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# Air Quality and Airflow Characteristic Studies for Passenger Aircraft Cabins

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## Abstract

This chapter summarizes the work done at the Airliner Cabin Environment Research Lab (ACERL) related to air quality, airflow characteristics, and human thermal comfort inside aircraft cabins. The laboratory is part of the Institute for Environmental Research (IER) at Kansas State University. It has a Boing 767 mockup cabin, bleed air simulator, and a Boeing 737 actual aircraft section that were all utilized to conduct experimental studies to understand air quality inside aircraft cabins. The studies summarized in this chapter include particle image velocimetry (PIV) investigations, particle dispersion, computational fluid dynamics (CFD) simulations, tracer gas and smoke visualization studies, and bleed air investigations. The chapter also summarizes other related studies including virus dispersion, air quality monitoring devices, and related developed air quality standards. The scope of this chapter is to summarize the setup and results of each of the above categories. This summary along with the cited references provides results for full size aircraft cabin environments, helps validate data for CFD simulations, and provides comparison data for other similar studies. This helps improve the design of future aircraft cabins and their ventilation systems and recommends changes to maintenance practices done that can improve the health and safety of humans inside these enclosed compartments.

**Keywords:** indoor air quality, airflow simulations, human health and safety, particle dispersion, aircraft cabin environment, bleed air, tracer gas

## 1. Introduction

Biological incidents such as severe acute respiratory syndrome (SARS) and swine flu (H1N1) transmission have been detected on flights. Ebola was the latest virus threat on board air-flights. Chemical incidents are also detected and reported inside commercial aircraft passengers' cabins. Odors and fumes from bleed air, viruses, and bacteria can result in serious health hazards for cabin crew members and passengers and have an important impact on aircraft air quality [1].

The purpose of this chapter is to summarize studies related to airflow studies, air speed and turbulence characteristics inside aircraft cabins. This can help aircraft manufacturers and operators in providing the occupants with acceptable air quality that meet safety guidelines and codes while maintaining the passengers' comfort in these enclosed and pressurized compartments.

In addition to that, the studies presented in this chapter provide important information to help in validating simulations and CFD codes developed to understand airflow behavior inside aircraft cabins.

## 2. Facilities and experimental setup

The Airliner Cabin Environment Research Lab (ACERL) houses two Boeing mockup cabins, a bleed air simulator, and a half cabin generic room. The details and specifications of each of the four structures are as follows:

### 2.1 Generic aircraft half-cabin mockup model

This generic model represents a half, twin-aisle, Boeing aircraft cabin. It has dimensions of L × W × H = 2.1 m × 2.1 m × 1.7 m in height (6.4 ft × 6.4 ft ×5.1 ft). The actual built-up room and a generic CAD model for this facility are shown in **Figure 1** [2, 3].

### 2.2 Boeing 767 cabin mockup

This structure represented a full size and wide body Boeing aircraft cabin mockup that was entirely built and validated at the ACERL. It consisted of 11 rows of seats, along the length of the cabin, with seven seats in the lateral (transverse) direction. The dimensions of the cabin mockup were 9.6 m (31 ft 5 in.) in length and 4.7 m (15 ft 6 in.) wide at the widest spot right above the arm seats area. The mockup cabin seats, the air supply duct, and linear diffusers are original parts from a salvaged Boeing 767 aircraft. Each seat in the cabin was occupied by an inflatable manikin, shown in **Figure 2c**, which was instrumented with a 10 m-long wire heater element to generate approximately 100 W (341 Btu/h) of distributing heat, representing heat gains from a sedentary human being. The supplied air to the cabin mockup was 100% fresh air with no recirculated air. Air temperature was controlled via a chiller and a heater loop as shown in **Figure 2b**. Prior to supplying the outdoor fresh air into the cabin mockup, a set of high-efficiency particulate air (HEPA) filters was installed in series with the supply duct, as shown in **Figure 2a**. Following the HEPA filter, the air was supplied to linear diffusers inside the cabin mockup. Air was exhausted from the bottom of the cabin mockup. The total airflow rate supplied to the cabin was approximately 660 l/s (1400 CFM) of fresh air, thus allowing 8.57 l/s (18 CFM) for every seat of the 77-seats available in the cabin. The
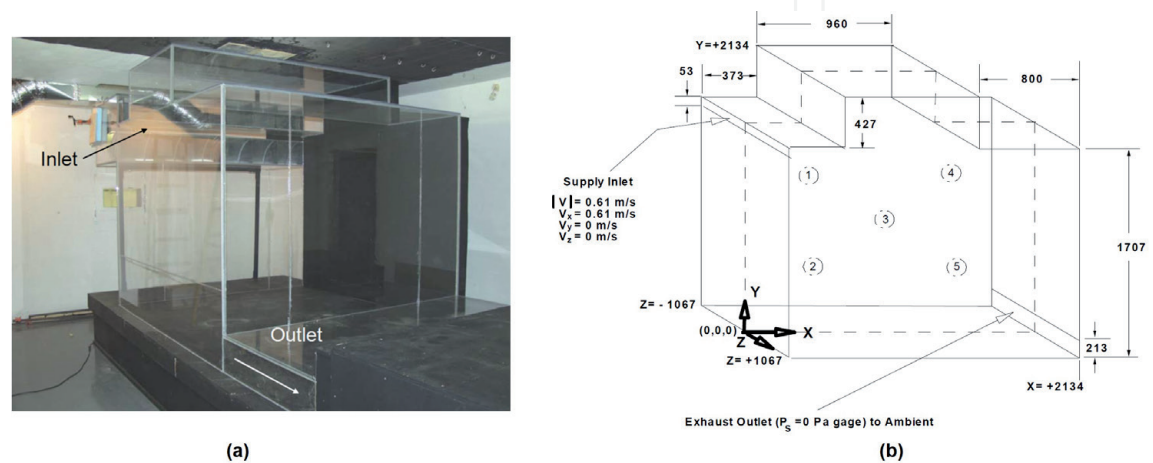


