Transport and Containment of Infectious Disease Expelled by Coughing in an Aircraft Cabin

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ABSTRACT

The dispersion characteristics of airborne pathogens released by the coughing of an individual in a wide-body aircraft cabin were studied using a coughing manikin placed in a Boeing 767 cabin mockup. A passenger isolation system, referred to as ISOPass, developed to contain airborne pathogens from an infected passenger from spreading in airplane cabins was also evaluated using the coughing manikin. The mockup cabin was partially-occupied by 55 thermal manikins to simulate passenger thermal load randomly seated in an arrangement of 11 rows and 7 columns. The coughing manikin was located in the sixth row. Five different cases of contagious passenger locations were studied representing window, aisle, and middle cabin seats. The main objective of this work was to better understand the dispersion characteristics of the airborne pathogens, to evaluate the maximum dispersion distances under specified ventilation conditions, and to evaluate the performance of the ISOPass system in preventing the spread of the infectious aerosols in the aircraft mockup cabin. The coughing manikin was set to cough approximately once every 1.25 minutes, with a volume of 4.2 liters of CO_2 tracer gas per cough. To ensure sufficient data was collected, each test ran for approximately 30 coughs. The tracer gas concentration was measured using CO_2 gas analyzers at the breathing height of 1.2 m up to 3.35 m radially away from the coughing location representing four rows of a standard aircraft. A total of 93 tests were conducted including the manikin in the window, aisle, and middle seats. The results showed that the dispersion of the cough highly depended on the airflow characteristics and the coughing manikin location within the cabin. It also showed that the ISOPass is effective in limiting the spread of potentially infectious aerosols within aircraft cabins. The results of this work can provide useful information for both aircraft designers and health agencies to mitigate the spread of contaminants from a contagious passenger or a crew member during flights and either forecast or understand the potential exposure of passengers and crew during an actual incident.

INTRODUCTION

Heightened awareness of illnesses like SARS, MERS, Ebola, and new variants of influenza have added to traditional disease concerns such as TB and measles that can spread or have the potential to spread on aircraft. Airborne transmission may be described as the transmission of microorganisms from a source to an individual by aerosols, resulting in infection and illness. Airborne disease transmission is often divided into droplet transmission and aerosol transmission. Droplet transmission is defined as disease transmission through ejected droplets that settle rapidly because of their larger size. Aerosol transmission is characterized as disease transmission through ejected particles that are smaller in size; typically less than 5 µm (Baron 2010). Such aerosols can be transmitted over short and long distances. Long range transmission occurs between far off areas and is mainly governed by the airflow from the ventilation systems and the movement of people (Kwon et al. 2012). The sizes of droplets and/or particles impact their circulation in ventilated spaces. Larger particles are subject to gravity effects which affect their transmission and distribution patterns.

In order to limit airborne disease transmission, a better understanding of the flow dynamics of a cough is required (Gupta et al. 2009). It has long been recognized that the droplets and aerosols expelled through coughing and sneezing can spread infectious disease like measles, influenza, bronchitis, chicken pox, tuberculosis, pneumonic plague, etc. (Sun and Ji 2007). Since the aerosols and droplets expelled by a cough have high initial momentum, transport of contaminants produced by coughing can vary from transport of contaminants produced by stationary injection sources (Sun and Ji 2007). The high-velocity cough airflow can induce instability at the mucous air interface, and droplets generated due to the instability mechanism can be carried a long distance by airflow after being expelled from the human respiratory tract (Wei and Li 2015).

A cough typically has a high velocity and a large quantity of droplets and aerosol. Kwon et al. (2012) have shown that the average initial coughing velocity was 15.3 m/s for males and 10.6 m/s for females, while the average initial speaking velocity was 4.07 m/s and 2.31 m/s respectively. The number of droplets during a single cough can be as high as 3000 (Wei and Li 2015). The reported volume of aerosols produced by a cough varies considerably in published literature. The total cough volume measured by (Zhu, Kato, and Yang 2006) had a range of 0.8–2.2 liters with an average of 1.4 liters which actually was the low end as compared with that from (Mahajan et al. 1994), who observed a range of up to 5 liters with an average of about 3 liters. Another study by (Noti et al. 2012), used a digital coughing simulator that had a 4.2 liter cough volume.

