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Infectious Passenger Isolation System for Aircraft

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ABSTRACT

Limiting the spread of infectious airborne diseases and airborne pathogens is an important consideration in aircraft environmental control system design. However, when a passenger suspected of having a highly contagious or otherwise very dangerous disease is identified in flight, it is desirable to further isolate the individual from other passengers. A research project was conducted to explore an isolation system that can be stored in a small space and deployed in flight if needed. This device is referred to as an "Expedient Passenger Isolation System" abbreviated as ISOPASS. The ISOPASS is a portable, negative-pressure isolation system that can be installed over a section of seats quickly by a flight attendant during flight. A prototype proof of concept ISOPASS was evaluated in this study. Measurements were conducted in a full-scale, 11-row mock-up of a wide-body aircraft cabin. Heated mannequins to simulate the thermal load of passengers inside the cabin were seated in the mockup. Carbon dioxide was used as a tracer gas and was mixed with helium to maintain neutral buoyancy in air. The tracer gas was used to simulate airborne pathogen spread and was injected at the breathing level at a seat within the ISOPASS. Tests were conducted with and without the ISOPASS in place. Matched pairs were used to mitigate potential statistical problems. Matched pair tests were completed with gaspers turned on and off. Measurements were repeated three times for each gasper setting. Concentration measurements were taken at the breathing level inside the ISOPASS at the seat next to the injection source, at the seat across the aisle adjacent to the ISOPASS, and at a seat far away from the ISOPASS near the front of the cabin. The with- and without-ISOPASS matched pair tests clearly show the ISOPASS prototype is highly effective at providing isolation in the aircraft cabin used in the study. Additionally, it was determined that the use of gaspers makes no measurable difference in the containment effectiveness of the ISOPASS.

INTRODUCTION

Aircraft air quality and passenger health impact a large population on a daily basis. The elevated altitude, low humidity, close proximity, and airborne contaminants affect passenger comfort and can contribute to the spread of disease. Because of this, aircraft air quality, cabin airflow, and ventilation continue to be major considerations in aircraft design and disease control solutions.

The Air Transport Center of Excellence for Aircraft Cabin Environmental Research (ACER) was formed to address these issues of aircraft air quality, airflow, and ventilation in commercial aircraft cabins. The ACER lab researches indoor air quality and fluid transport in aircraft cabins using experimental data collection along with mathematical models and Computational Fluid Dynamics (CFD) analysis and other investigative methods.

The research presented in this paper focuses on the evaluation of the effectiveness of an experimental prototype portable negative pressure passenger isolation system that could be stowed onboard and deployed in-flight if needed. The prototype is referred to as the Expedient Passenger Isolation System (ISOPASS). A mock-up of a Boeing 767 cabin section is used in this research. The mock-up cabin has 11 rows of seats in a 2-3-2 arrangement. The central three rows of the mock-up cabin are equipped with the overhead personal ventilation vents called "gaspers". CO_2 is used as a tracer gas and is mixed with helium to achieve neutral buoyancy in air. This tracer gas is injected from a point source inside the cabin at the ISOPASS location, and the air is sampled at several different locations throughout the cabin to determine the concentration at these points. A test was run both with the ISOPASS installed and with no ISOPASS in matched pairs, and for each gasper condition, gaspers on and gaspers off. Each test was repeated at least three times.

The ISOPASS is designed to be installed over two seats by a flight attendant during the flight. It consists of a vinyl enclosure which is secured at the top to the bottom of the overhead bin and to the seat backs and the cabin wall using Velcro. The base of the ISOPASS is held on the floor by weights along the bottom of the skirt. The entrance to the ISOPASS is shut using magnetic strips. A battery-powered fan is located beneath the seat and exhausts air from the ISOPASS through a tube connected to a cabin exhaust vent located near the floor level on the cabin wall. From there, the potentially contaminated air either passes through the aircraft's HEPA filtration system to remove any airborne contaminants before returning to the cabin or is dumped overboard through the aircraft outflow valve. The ISOPASS exhaust generates a negative pressure inside the ISOPASS, and ventilation air enters through gaps around the corners and base of the ISOPASS. For testing the effectiveness of the ISOPASS at containing airborne contaminants, the tracer gas was injected through a point source inside the ISOPASS.