(a)  (b)

**Figure 1.**
*Half full scale cabin (a) generic room [2] and (b) generated CAD model [3] (dimensions in mm).*
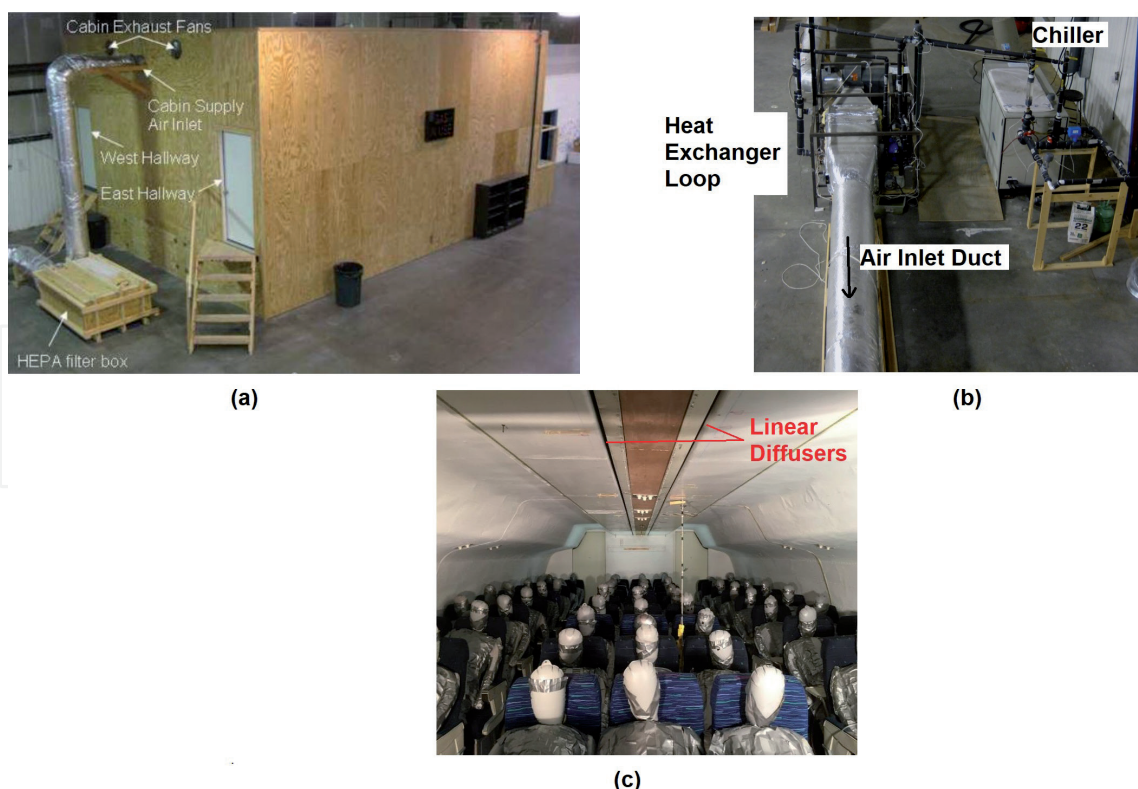
**Figure 2.**
*Boeing 767 cabin mockup (a) exterior, (b) supply air system and control, and (c) interior of the cabin with inflatable manikins in each seat shown [1, 4, 5].*

temperature of the air inside the cabin was controlled to 23–25°C which met the recommended design values for inside passenger aircraft cabins. It was important to insure that the air supplied through the two linear diffusers was balanced to maintain airflow uniformity inside the cabin. Also, the duct supplying the two diffusers had a decreasing diameter along the length of the cabin to allow uniform pressure. Although the uniformity of the air exiting the cabin was not a necessity, the exhaust area was uniform along the full length of the cabin and was open into a larger plenum that has negligible pressure gradients.