Experiments and computational fluid dynamics (CFD) simulations are the two most effective approaches used to investigate indoor air pollutant transportation within aircraft cabins. Experiments are usually conducted on either a full scale or a mock-up section of airplane cabin (Yan et al. 2009). CFD simulations of temporal distributions of expiratory aerosols allow for easier analysis but can be impractical or unfeasible to perform for a full-length cabin. Acikgoz et al (2011) simulated a coughing passenger in an airplane cabin using CFD. The simulated infected passenger coughed for 0.5 s with 22 m/s coughing velocity and expels 150 mg of liquid water droplets of various sizes. The study simulated both horizontal and oblique coughing directions. The authors concluded that the exposure of the host passenger to airborne pathogens was strongly dependent on seat position relative to the infected passenger and cough direction. Yang et al. (2018) investigated the effect of cough-jet on local airflow and contaminant transport in a typical cabin environment using CFD. The infectious contaminants were simulated using a coughing passenger seated in different seats inside the cabin. The authors found that the jet caused by the cough had significant effects on airflow in front of the coughing passenger for a short period of time. Also, it was found that, in order to have the results precisely represent the transport and distribution of cough-generated airborne contaminant, the cough-jet model has to be applied. Between 0–0.5 s after the cough and at a distance of less than 0.45 m from the mouth, the cough-jet dominates the airflow. Beyond this period, the effects of the jet produced by the cough, gradually decrease until the airflow goes back to the steady state. The dispersion and deposition characteristics of polydispersed expiratory aerosols were investigated in an aircraft cabin mockup to study the transmission of infectious diseases by To et al (2009). Results showed that a significant amount of aerosol reached the row of seats in front of the cougher and the aerosols were then dispersed by the bulk air movements in the lateral direction. It took 20–30 s for the aerosols expelled by the cough to reach the breathing zones of the passengers seated within two rows from the cougher. Increasing the ventilation rate improved the dilution and reduced the aerosol exposure to passengers seated close to the source. Doing so also increased the aerosol dispersion which heightened the exposure to passengers seated further away. The authors noted that 60–70% of the mass of expiratory aerosols were deposited, on surfaces close to the source, suggesting that disease transmission risk via indirect contact in addition to airborne risk is possible. In related research (Lindsley et al. 2013), a cough aerosol simulator was constructed to produce a humanlike cough in a controlled environment. The simulator was used with live pathogens, including influenza virus, which allows isolation precautions used in the healthcare field to be tested without risk of exposure for workers (Lindsley et al. 2014). Bennett et al. (2013) produced a general aircraft cabin air-contaminant transport effect model that was applied to datasets from different sources. They showed that if the source passenger was assumed to breathe, cough, or sneeze in the forward direction, a one-row offset can be applied so that the row in front of the index row became the effective source location.

In order to mitigate the disease spread from an infected passenger, the International Air Transport Association (IATA) recommends moving the sick passenger to keep them at least 6 feet away from other passengers (International Air Transportation (IATA 2017). This is not always possible, especially on smaller aircraft. Likewise, the World Health Organization (WHO) recommends relocating the infected passenger to a seat away from others and to use facemasks when possible, by both the sick passenger and the flight attendant that is attending to them (World Health Orginzation 2013). At the moment, there is limited established procedures to reduce on-board spread of the contagion beyond basic hygiene and disinfectant procedures (Centers for Disease Control and Prevention 2019). Darrah (2018) studied the utilization of a passenger isolation system on a Boeing 767 mockup. The study showed that the passenger isolation system is effective at containing tracer gas released through a gas distribution hose and preventing its spread in the cabin. The work reported in this paper is directed to better understand the dispersion mechanisms of aerosols produced by coughing of a passenger in aircraft cabins. It also investigates the feasibility of a passenger isolation system, referred to as ISOPass, in containing infectious aerosols within a cough.

MATERIALS AND METHODS

A Boeing 767 aircraft cabin mock-up located at Kansas State University was used in this study. The mock-up has a length of 30.9 ft. (9.41 m) and a width of 15.5 ft. (4.72 m) as shown in Figure 1. It contains 11 rows of seats separated by two aisles with the seats arranged in a 2-3-2 configuration. The rows are numbered from the front of the cabin to the back of the cabin. The seat columns are labeled A through G from left to right. The mock-up cabin was equipped with thermal manikins to replicate human thermal load. The heated manikins were seated as shown in Figure 2. Each manikin was uniformly wrapped with heater wire on the arms, legs, chest, and head. Each manikin is plugged in to a 115 V outlet and generates about 100 W (340 BTU/hr.) of heat. This accounts for the average sensible thermal output of a resting adult, 70 W (238 BTU/hr.), plus additional heat from in-flight entertainment systems, avionics, and personal electronics such as laptops.