PROCEDURE OVERVIEW – ISOPASS TRACER GAS CONTAINMENT

To test the containment effectiveness of the ISOPASS prototype within the 767 cabin, tracer gas was injected through a point source at approximately the breathing level within the ISOPASS. Tests were conducted with and without the ISOPASS in place in matched pairs, to mitigate potential statistical problems associated with repeating the same condition multiple times in succession. Additionally, the tests were completed both with gaspers on and with gaspers off. Each matched pair was repeated three times; 3 repetitions x 2 ISOPASS conditions x 2 gasper conditions for a total of 6 matched pairs, or 12 individual tests. For each test, the exhaust fan was set to 60%, with a fresh battery. This corresponds to approximately 160 cfm (1430 liters/min) at the start of the test.

Concentration measurements were taken inside the ISOPASS in the seat next to the injection source, in the seat across the aisle adjacent to the ISOPASS, and far away from the ISOPASS near the front of the cabin. Each of the sampling tubes was positioned at approximate breathing level. The radial distances between the injection point and the sampling tubes were 14" (0.356 m), 44" (1.12 m), and 128" (3.25 m), respectively. The uncertainty of the CO_2 analyzers is 1% of the range of the analyzer. This corresponds to 20 parts per million (ppm) for each of the A-1, A-2, and A-4 analyzers.

REPRESENTATIVE RESULTS AND ANALYSIS

Presented here are tests that are representative of the overall results for each ISOPASS condition, ISOPASS on and ISOPASS off, and for each gasper condition, gaspers on and gaspers off. Full results are available in (Darrah, 2018). The ISOPASS on tests are conducted with the ISOPASS prototype fully in place and with the flap closed completely. ISOPASS off tests are conducted with the ISOPASS completely removed from the cabin, and the ISOPASS exhaust fan off. The injection point and analyzer locations remain the same between the ISOPASS on and ISOPASS off conditions and are referred to with respect to the ISOPASS whether it is in place or not.

The CO_2 injection rate is approximately 5.0 liters/min (0.176 cfm) for all tests, with an accompanying helium injection rate of 3.07 liters/min (0.108 cfm). Heated mannequins were placed in 54 of the 77 seats in the mock-up to provide thermal loading in the cabin. The heated mannueqins were spread uniformly throughout the cabin.

ISOPASS Off

Testing without the ISOPASS gives a point of comparison when considering the effectiveness of the ISOPASS.

Gaspers Off. With gaspers off, the airflow around the cabin is wholly controlled by the central ventilation and the heat from the mannequins. FAA ventilation requirements are typically met without the need for gaspers and many aircraft are not equipped with them, making these tests realistic in practice. The gaspers off tests are conducted with the gasper fan shut off and the gaspers themselves fully closed.