## 2.3 Boeing 737 sectional cabin

Two different sections of actual narrow body Boeing 737 aircraft cabins were used. The first one included three rows of seats with a total number of 18 seats. The seats were equipped with heated cylinders releasing approximately 100 W (341 Btu/h) except one seat that was equipped with a thermal manikin simulating a human body generating 100 W (341 Btu/h), as well. Cabin dimensions are shown in **Figure 3**. The other cabin size was 5.6 m (18.3 ft) in length, 3.6 m (11.8 ft) in width, 2.8 m (9.2 ft) in height and is shown in **Figure 4**. It consisted of five rows with 30 seats in total. All seats were equipped with similar inflatable-heated manikins as was described and used in the Boeing 767 cabin mockup. The airflow and temperature for both cabins were controlled meeting the specifications described for the Boeing 767 cabin mockup described previously.

## 2.4 Bleed air simulator

To help in identifying contamination sources onboard actual aircraft, HEPA filters were extracted from the air recirculation ducts from actual aircraft and were analyzed using the bleed air simulator shown in **Figure 5**. To simulate oil leakage,
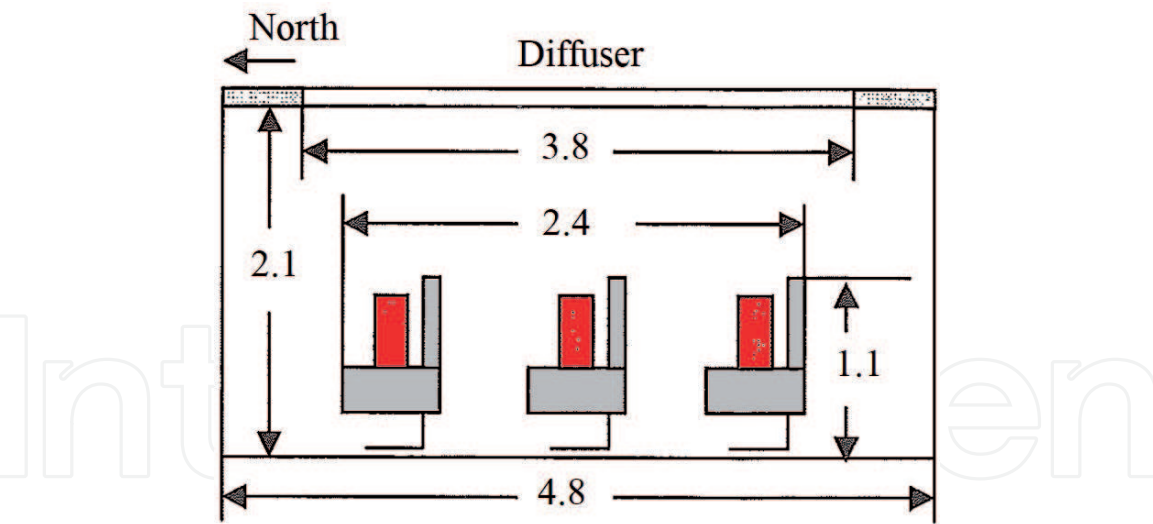
**Figure 3.**
*3-rows B737 cabin side view schematic (dimensions in mm) [6].*



**Figure 4.**
*5-rows B737 (a) exterior and (b) interior with inflatable heated manikins [7].*
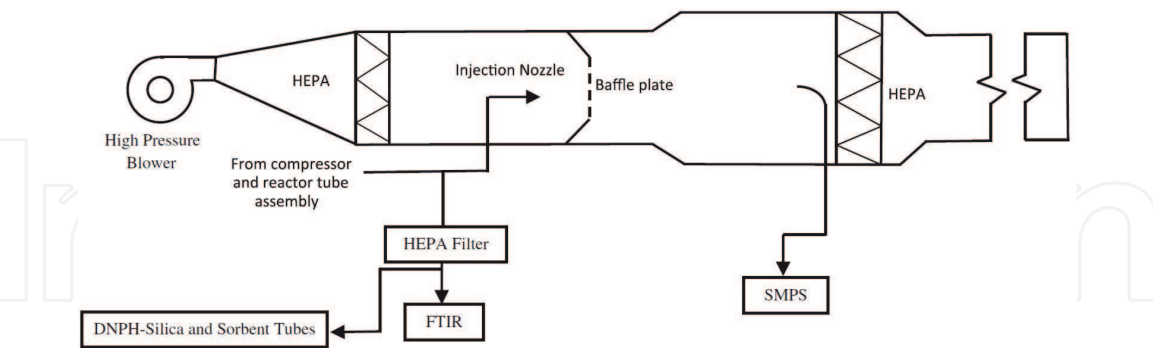


**Figure 5.**
*Bleed air simulator [8].*

a compressor was used with an oil generator forcing oil droplets in the testing duct where the filters were installed. A reciprocating compressor followed by a heated tube was used to create controlled temperature and pressure conditions representative of bleed air from an aircraft engine. Aerosolized lubricating oil was injected into the airflow upstream of the compressor and the particulate characteristics were measured downstream of the heated tube. Gas chromatograph-mass spectrometry (GC/MS) was used in the analysis [9].