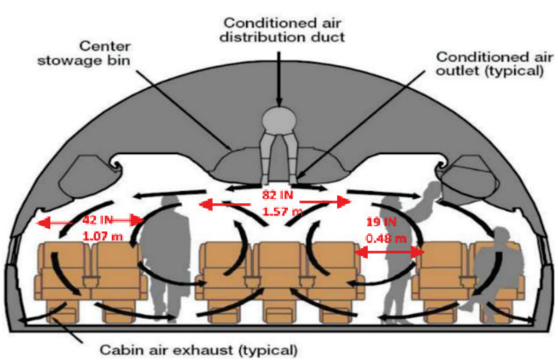

Figure 1 Boeing 767 cabin ventilation from (Hunt and Space 1994), with dimensions added.


Figure 2 Boeing 767 cabin mock-up with heated manikins

The air supply system supplies the mock-up cabins with conditioned air to simulate a real aircraft environment and meeting FAA ventilation requirements. The Boeing 767 cabin, with 77 seats, is supplied with 1400 CFM (40 m^3/min) of conditioned air. Fresh air is drawn in from outside and passes through the dehumidifier unit and into the air conditioner, which maintains the air at 60 °F (15.6 °C). The air is then delivered to the cabin. For these tests, the dehumidifier was not operated. Additionally, only fresh air is used for these tests; no recirculated air is used. Since

HEPA filters are normally used on recirculation air, it is believed to be pathogen free. However, tracer gas would not be removed by these filters if recirculation were employed in the mockup. Therefore, using 100% outside air is the appropriate configuration if the tracer gas is to accurately reflect airborne pathogen dispersion.

Tracer gas samples were collected using a sampling tree of 4 ports that allows sequential sampling. The ports are equally spaced with a distance of 0.84 m. The samples were collected at the breathing level, 1.2 m above the cabin floor. For the closest location, the samples were drawn at the mouth of the coughing manikin. The gas analyzers were a nondispersive infrared (NDIR) type with a typical accuracy of < 1% of span concentration over the calibrated range. In a previously published work, a comprehensive uncertainty analysis was carried out on the same setup. The uncertainty value was estimated at each distance from the source. The uncertainty estimates in the measurements varied based on the increase in tracer gas concentration over background levels from 6% in the vicinity of the source where the increase is large to 19% at the furthest measured distance of 3.35m where the increase is small (Mahmoud et al. 2019).

Simulated coughs from a passenger were generated using a cough simulation manikin described previously (Lindsley et al. 2013). The cough manikin was modified to produce coughs containing CO_2 as a tracer rather than aerosol particles. The cough airflow was produced by a metal bellows driven by a computer controlled linear motor. It was based on coughs recorded from influenza patients and had a volume of 4.2 L and a peak flowrate of 11.4 L/s with the entire cough lasting approximately 1 second. The coughing manikin is shown in Figure 3. This volume is at the high end of the range discussed previously and, thus, the resulting cough may be considered a worst-case condition. The coughing frequency for this study was one cough every 1.25 min. To insure sufficient CO_2 supply, each test was run for 30 coughs for each sampling tree location. The CO_2 gas was supplied to the coughing manikin through two 100-liter Tedlar bags. The bags are prefilled with pure CO_2 before each test. When a cough is activated, the manikin mouth valve is closed, and the manikin bellows are filled with the CO_2 gas using the Tedlar bags. Once the bellows are filled with the CO_2, the manikin mouth opens, and the bellows rapidly compress causing the cough to be released.

The passenger isolation system (ISOPass) is a compact, lightweight, and rapidly deployable intervention that in-flight airline cabin personnel can use to protect passengers and crew from exposure to infectious passengers. The ISOPass is designed to be installed over two adjacent, same-row seats by a flight attendant during the flight as shown in Figure 4. The ISOPass has a battery powered exhaust fan located in the feet area. Its discharge is ducted to the cabin exhaust port. In an actual aircraft, the contaminated air would either exit the aircraft through the outflow valve or pass through the recirculation filters if returned to the cabin. The ISOPass exhaust generates a negative pressure inside the enclosure, and ventilation air enters through gaps around the edges of the ISOPass as well as the supply air gaspers.

Figure 3 Utilized coughing manikin. Adopted from (Noti et al. 2017)

Figure 4 The coughing manikin inside the ISOPass

In this paper, the results of the tracer gas coughing dispersion for 93 tests in the Boeing 767 mock-up are presented. Five coughing manikin locations were tested separately and marked with a star symbol in Figures 5-(a-f). For each coughing manikin location, the sampling tree was positioned in several orientations to capture the tracer gas concentration at different radial distances in different orientations. Figures 5 b-f show the sampling tree orientation of each test where the underlined test number indicates a test with the ISOPass deployed. The sampling tree is depicted by the long solid line where the solid block is the solenoid valves block which controlled the opening and closing of the valves to the ports where the sampling is happening.