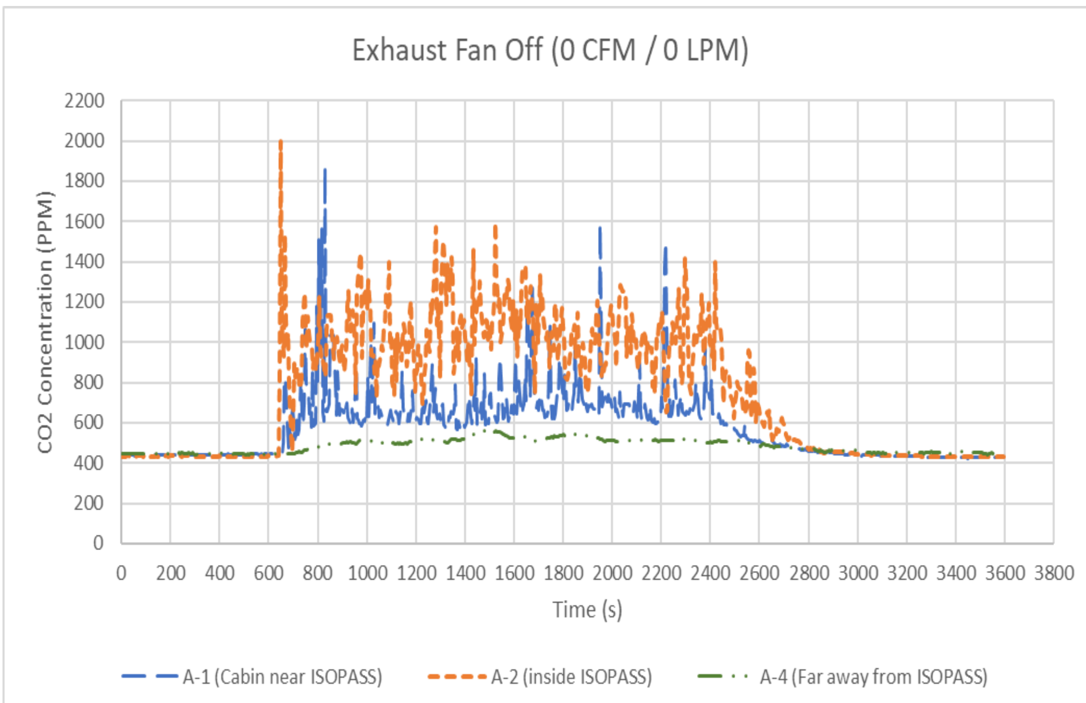

Figure 1 Respresentative results with the ISOPASS off, gaspers off

Average background CO_2 concentrations before the tracer gas injection over all three repetitions are as follows:

A-1 (Cabin near ISOPASS): 431 ppm
A-2 ("Inside" ISOPASS): 430 ppm
A-4 (Cabin Away From ISOPASS): 450 ppm

Once the tracer gas injection began and reached steady state, the average concentrations became as follows:

A-1 (Cabin near ISOPASS): 703 ppm

A-2 (“Inside” ISOPASS): 1281 ppm
A-4 (Cabin Away From ISOPASS): 510 ppm

From this we can see that the concentration across the cabin increases, as expected. We can define the percent-difference as the change in CO_2 concentration at steady state with the gas injection on with respect to the background prior to the injection. The percent-difference for each sampling location are approximately:

A-1 (Cabin near ISOPASS): +63%
A-2 (“Inside” ISOPASS): +198%
A-4 (Cabin Away From ISOPASS): +13%

As expected, the ISOPASS off, gaspers off experiments show dispersion of the tracer gas throughout the cabin, with the highest percent increase in concentration being nearest to the injection point and becoming progressively lower at further locations. With the tracer gas injection off, the average A-1 values for each repetition were within 18 ppm of each other, average A-2 values were within 12 ppm, and average A-4 values were within 20 ppm. With the tracer gas injection on, the average A-1 values for each repetition were within 27 ppm of each other, average A-2 values were within 686 ppm, and average A-4 values were within 26 ppm. The larger variation between repetitions at the A-2 analyzer with the tracer gas injection on is expected, since the analyzer is close to the injection source.

Gaspers On. With gaspers on, airflow patterns may be disrupted and could affect the distribution of the tracer gas through the cabin. The 767 mock-up cabin is equipped with just three rows of gaspers, rows 5, 6, and 7. For the sake of these tests, every gasper in the 767 mock-up cabin was fully opened and directed straight down. Gasper pressure was maintained at 2” H_2O (498 Pa). Representative results are shown in Figure 2.