Important key factors that can affect the accuracy of the results obtained were the duration of oil existence on the filters, storage conditions and duration of the filters, and oil evaporation [10].

## 3. Summary of studies

The progress of the studies conducted at the ACERL Lab is summarized as shown in **Table 1**. Investigation started with PIV techniques for structures' validation and to help in validating the computational fluid dynamics (CFD) codes development. This included multiple studies such as by [3, 6, 13, 16]. At the same time, literature was conducted to understand and evaluate air quality inside aircraft cabins such as by [11, 12, 14, 18]. In 2006, a new phase of investigation for air quality and airflow was approved by the US Federal Aviation Administration (FAA). The team started their investigation inside the B767 cabin mockup described in Section 2.2 and shown in **Figure 2**. The investigation started with particles dispersion inside the aircraft cabin mockup while working on more literature including air characterization inside aircraft cabins, contamination and viruses monitoring development, and other viruses related literature studies. After obtaining enough initial results,

| | CFD | PIV | Tracer gas | Particles | Bleed air | Others |
|---|---|---|---|---|---|---|
| 2001 | | Hosni and Jones [6] | | | | |
| 2002 | | | | | | Jones [11, 12] |
| 2003 | Hosni and Jones [13] | | | | | Jones [14] |
| 2005 | Lin et al. [3], Lebbin et al. [15] | | | | | |
| 2006 | Lin et al. [16], Lebbin et al. [17] | Lin et al. [16] | | | | Jones [18] |
| 2008 | | | | Padilla [19] | | Jones [20, 21] |
| 2010 | | Ebrahimi et al. [22] | | Shehadi et al. [23] | | Jones [24], Loo et al. [25] |
| 2011 | | | Trupka et al. [26, 27] | Beneke et al. [28] | Korves et al. [29] | |
| 2013 | | Ebrahimi et al. [2, 30, 31], Isukapalli et al. [32] | Anderson et al. [33] | | | Korves et al. [34] |
| 2014 | | | Shehadi et al. [35] | Powell et al. [36] | Eckels et al. [9], Mann et al. [37] | |
| 2015 | | | Shehadi [4], Keshavarz et al. [38] | | | Shehadi et al. [39] |
| 2016 | | | Patel et al. [5] | | Omana et al. [10] | Shehadi et al. [40] |
| 2017 | | | Patel et al. [7], Amiri et al. [8] | | Jones et al. [41], Space et al. [42] | |
| 2018 | | | | | Shehadi et al. [1] | |
| 2019 | | | Shehadi [43] | | | |

**Table 1.**
*Studies done at the ACER Lab (indexed as in the reference section) and their corresponding study category.*

different approaches were followed using CFD and tracer gas testing while continuing to work on particle dispersion investigations. At the same time, bleed air studies using the bleed air simulator shown in **Figure 5** were taking place to analyze the chemical composition of oil that penetrate through the aircraft circulation HEPA filters, to understand the behavior of oil under high temperatures and pressures and to help assess their impact on human health and comfort inside the aircraft. Beyond that, CFD, tracer gas, and bleed air investigation were all conducted in parallel while checking on available literature related to bacteria and virus outbreaks inside aircraft cabins and other fume and bleed air issues, as well. The reviewed studies are presented in a chronological order as presented in **Table 1**.

### 3.1 Particle image velocimetry (PIV) studies

The initial testing and verifications started using PIV techniques inside a generic half cabin model and sectional Boeing 737 as described in Sections 2.1 and 2.3 and shown in **Figures 1** and **3**. Hosni and Jones [6, 13] used the sectional narrow body Boeing 737 aircraft cabin, shown in **Figure 3**, to measure velocity and turbulence intensities inside a 3-row B737 airplane cabin. PIV techniques were used to meet these objectives. Each row consisted of six seats in the lateral (transverse) section of the cabin resulting in total 18 seats. A thermal manikin was used in one seat to simulate the human body inside the cabin and the remaining 17 seats were equipped with 100 W (341 Btu/h) cylindrical heaters simulating heat output of seated passengers. A total of nine planes were used for PIV measurements with individual measuring sections of 0.61 m × 0.61 m (2 ft × 2 ft) each. The results for airflow velocity and turbulence intensities were to be used to validate further developed CFD codes.