To simplify the data analysis and representation, the 93 tests were divided into ISOPass undeployed tests and ISOPass deployed tests. The undeployed ISOPass tests were further divided into group 1 and group 2. Group 1 includes tests with longitudinal or diagonal sampling tree orientation while group 2 includes tests with lateral sampling tree orientation. Test numbers are shown for each orientation in Figure 5 so that each result shown later can be associated with a specific coughing manikin location and sampling tree orientation.

A typical test is conducted in the following sequence:

1. Mockup cabin is operated until thermal steady state conditions are achieved.
2. 10 minutes pre-test without coughing.
3. 15 minutes steady state with coughing, no sampling.
4. 6 minutes of coughing for each sampling tree port.
5. 10 minutes post-test without coughing.

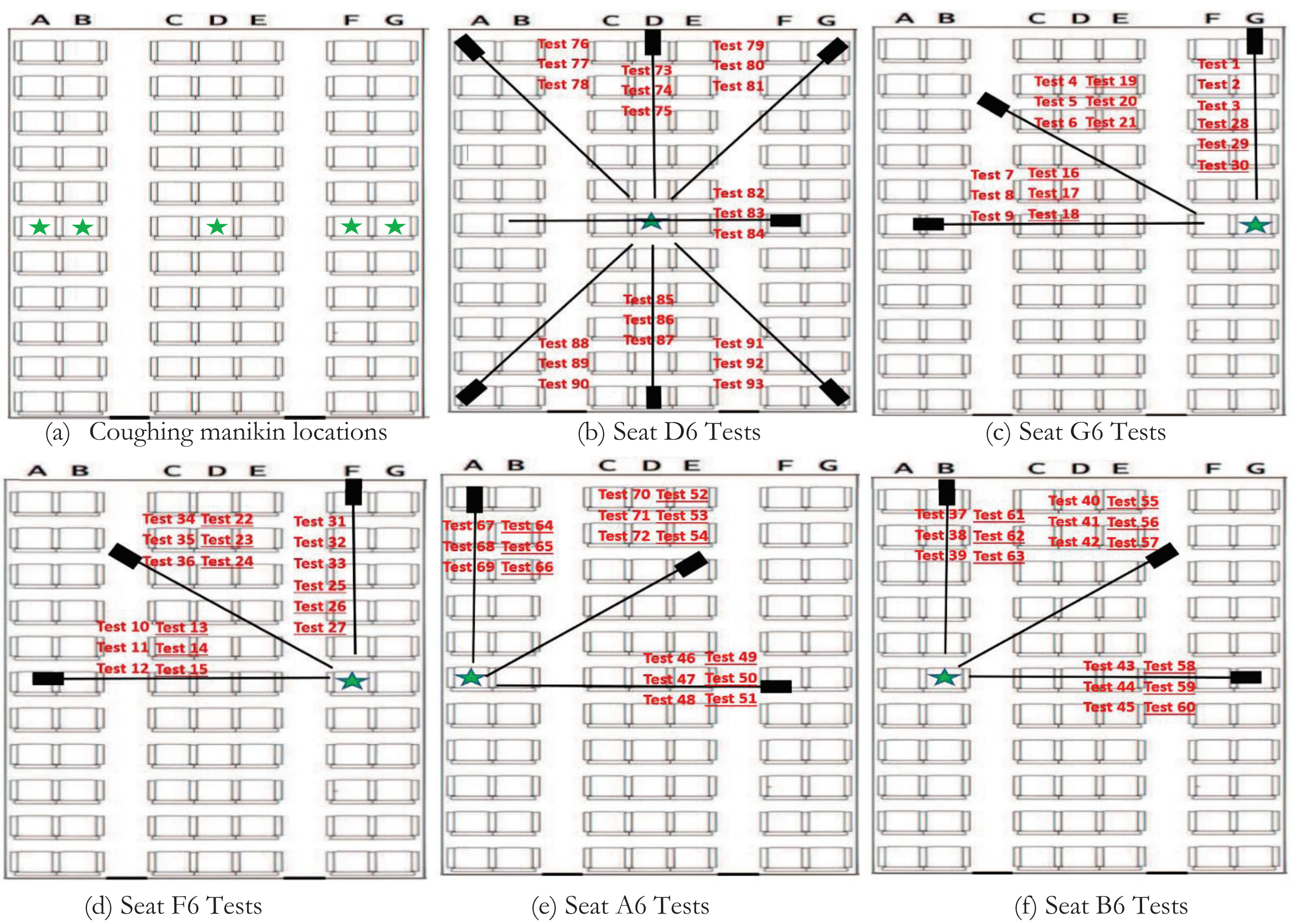

Figure 5 Coughing manikin location and sampling tree orientation in each test. Underlined test numbers indicate a test with the ISOPass deployed.