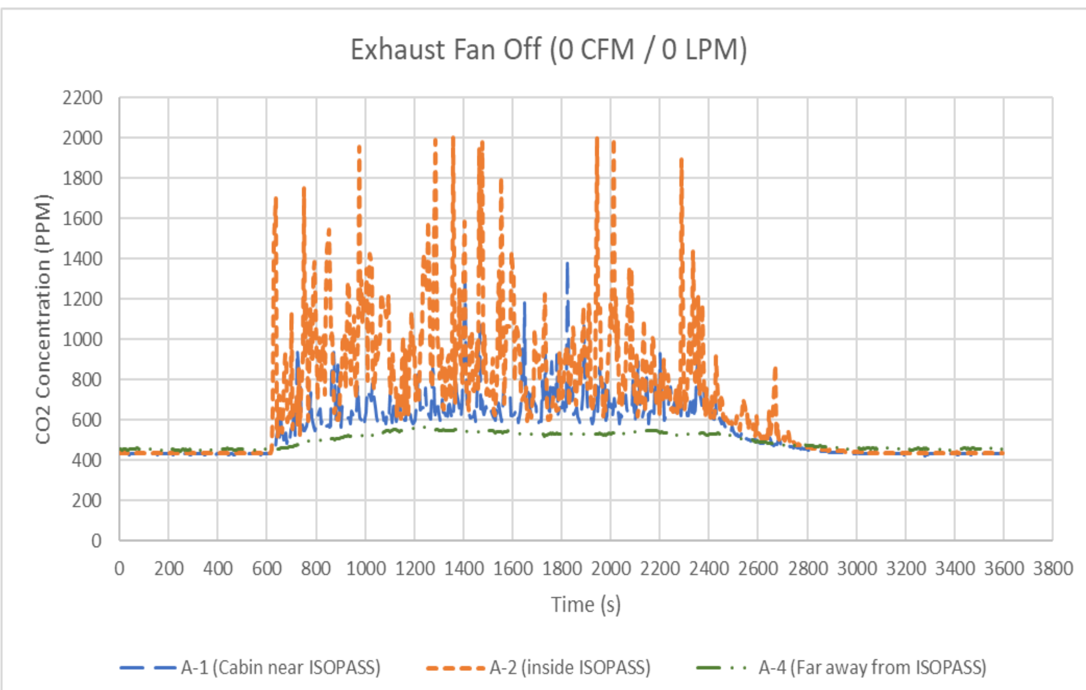

Figure 2 Representative results with the ISOPASS off, gaspers on

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Average background CO_2 concentrations before the tracer gas injection over all repetitions are as follows:

A-1 (Cabin near ISOPASS): 426 ppm
A-2 ("Inside" ISOPASS): 430 ppm
A-4 (Cabin Away From ISOPASS): 453 ppm

At steady state CO_2 concentration in the cabin, the average concentrations became as follows:

A-1 (Cabin near ISOPASS): 707 ppm
A-2 ("Inside" ISOPASS): 940 ppm
A-4 (Cabin Away From ISOPASS): 511 ppm

As observed with the gaspers off, the concentrations across the cabin increase. The percent-difference for each sampling location are found to be:

A-1 (Cabin near ISOPASS): +66%
A-2 ("Inside" ISOPASS): +119%
A-4 (Cabin Away From ISOPASS): +13%

With the ISOPASS removed, we do not observe much difference between the gaspers on and gaspers off conditions. With the tracer gas injection off, the average A-1 values for each repetition were within 15 ppm of each other, average A-2 values were within 16 ppm of each other, and average A-4 values were within 11 ppm of each other. With the tracer gas injection on, the average A-1 values for each repetition were within 39 ppm of each other, average A-2 values were within 218 ppm of each other, and average A-4 values were within 47 ppm of each other. Overall, we observe very similar distribution of tracer gas through the cabin for both gasper conditions without the ISOPASS.

ISOPASS On.

With the ISOPASS installed in the 767 cabin, we expect that the tracer gas will be contained well, and that there will be a measurable reduction in the percent-increase of CO_2 concentration in the cabin outside of the ISOPASS. For each test, the ISOPASS exhaust fan was set to 60%. Actual exhaust flowrate was measured by a 4" (10.16 cm) diameter vane anemometer placed in the exhaust stream.

Gaspers Off. With gaspers off, the source of fresh air to the passenger inside the ISOPASS is from the leakage points around the ISOPASS, such as the corners, slight gaps in the entrance, gaps along the floor where the ISOPASS is draped, etc. Most of the fresh air drawn in by the exhaust fan is around the floor where the exhaust pipe is located, and as a result, tracer gas builds up in the passenger breathing space, eventually being drawn down to the bottom of the ISOPASS and into the exhaust pipe. This causes a high concentration of CO_2 in the upper portion of the ISOPASS and a stratified concentration in the exhaust stream. As a result, the CO_2 concentration exceeded the range of the A-2 analyzer as is seen in Figure 3, where example results for the gaspers-off condition are presented.

