienced higher exposures than elsewhere on the airplane. Ultimately, there is no simple equation-based relationship between distance from the index passenger and exposure. An index passenger in Seat 3E is 0.9 m (3 ft) away from Seat 2D and 2F. Despite both seats being the same distance from the index, Seat 2F experienced six times less exposure than Seat 2D.

FIGURE 6 Exposure seat maps for CFD simulations with the highest individual occupant exposure to a single cough in the ICS and airplane, and exposure to eight hours of breathing in the airplane. Each bubble represents the position of an occupant, and the size of the bubble represents the nonvolatile mass inhaled as (a) a percentage of the mass released, and (b) the total mass inhaled, µg.

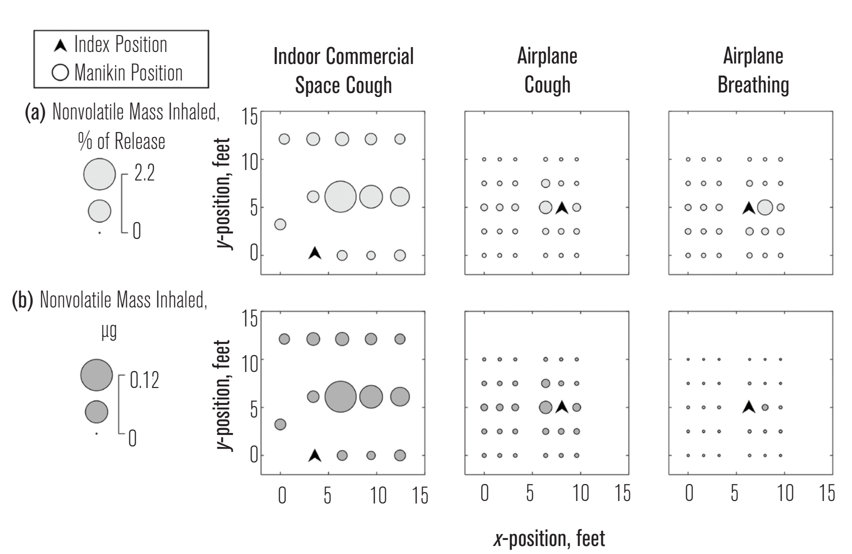
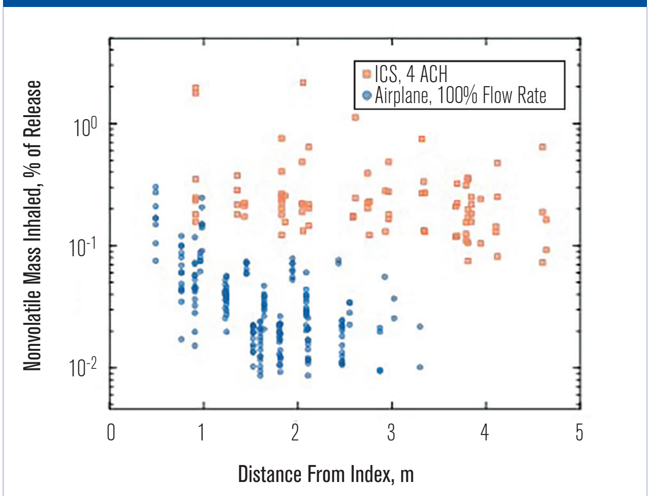


FIGURE 7 Nonvolatile mass inhaled by occupants as a function of distance (m).



For comparison (not shown), individual exposures assuming a well-mixed environment were also calculated. The CFD output of particle mass concentration within the entire volume of the five-row cabin section (excluding space occupied by passengers) was used to calculate mass within a 0.8 ft^3 (0.02 m^3) breathing zone versus time, then sinusoidal breathing was applied to estimate the mass inhaled if particles in the cabin were well-mixed.

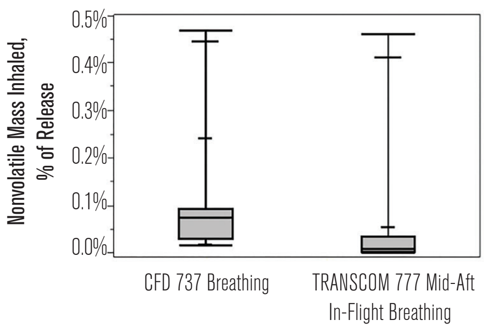
Because the position of passengers on an aircraft is fixed with relatively little movement while in flight, assuming aerosols are well-mixed within the cabin results in a significant overestimation in exposure for the majority of occupants and a significant underestimation for others. For breathing on an aircraft, assuming the mass within the cabin was well-mixed results in individual exposure of 0.044% (standard deviation 0.002%) of the mass released, which underestimates the maximum exposure by 920%, and overestimates the minimum exposure by 76%.