MATERIALS AND METHODS

Figure 6 shows a comparison between Test 3 with the ISOPass undeployed and Test 30 with the ISOPass deployed. When the ISOPass was deployed, the 0.0 m sampling location is inside the ISOPass. As is seen in Figure 6, there is no detectable increase in tracer gas concentration at any location outside the ISOPass. The result was the same for all cases where the ISOPass was deployed. This result is consistent with the experiments conducted by Darrah (2018). Given that the results are all the same, data for each coughing manikin location and sampling tree location are not presented for the ISOPass deployed case.

For Test 3, without the ISOPass, Figure 6 shows that the average CO_2 concentration is highest near the coughing manikin and decreases to near background (supply air) levels at the 3.35 m location. However, the dispersion pattern varied substantially depending on the location and the direction from the coughing manikin. It is not feasible to include a plot like Figure 6 for every location and orientation. However, Figures 7 and 8 present all of these data in a condensed form. Figure 5 identifies the coughing manikin location and sampling tree orientation for each test number. Then, for each test number, Figures 7 and 8 show the concentrations for each location corresponding to the locations in Figure 5.

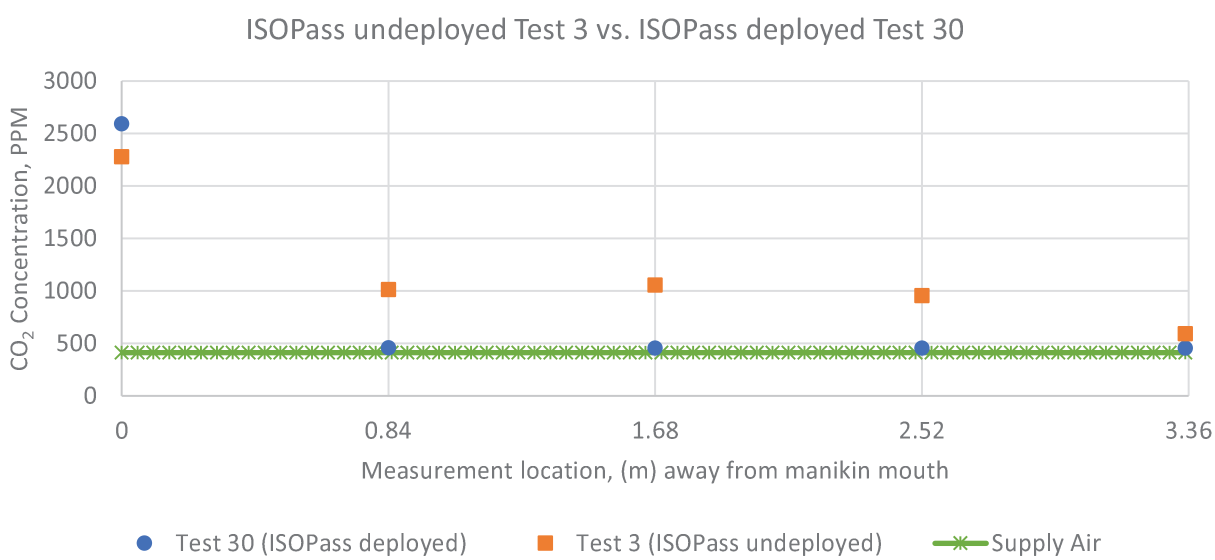

Figure 6 Comparison of ISOPass undeployed test 3 vs. ISOPass deployed test 30

Figure 7 shows that the maximum tracer gas concentration was at the coughing manikin seat for all group 1 tests. For tests with a longitudinal sampling tree orientation in group 1, the tracer gas concentration decreased with distance from the coughing manikin when it was placed in the middle of the cabin such as in tests 73-75. This was also noticed on the right side of the cabin in tests 1-3 and 31-33. On the other hand, some tests with a longitudinal test sampling tree direction had the concentration at 1.68 m and 2.52 m away from the coughing manikin higher than the concentration at 0.84 m such as tests 37-39 and 67-69. Behind the manikin, tests 85-93 show that the concentration of the tracer gas remained almost unchanged. The forward momentum of the cough appears to minimize the dispersion of the tracer gas in the rearward direction. However, care should be exercised in generalizing this result as the coughing manikin is in a fixed, forward facing position while a person may not always cough in this direction.