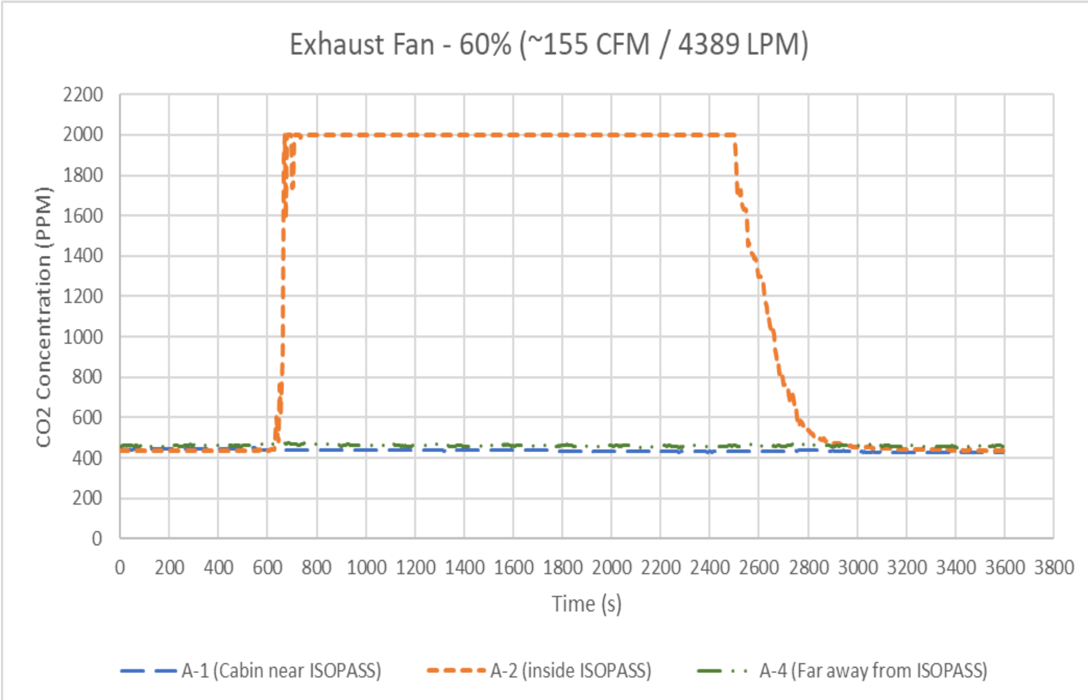

Figure 3 Respresentative results with the ISOPASS on, gaspers off

Average background CO_2 concentrations before the tracer gas injection are as follows:

A-1 (Cabin near ISOPASS): 431 ppm
A-2 (Inside ISOPASS): 430 ppm
A-4 (Cabin Away From ISOPASS): 453 ppm

After the tracer gas injection began, and upon steady state CO_2 in the cabin, the average concentrations became as follows:

A-1 (Cabin near ISOPASS): 427 ppm
A-2 (Inside ISOPASS): 2000 ppm (at least)
A-4 (Cabin Away From ISOPASS): 453 ppm

The upper concentration limit for the A-1 and A-2 analyzers is 2000 ppm. The actual concentration inside the ISOPASS is likely much higher but cannot be accurately measured by the equipment. The percent-difference for each sampling location are approximately:

A-1 (Cabin near ISOPASS): -1%
A-2 (Inside ISOPASS): +358% (at least)
A-4 (Cabin Away From ISOPASS): 0%

The ISOPASS then is very effective at containing the tracer gas injection with the gaspers off. The percent-differences in concentrations outside the ISOPASS never go into the positives, and only vary by about 2% at most.

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Additionally, this represents a difference of around 10 ppm, which is well within the uncertainty of the analyzers. With the tracer gas injection off, the average A-1 values for each repetition were within 21 ppm of each other, average A-2 values were within 15 ppm of each other, and average A-4 values were within 16 ppm of each other. With the tracer gas injection on, the average A-1 values for each repetition were within 14 ppm of each other, average A-2 values were each the same, surpassing the 2000 ppm limit of the analyzer, and average A-4 values were within 13 ppm of each other

Gaspers On. There was still the question as to whether the gaspers would affect the ISOPASS containment effectiveness by forcing some of the tracer gas out of the ISOPASS, changing the airflow patterns in the ISOPASS, etc. Additionally, it is valuable to compare the ISOPASS off, gaspers on data to the ISOPASS prototype and verify the effectiveness of the ISOPASS model for multiple realistic conditions. The results with the gaspers on are shown in Figure 4.