In 2005, two other studies were published. The first one included a comparison between computational results from large eddy simulation (LES) and experimental PIV results inside a generic cabin model. The cabin model dimensions were L × W × H = 2.1 m × 2.1 m × 1.7 m, as shown in **Figure 1**. LES predictions and PIV results were in agreement and so did the energy spectral analysis [3]. The second study by Lebbin et al. [15] compared results of airflow measurements using various measurement tools and equipment inside the same generic cabin model as shown in **Figure 1**. Some of the measurement tools include stereoscopic PIV (SPIV), sonic anemometer, hot-wire anemometer, and draft instrument. The study showed the benefit and significance of using a noncontact measurement system such as an SPIV system. Another study comparing LES with PIV for the airflow in the same generic cabin model was published in 2006 by Lin et al. [16]. The study came to the same conclusions as [3].

In 2006, Lebbin et al. investigated the effect of different nozzle sizes on the air inlet velocity inside the generic room described in **Figure 1** using SPIV technique. Reynolds number was held constant at the inlet slot of the room with a value of approximately 2226. It was noted that the center of rotation of the overall airflow significantly changed with a change in the size of the air inlet slot size, whereas the turbulence levels in the room was not affected significantly since Reynolds number was not changed [17].

### 3.2 Particle dispersion studies

Following PIV testing and before conducting any infectious and bacterial transport investigations, particulate transport and behavior inside aircraft cabins were studied. Padilla [19] investigated particulate transport in a half cabin generic room shown in **Figure 1**. Two different particle sizes were investigated: 3 and

10 μm. Each of the two particle sizes was investigated separately. Particles were injected at a constant point inside the room at a height of 606.6 mm (24 in.) above the floor on the centerline of the test room. Particles were measured at five different locations throughout the cabin. It was found that the normalized concentrations of 3 μm particles were close to one which confirmed the well air mixing inside the room. However, the 10 μm testing showed much lower normalized concentrations approximately 0.1. Several changes were done to the injection nozzle and cabin pressure and the results came to 0.4 and 1.5. Therefore, it was concluded that the 3 μm particles followed the airflow inside the cabin. A similar conclusion was difficult to reach for the 10 μm particles.

Particle dispersion inside an 11-row B767 cabin mockup was experimentally investigated by Shehadi et al. [23] to determine the best location for placing a particle detection sensor in the transverse direction of the B767 cabin mockup shown in **Figure 2**. The cabin mockup consisted of seven seats in the transverse direction with two linear diffusers around the center line of the cabin ceiling supplying air to the cabin mockup. Poly-disperse talcum powder, with a density of 0.95 g/cm³, was used as the testing agent and was released to simulate a sneeze from a seated passenger. Pressurized air was instantly directed into the powder forming a powder cloud at a height equivalent to the nasal area of a seated passenger. It was concluded that a properly placed sensor can accurately detect released particles in the transverse direction of the cabin when released in the same row as well as one adjacent row ahead and behind the release-row. This was identified as near field detection. Another study investigating particles dispersion inside the B767 cabin mockup cabin was done by Beneke et al. [28]. The paper indicated that regions around the release source had the highest exposure of particles released and the highest variations, as well. This exposure and variation level followed an exponential decay along the length of the cabin from the release-source at the second row of the cabin mockup toward the back wall (far field detection). A recent study in the same Boeing 767 mockup cabin investigating particles between 05 and 5 μm showed that there is a 20–35% additional drop in normalized particle counts per row away from the release row in the longitudinal direction [43].

Powel et al. [36] investigated particle deposition rates inside the B767 cabin mockup shown in **Figure 2**. Particle deposition was investigated over multiple locations inside the cabin and was collected at different surface orientations, horizontally and vertically aligned. Particles were collected on clean tape surface and were optically counted using fine small grids under a photographic type microscope. It was found that the surface orientation played a significant role in particle deposition rates with approximately 1-order of magnitude difference between vertical and horizontal orientation.

### 3.3 Computational fluid dynamics (CFD) studies

Tracer gas, smoke visualization and particle testing were all done inside the generic room mimicking a half aircraft passenger cabin, inside actual cabin sections, and inside a cabin mockup to understand airflow and turbulence characteristics such as velocity and turbulence intensity. Each study was conducted with new and different goals. However, all the studies were intended to support the development and validation of mathematical and computational models for airflow and particles or gas dispersion in aircraft cabins.

Ebrahimi et al. [22] conducted several computational studies for the Boeing 767 cabin mockup, shown in **Figure 2**, investigating the airflow and turbulence characteristics and validating CFD models by comparing against available experimental data. Large Eddy Simulation (LES) and Reynolds Averaged Navier-Stokes

(RANS) methods were used for simulation in the study. Computational results were validated against previously presented data in the PIV studies section. Other CFD results from literature were used against the simulated results for further validation. Nozzle height effects from the cabin floor on the airflow behavior were investigated in the study. Results from LES with Werner-Wengle wall function were found to predict unsteady airflow velocity fields inside the Boeing 767 cabin mockup with relatively high accuracy. However, in places where air circulation took place and accuracy was not as good, the RGN k-ε model with the non-equilibrium wall function model predicted the steady-state airflow velocities with good agreements with experimental results [2]. In a later CFD study by Ebrahimi et al. [30], the calculated velocity was used to predict tracer gas and particle dispersion simulation inside the full-scale, 11-row, Boeing 767 aircraft cabin mockup shown in **Figure 2**. In the same study by Ebrahimi et al. [30], RANS method and the RGN k-ε model were used for airflow simulations and turbulence modeling, respectively. Three different grid sizes were examined for grid uncertainty analysis. To start the simulations, initial airflow velocities exiting the supply nozzles were experimentally measured using omni-probes. The boundary conditions were further refined by conducting continuous comparisons between experimental and simulated results.