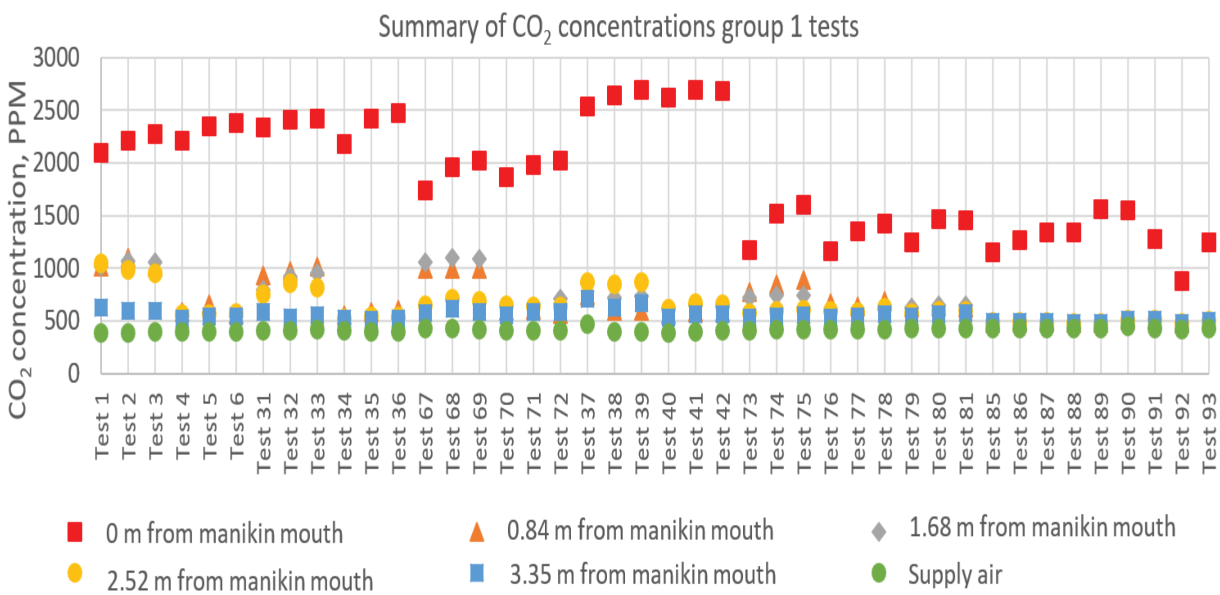

Figure 7 Tracer gas concentration at different sampling locations for group 1 tests

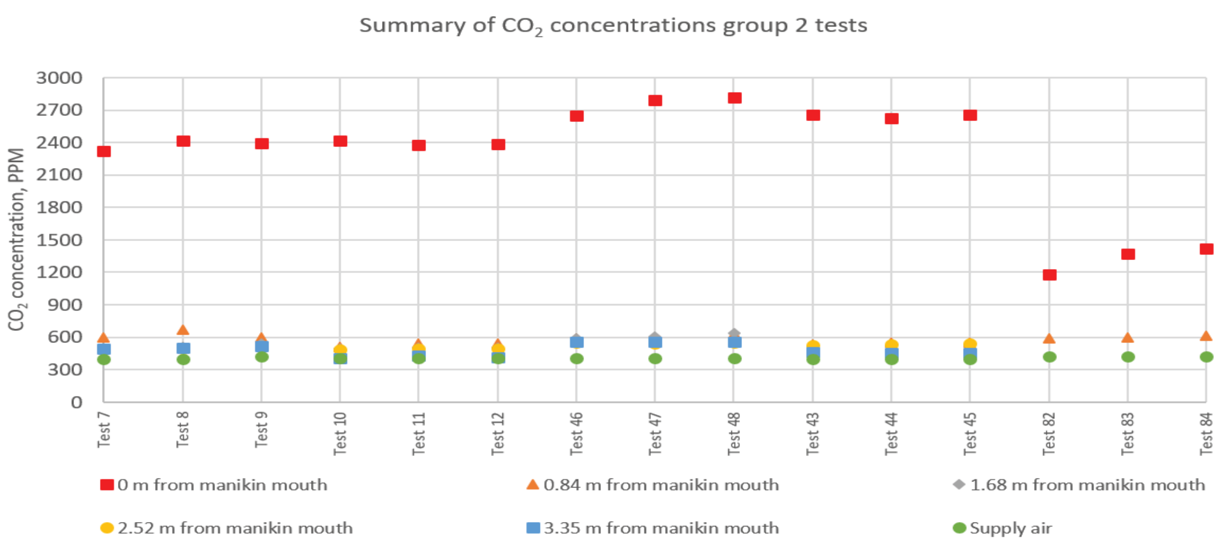

Figure 8 Tracer gas concentration at different sampling locations for group 2 tests