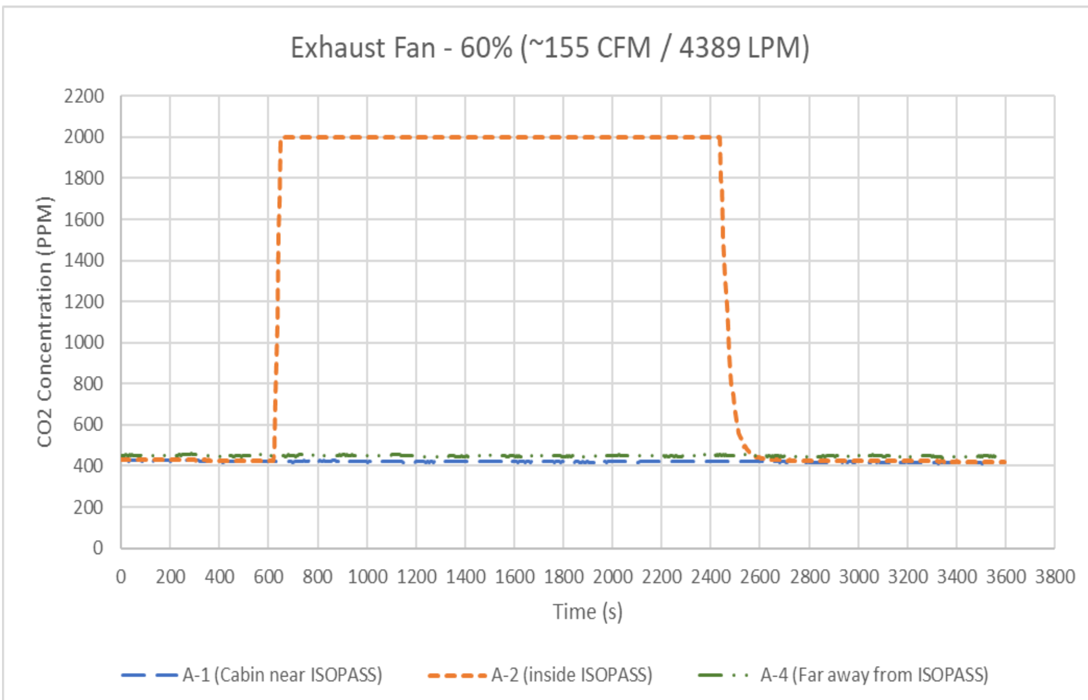

Figure 4 Representative results with the ISOPASS on, gaspers on

Average background CO_2 concentrations before the tracer gas injection are as follows:

A-1 (Cabin near ISOPASS): 438 ppm
A-2 (Inside ISOPASS): 432 ppm
A-4 (Cabin Away From ISOPASS): 451 ppm

After the tracer gas injection began and upon steady state CO_2 in the cabin, the average concentrations became as follows:

A-1 (Cabin near ISOPASS): 430 ppm

A-2 (Inside ISOPASS): 1999 ppm (at least)
A-4 (Cabin Away From ISOPASS): 451 ppm

As before, the analyzer sampling from inside the ISOPASS peaks out at approximately 2000 ppm, although the concentration could be much higher. The percent-difference for each sampling location are approximately:

A-1 (Cabin near ISOPASS): -2%
A-2 (Inside ISOPASS): +363% (at least)
A-4 (Cabin Away From ISOPASS): 0%

The inclusion of gaspers inside the ISOPASS makes no measurable difference in its containment effectiveness. As with the gaspers-off tests, the results here vary only by a couple percent at most and are well within the uncertainty of the CO_2 analyzers. With the gas off, the average A-1 values for each repetition were within 31 ppm of each other, average A-2 values were within 9 ppm of each other, and average A-4 values were within 10 ppm of each other. With the gas on, the average A-1 values for each repetition were within 18 ppm of each other, average A-2 values were within 5 ppm of each other, exceeding the 2000 ppm limit at most points, and average A-4 values were within 7 ppm of each other. The passenger may want to open the gaspers to create a more comfortable environment inside the ISOPASS. These tests suggest that this gasper use will not measurably impact the performance of the ISOPASS.

ADDITIONAL EVALUATIONS

In additional expiriments, we also found that the exhaust fan speed can be reduced to 30% without any leakage from the ISOPASS with the gaspers off. With gaspers on, the exhaust fan speed can be reduced to 20% with the same result. A cursory evaluation with a coughing mannequin was also completed. The results of the coughing simulation are largely comparable to those of the continuous injection matched pair tests, suggesting that the force and direction associated with coughing does not affect the containment effectiveness of the ISOPASS. The coughing mannequin does appear to somewhat affect the gas distribution and flow pattern around the cabin without the ISOPASS in place.

Research has also been conducted with matched pair tests inside of a 737 cabin section, which is a section of an actual aircraft cabin. The testing in the 737 cabin provides data in a narrow body aircraft in addition to the wide bodied 767, as well as provide confirmation that the ISOPASS prototype works in an actual cabin as well as in the mock-up. Results of these tests are largely the same as in the 767 cabin. Additionally, further experimentation was done to determine the minimum fan speed at which the ISOPASS is still effective. These experiments are included in (Darrah, 2018).

CONCLUSION

With the ISOPASS on and off matched pair tests performed in the 767 cabin, it is clear that the ISOPASS prototype is entirely effective at containing the tracer gas and preventing its spread in the cabin. Additionally, the matched pair tests were conducted for both gaspers on and gaspers off conditions and it was determined that the inclusion of gaspers in the ISOPASS makes no measureable difference in the performance of the ISOPASS with an exhaust fan speed of 60%.

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