CFD modeling inside the Boeing 767 cabin mockup was used to understand the pesticide deposition rates. Pesticides are usually used by many countries for disinfection purposes. Different spraying patterns with different angles were simulated at both low and high cabin air exchange rates. The pesticide deposition samples were collected at the lap and seat top levels. The developed models predicted results with high accuracy when simulating high air exchange rates but underestimated the concentrations at window seats when under low air exchange rates. No major variations were found in deposition characteristics between sideways and overhead spraying angles [32].

In 2011, while simulating different scenarios for the Boeing 767 cabin mockup, Ebrahimi et al. [31] conducted computational analysis for the generic half cabin room, shown in **Figure 1**, using the Lagrange-Euler approach. Air was modeled as continuous phase whereas particles were treated as discrete. The discrete and continuous phases were solved through the calculation of drag and buoyancy forces acting on particles. Reynolds Averaged Navier-Stokes (RANS) method was used for velocity calculations while checking the dependency of RANS simulations on grid size through a controllable local mesh refinement scheme. It was found that unstructured grid with tetrahedral and hybrid elements provided better results than structured grid with hexahedral elements [31].

### 3.4 Tracer gas studies

Following PIV, CFD simulations, and particle dispersion testing, tracer gas testing was used to investigate airflow speed, orientation, and turbulence characteristics. Tracer gas has been widely used in experimental studies to study ventilation effectiveness, airflow circulations, airflow velocities, and other parameters inside aircraft cabins, enclosed environments and structures, buildings, hospitals, and many other applications. Some of the properties of the tracer gases to reveal unbiased results are reactivity and sensibility, should be non-reactive, should not react chemically or physically with any part of the system under study, and should be insensible otherwise the results obtained from the processes under investigation would be biased. In other words, tracer gases shall not affect the airflow or air density of the system, should not change the state of air, its chemical properties, and should mix and follow the airflow well. In addition to that, the tracer gas used should have measurable criteria in order to be quantified. On top of all of the above

properties, the used tracer gas shall be safe and should be non-flammable, non-toxic, and non-allergenic [4]. All of the tracer gas studies that will be presented here-in were conducted inside the Boeing 767 cabin mockup described in **Figure 2**, except the study done by Patel et al. [7].

Smoke visualization techniques along with tracer gas, mainly made up of carbon dioxide and mixed with helium to maintain equivalent buoyancy with air in the cabin, was used to understand airflow behavior inside the Boeing 767 cabin mockup described in **Figure 2**. The tracer gas was released and sampled randomly throughout the cabin mockup. Smoke visualization results showed that the flow inside the cabin was chaotic and difficult to quantify. Quantitative results obtained from tracer gas testing helped in identifying several swirling and circulations inside the cabin. Some circulations were clockwise and others were counter clockwise directed. The circulations inside the cabin mockup were believed to be part of the driving mechanism in transporting tracer gas through the longitudinal direction of the cabin [35]. More analysis was done by Shehadi et al. [1] to analyze airflow and turbulence characteristics inside the same Boeing 767 cabin mockup. Tracer gas sampling was used as the main technique. Several eddies and circulations inside the cabin were identified with two large-size circulations dominating over the front and middle sections of the cabin mockup. The airflow in the aft section of the cabin was shown to be more chaotic and experienced more complex flow characteristics than in other sections of the cabin. Uncertainty calculations were done to check on the measurements' accuracy and validation and it was approximately ±14% including bias and random uncertainties. Also, it was concluded that the longitudinal length of the cabin controls the number of air circulations that could be present in cabins of similar aircraft model and type.

In another study, carbon dioxide was used as a tracer gas to simulate a gaseous decontamination agent inside the Boeing 767 mockup cabin shown in **Figure 2**. Supplementary axial fans were used in both and either aisles of the cabin mockup in separate cases and scenarios. Geometric, thermal, and airflow boundary conditions were also measured and documented. Gaseous transport inside the cabin was shown to be non-symmetrical between the two transverse sections of the cabin at several locations although the cabin and boundary conditions were symmetrical. This asymmetry was due to horizontal circulations of air that naturally formed in the cabin. This circulation had a substantial impact on longitudinal gaseous transport [38].