Alignment With Empirical Studies

The modeling results are broadly consistent with the results of experimental work[12] funded by the United States (U.S.) Transport Command (TRANSCOM) Air Mobility Command (AMC) division of the U.S. armed forces. Briefly, the US TRANSCOM study released tracer aerosols at various seat locations throughout 777-200 and 767-300 model aircraft, both on the ground and in flight. Tracers were then measured at 40+ sensor locations for each release of ~180 million particles over a one-minute period. Of the over 300 releases performed, the mass inhaled for nine releases were compared to breathing CFD simulations (*Figure 8*). These nine releases contain the overall highest exposure observed for all 300 releases and contain breathing particles releases in-flight in the mid-aft section of a 777-200. As seen in *Figure 8*, exposure levels of susceptible passengers were below 0.1% of the mass released in the vast majority of cases, which was lower than the exposure levels in the model presented herein.

Figure 8 (left) shows a quantile box plot of the nonvolatile mass inhaled by the nearest eight occupants to the index passenger for the six CFD breathing model simulations compared to the nine empirical experiments. The seats included in the comparison are the two seats closest to the index within the same row and side of the aisle, and the three seats directly fore (in front of) and aft of (behind) those. These seats were selected to enable a direct comparison despite the different seat arrangements on the two aircraft—and because they contain the occupants that experienced the highest exposures in both the CFD and TRANSCOM data.

FIGURE 8 TRANSCOM in-flight breathing study and the CFD breathing study resulted in similar masses inhaled. Comparing the eight seats nearest the index (as a worst case), on average the six CFD breathing simulations resulted in higher localized exposure than the nine TRANSCOM 777 mid-aft in-flight breathing experiments. Horizontal bars represent the maximum, 97.5th quantile, 90th quantile, 75th quantile (Q3), median, 25th quantile (Q1), 10th quantile, 2.5th quantile and minimum values.



	CFD 737 Aircraft Breathing	TRANSCOM 777 Mid-Aft In-Flight Breathing
N	48	62
Max	0.47%	0.46%
Q3	0.093%	0.035%
Median	0.075%	0.009%
Q1	0.031%	0.002%
Min	0.015%	0.000%

Both the CFD and empirical studies conclude that there was low exposure to aerosol for neighboring passengers. The median nonvolatile mass for worst-case occupants was 0.075% in the CFD model, compared to 0.009% for the TRANSCOM empirical study, while the maximum was 0.469% for the model and 0.461% from the empirical study.

The good, and slightly conservative, alignment of the CFD model to the empirical results demonstrate the applicability of the CFD model.

Discussion

The airplane cabin is a mixed-flow system that shares more characteristics of a plug flow system than a uniformly mixed system. This results in higher concentrations of infectious agent particles near the infected individual, and lower concentrations present in the seats at greater distance. Distance alone is a poor predictor of the nonvolatile mass inhaled under all circumstances on an aircraft and, at least in the case of a cough-plume, for a building environment.

While the airplane cabin is a unique environment compared to other spaces, there are some areas where ICS can benefit from understanding the airplane cabin environment. In some ICS configurations, the lack of high efficiency filtration assists in spreading aerosols from one occupant to another. However, for a cough with exposure prior to recirculation, better filtration would not help the ICS. Similarly, an ICS with standard configurations can be designed to minimize exposure, through changes in designed airflow gradients, rather than emphasizing mixing within a space.

For the case of the COVID-19 pandemic, the plume from either coughing, talking or breathing at close range, where air-handling is not well managed, may be the most important form of disease transmission. Future efforts should look to confirm how breathing and talking models behave within an ICS space, as it will add clarity to physical distancing guidelines that are currently recommended by government agencies. However, since occupants are able to move around freely within an ICS, a well-mixed environment may be a more reasonable assumption. It is not easy to trace who was exposed to the cough plume when occupants are in motion. Additional information regarding airflow in the room at the time of the cough, where the index person was located, what direction they coughed and where each susceptible person was located is required. Therefore, it is recommended to minimize exposure risk for occupants of an ICS by implementing best practices of increased ventilation, improved filtration and improved airflow patterns (where practical).

Similarly, it is difficult to model human behavior in an aircraft cabin. This study does account for movement of occupants up and down the aisles and assumes forward-facing occupants. This study does not attempt to calculate infectiousness of SARS-CoV-2 or other viruses and does not consider fomite or droplet transmission and focuses instead on the inhaled mass of aerosols. In environments where there is poor airflow that is not confined to a specific direction of flow where people spend long periods of time in close proximity, there is of course risk of transmission.

Conclusion

The results of CFD analysis and test results demonstrate the necessity of an advection-dispersion model using a large dynamic set of data points to model aerosol exposure within the aircraft cabin. The cough simulation in an aircraft cabin shows that the system is neither well-mixed nor steady state. This was verified by the TRANSCOM empirical study. The breathing model shows that while an infected person's emission of aerosols may indeed be steady state, the cabin is certainly not well-mixed and the mass inhaled even over an eight-hour flight is still only a fraction of that generated by a cough.

The airflow patterns and high particulate removal efficiency in the aircraft cabin demonstrate the lack of applicability of the well-mixed model assumption (required for estimates made via the Wells-Riley formalism), which is traditionally applied to buildings. From the CFD model and the TRANSCOM study, low masses of particulates are shown to spread from person to person in airplane cabins.

Further information on these topics can be found in https://doi.org/10.1101/2021.03.24.21254275

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