For diagonal front right sampling tree orientation tests 40-42, 70-72, and 79-81, the concentration at 1.68 and 2.52 were higher than the concentration at 0.84 m. On the other hand, tests with diagonal front left orientation 4-6, 34-36 and 76-78 showed a similar trend to the front longitudinal sampling tree test orientation where the tracer gas concentration decreased gradually away from the manikin.

Similar to Figure 7, Figure 8 shows that the maximum tracer gas concentration was detected at the coughing manikin seat and decreased in the lateral direction away from the coughing manikin. Figure 7 also shows that the tracer gas concentration was not greatly above background in the lateral direction, except at the source, in all of the tests with the lateral sampling tree orientation. The maximum increase away from the source was 260 ppm recorded in test 8 at

0.84 m away from the coughing manikin.

The standard deviation was calculated for each sampling tree orientation and measurement location. The typical standard deviation is listed in Table 1 for each sampling tree orientation and distance from the coughing manikin. The variation near the coughing manikin is large which should be expected. The CO_2 is supplied in a series of short bursts, so the source is inherently variable. Further from the coughing manikin where more mixing has occurred and the bursts are smoothed, the variation drops markedly. It is also noted that the variation in the supply air is very low, near the lower limit of the ability of the NDIR sensors to detect variations. This stable background is important as it is the increase in concentration above the background that is the variable of interest.

Table 1. Typical standard deviation values.

Sampling location, (m) away from manikin mouth	Longitudinal direction standard deviation, PPM	Lateral direction standard deviation, PPM	Diagonal direction standard deviation, PPM	Overall average standard deviation, PPM
0	860	55	940	830
0.84	490	61	40	200
1.68	500	43	64	200
2.52	420	7	41	160
3.35	72	9	16	32
Supply Air (background)	4	7	4	5

CONCLUSION

In this paper, the results of 93 tests of a coughing manikin inside a wide-body aircraft cabin were presented. Five different locations for the coughing manikin were evaluated and tracer gas samples were collected at different distances and orientations from the coughing manikin. Due to the cough momentum, and the airflow pattern inside the cabin, the concentration at further distances from the coughing manikin were sometimes higher than in the vicinity of the manikin. Also, the concentration of the tracer gas at the rear of the cabin was negligibly affected by the coughing manikin. The cough generated by the manikin did not seem to increase the concentration of the tracer gas in the lateral direction as much as in the longitudinal and diagonal forward directions. Using a passenger isolation system, referred to as ISOPass, the containment of the tracer gas was tested and the ISOPass was proven effective. When the ISOPass was deployed, the tracer gas concentration outside the ISOPass remained unchanged. This work provides both a better understanding of the dispersion characteristics of a cough inside an airplane cabin and presents an effective tool to contain pathogens from spreading to passengers and crew. This work will help mitigate contagious diseases spread in aircraft cabins and assist in following up with confirmed and potential cases after flights, especially those of longer duration. The ISOPass can serve as a new intervention for the airline industry to help reduce the spread of contagious diseases by working with industry stakeholders such as manufactures to learn of requirements and limitations to implement this effective new tool industry-wide

AKNOWLEDGMENTS

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ASHRAE 2020
Virtual Conference

2020 ASHRAE Virtual Conference

June 29th - July 2nd, 2020

Track: Fundamentals and Applications

Panel 1 (Intermediate)

The Benefits of Off-Site Construction

Sponsor: 1.5 Computer Applications

Chair: Michael Cooper, P.E., Member, Bernhard, Metairie, LA

Design for Manufacture and Assembly (DfMA) strategies are causing major disruptions in the Engineering and Construction value chain. Off-Site activities are now being maximized to minimize On-Site work results. The maturation of digital tools has radically altered the value proposition for the design and delivery of built solutions. Critical enablers of this value shift include data-rich 5D BIM models, data analytics, enterprise level supply chain, factory automated processes, just-in-time logistics,and lean manufacturing principles. Our panelists will explore how DfMA is now possible, the scale that can be achieved, and the compelling value benefits that can be captured.