Tracer gas made up of carbon dioxide was used to investigate the effect of a moving cart by a cabin crew in one of the aisles inside the Boeing 767 aircraft cabin mockup described in **Figure 2**. Tracer gas was injected inside the cabin at constant rates and then was quantitatively sampled using non-dispersive infrared (NDIR) sensors at different locations inside the cabin. The impact of the moving cart and the attached dummy, which represented a cabin crew, was insignificant compared to the transport via cabin air motion [26, 27]. Most of other variables and disturbances in airliner cabins related to the impact of a beverage cart and the cabin crew driving it do not appear to provide a significant path for longitudinal dispersion of contaminates.

The effect of gaspers or personal air outlets used in aircraft cabins on the airflow and transport phenomena inside the Boeing 767 cabin mockup was investigated by Anderson et al. [33]. Tracer gas was released and sampled in the breathing zone of a seated passenger using a thermal manikin. While keeping the airflow supply at constant rate, personal supply gaspers were found to impact local exposure by disrupting the contaminant plume. In some cases, there was significant reduction in close-range, person-to-person exposure, while in other cases there was negligible or even negative impacts. No concrete conclusions or universal guidelines could be identified for the use of gaspers due to the unpredictable behavior of the plumes

and due to variations in their behavior from location to location. However, it was found in most cases that it was more effective to use the gaspers by the source person rather than by the exposed person as the air leaving the gasper nozzles tended to push the contaminant plumes from the source person down and out of the breathing zone [33].

Local ventilation effectiveness inside the B767 cabin mockup and the 5-rows Boeing 737 cabin section described in **Figures 2** and 4, respectively, was investigated by Patel et al. in [5, 6], respectively. Experiments inside both cabin models were conducted using tracer gas. Tracer gas, composed mainly of carbon dioxide, was sampled at all of the 77 seats inside the 11-row Boeing 767 cabin mockup. The overall ventilation rate was found approximately at 27 air changes per hour (ACH) based on total supply air flow. The ventilation effectiveness ranged from 0.86 to 1.02 with a mean value of 0.94. These ventilation effectiveness values were higher than what typically is found in other indoor environments. This gain in effectiveness is likely due to the relatively high airspeeds that can improve mixing rates [5]. On the other hand, experiments inside the 5-rows sectional Boeing 737 were carried with similar thermal manikins as was used in the Boeing 767 cabin mockup [7]. Local ventilation effectiveness was found to be uniform throughout the Boeing 737 cabin regardless of the location inside the cabin. For gaseous transport, similar conclusions were found in both cabins, Boeing 767 and Boeing 737, where gaseous transport was significantly transported in the transverse and longitudinal directional of the cabins.

### 3.5 Bleed air characterization studies

Bleed air studies were done to investigate bleed air contaminants generated during incidents such as fume or oil thermal degradation incidents inside aircraft cabins. Multiple devices and different techniques were used to investigate bleed air contamination inside aircraft.

Contamination source identification is very difficult and would require multiple occurrences inside aircraft cabins [10]. Eckels et al. [9] recommended analyzing the high-efficiency particulate air (HEPA) filters used with the air recirculation ducts of aircraft in nearly all commercial aircraft. This procedure and technique would provide a chemical map database or library for contamination particles found on HEPA filters and ultimately inside aircraft cabins. A bleed air simulator was built for this purpose and is shown in **Figure 5**.

Gas chromatography/mass spectrometry (GC/MS) was found useful in providing information about the likely contamination source, but further research was deemed necessary to validate the methods. For example, the effect of oil existence duration on the filters can change the whole conclusions. If oil contamination on HEPA filters is not time specific, then if it has occurred recently or weeks or months prior to the testing of the filters, it would not have much difference. It could be the result of continuous low-level contamination or it could be the result of one or a few significant events. Knowledge of the stability of the oil on HEPA filter media is thus crucial for the validation of GC/MS testing and analysis [10]. Air filter sampling and the ResPlex II assay were found to be an effective method in identifying and characterizing viruses in aircraft cabins' air by analyzing the cabin filters [29].

Results from [9] in the bleed air simulator, shown in **Figure 5**, when investigating standard and nonstandard filters, showed a concrete link between tricresyl phosphates (TCPs) and a homologous series of synthetic pentaerythritol esters from oil and contaminants. High correlation was found for nonstandard filters than with standard ones.

Mann et al. [37] compared results of four particle counters used inside the bleed air simulator that was described in Section 2.4 and shown in **Figure 5**. The particle counters included a scanning mobility analyzer, an aerodynamic particle-sizer, an optical particle counter, and a water-based condensation particle counter. The covered particle sizes ranged between 13 nm and 20 μm. Effects of temperature and pressure on particles generation were investigated. It was found that high temperatures can increase ultrafine particles existence, whereas the pressure of the bleed air had little discernible effect on both particle size and concentration.