Project Manager

Robin Bryant*, ASHRAE, Fort Myers, FL*

Construction Manager

Bryan Holcomb*, Bernhard, Metairie, LA*

Paper Session 3

Phase Change Materials, Energy Recovery Ventilation and Cool Thermal Storage Design Guide

This session focuses on the integration of phase change materials and thermal storage in various building equipment. The first paper presents a novel ERV coupled with a bio-based PCM. The design of this ERV was optimized using multiphysics analysis, prototyed, tested and results presented. The second paper investigates the impact of sensor response on the predicted effectiveness of fixed-bed-regenerators through numerical and experimental study. The third paper presents the factors that impact the efficacy of PCM integrated with buildings and the corresponding cost and energy savings potential.

Design of Energy Recovery Heat Exchanger Coupled with Phase Change Materials for Building Temperature Control
Weihuan Zhao, ***Sidney Hartz***, *Dacen Kinser, Marybeth Fuhlman, Parker Walvoord, Matthew Rushing, Sergio Turrubiartes and Carlos Zapata, University of North Texas, Denton, TX*

Using Bio PCM As Sensible Heat Storage in a Hot Arid Climate: A Case Study
Neda Askari Tari, *Maryam Nozaripour and Kristen Parrish, Ph.D., Arizona State University, Tempe, AZ*

Temperature Measurement Correction for the Determination of the Effectiveness of Fixed-Bed Regenerators for HVAC Applications
Hadi Ramin, Student Member, *University of Saskatchewan, Saskatoon, SK, Canada*

Paper Session 9

Ventilation: From Offices to Aircraft

This session highlights the current status and future needs for ventilation codes. The first paper presents a comparison of the office building ventilation codes in Asia Pacific and North America. The second paper highlights the need for dedicated codes for the proper ventilation of areas containing lithium-ion battery operations. The third paper uses transient Computational Fluid Dynamics (CFD) to evaluate the impact of space volume on the dilution of contaminants and occupant exposure. The session concludes with an experimental study that aims at better understanding the dispersion characteristics of airborne pathogens under specified ventilation conditions in a aircraft cabin.

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Co-Working Space Ventilation Code Study
Yijun Yang, Ph.D., P.E., Associate Member *and* ***Daniel Hallett, CEng***, *The We Company, New York, NY*

Ventilation and Hazard Considerations of Lithium-Ion Battery Operations: Current Status and Future Needs
Sean O'Hern, Ph.D., P.E., Associate Member, *Michael Barry, Ph.D., P.E. and Joel Sipe, Ph.D., P.E., Exponent, Inc., Menlo Park, CA*

CFD Analysis of Air Change Rate (ACR) and Space Volume on Contaminant Dilution
Kishor Khankari, Ph.D., Fellow ASHRAE, *AnSight LLC, Ann Arbor, MI*

Paper Session 11

Refrigerants, Components and Systems

This session presents working fluid trends for absorption as well as conventional vapor compression based systems. The third paper presents a novel vortex tube integrated vapor compression cycle and the fourth paper presents a novel additively manufactured microchannel-based chilled water heat exchanger. Finally, the session concludes with measurement of single and two-phase R134a flow in multi-port tube.

Parametric Analysis of Binary Mixtures across the Solution Heat Exchanger of Absorption Refrigeration System
Kadam Sambhaji, Ph.D.[1], ***Ibrahim Hassan, Ph.D., P.E., Member***[1], *Aziz Rahman, Ph.D.*[1], *Athanasios Papadopoulos, Ph.D.*[2] *and Panos Seferlis, Ph.D.*[2], *(1)Texas A&M University at Qatar, Doha, Qatar, (2)Chemical Process and Energy Resources Institute (CPERI), Thessalonik, Greece*

Low GWP Refrigerant Trends for Ice Skating Rinks
Stephen Kujak, Member[1], *Charles Allgood, Ph.D.*[2] *and David Gauvin, Associate Member*[1], *(1)Trane, La Crosse, WI, (2)Chemours, Wilmington, DE*

Thermodynamic Performance Analysis of a Novel Vortex Tube Integrated Vapour Compression Cycle
Akhilesh Arora, Ph.D., Associate Member, *Delhi Technological University, Delhi, India*

Measurement of Adiabatic Single and Two-Phase Pressure Drop Behavior of R-134a in Parallel-Port Microchannel Tube
Arindom Joardar, Ph.D., Associate Member[1], *Thomas Visalli*[1] *and Tobias Sienel*[2], *(1)Carrier Corporation, Syracuse, NY, (2)Carrier, Syracuse, NY*

Additively-Manufactured Microchannel Polymer Chilled Water Heat Exchanger
Erfan Rasouli, Ph.D., Adam Strong and ***Vinod Narayanan, Ph.D., Member***, *UC Davis WCEC, Davis, CA*