Another study analyzing the concentration, number of counts and size of different chemicals was done by Amiri et al. [8]. Various temperatures and pressures were considered inside the bleed air simulator described previously. The results showed that different aldehydes were formed with increasing concentrations with pressure and temperature. Carbon-monoxide was noticed to increase in concentration with both increasing pressure and temperature across all temperatures and pressures evaluated. It was noticed that the minimum bleed-air temperature resulted in maximum particle sizes and minimum concentrations.

To check on the compliance air quality with aircraft codes and design guidelines, specifically the ANSI/ASHRAE Standard 161, in detecting contamination from lubricating oil, a four-part experimental program was done by Jones et al. [41]. For the first part, the bleed air simulator was used to check on the temperature and pressure effects. For the second and third parts, turbine shaft engines mounted in test stands were used. The fourth part of the program was done on a NASA Vehicle Integrated Propulsion Research (VIPR) study which was conducted on an US Air Force C-17 Globemaster III military transport aircraft. Particulate size distributions and concentrations were measured with aerodynamic particle sizer and scanning mobility particle sizer, as well. Very low contamination rates were found. However, it was noted that many of the droplets may be even smaller than 10 nm which raises the necessity for developing ultrafine particle detection and sensing of low contamination levels. The results for the VIPR program showed that chemical contaminants from the injected engine oil could be captured by various types of sampling media. After analysis, it was found that no significant concentrations of contaminants in bleed air exceeded established OSHA PEL and STEL limits [42].

### 3.6 Other studies

Other studies included developing air quality standards such as by [14, 18, 20, 21] and summarizing data from literature and previous studies that can help in regulating air quality inside passenger aircraft [11]. Other studies investigated advanced models for predicting the transport of infectious disease, viruses and contamination in airplanes [24] and analyzed bacteria development on airplane HEPA filters that can facilitate the design of biosensors for infectious organisms' detection on commercial aircraft [34].

A study by Loo and Jones [25] discussed the requirements for developing a portable unit that can detect and measure air quality on board actual flights. Some of the recommendations for a good and reliable sensor unit were: (1) cost should be less than $1000 for each unit after development is completed, (2) certified for electromagnetic interference (EMI) that would allow it to operate during all phases of a given flight, (3) no special security procedures, (4) can be carried on with no special requests, (5) can be operated by anyone, (6) should have a rechargeable battery that can run for at least 10–16 hours without battery recharging or replacement, (7) should require only simple, or infrequent, calibration, (8) should allow time and date stamping for all data, and (9) easy interfacing to a computer for

downloading to a central database. Testing was done onboard number of actual flights, approximately 15 flights, and the following were some of the observations on most flights that were tracked:

1. cabin altitude average remained below 1000 ft,

2. $CO_2$ levels ranged between 900 and 1700 ppm,

3. cabin temperature ranged between 22 and 29°C (71.6–84.2 F),

4. relative humidity ranged between 35 and 50% at the beginning of the flights and dropped to 10–25% as flight progressed, and

5. sound level was approximately 86 dBA.

Other studies investigated air fume, smoke and other related incidents on board actual flights and the associated incurred costs that can result due to delays and cancellations in corresponding flights. Shehadi et al. [40] reviewed databases from NASA, US Federal Aviation Administration (FAA), US Department of Transportation (DoT) and analyzed incidents on 33 aircraft models and sub-models. The study considered the different engines' and auxiliary power units' (APU) makes and models. The analysis showed that thousands of flights would need to be monitored to determine the root cause/source for a reported incident. Although the cost of the thought study might be high, but the associated costs due to delays and cancellations of flight due to such incidents can be approximately $32,000–$47,000 per aviation incident totaling approximately $4.5-million–$7-million US dollars in 2012 [39].

## 4. Conclusions

A review for studies done at the Airliner Cabin Environment Research Lab (ACERL) housed at Kansas State University was done in this chapter. Studies were categorized as per the method of study such as PIV, particle dispersion, CFD, tracer gas, and bleed air. The studies investigated airflow and turbulence characteristics in various airline cabin structures such as a generic room, Boeing 767 and 737 mockup cabins, actual aircraft, and a bleed air simulator. The objective of this chapter is to provide a database of experimental and computational study references that can be used to validate further computational investigation which in turn would help in designing a state-of-art contamination and bacterial sensors to be used on board flights and ultimately would help in improving the quality of air inside airplane cabins. The studies can also help aircraft designers improve the design of the ventilation system in the aircrafts and would provide guidelines for maintenance teams to follow better practice that can prevent previous incidents such as bleed air contamination.

Tracer gas and powder particles were used to simulate the dispersion of bacteria and viruses. It was observed, particularly with the longitudinal dispersion, that the various forms of contaminants behave in a similar dispersion manner. However, the relative bacteria concentrations appear to drop off more quickly with distance than those with the tracer gas and solid particles. This might be caused due to the fact that only viable bacteria would be counted during the studies. This might provide bias or incorrect results as some bacteria would be removed by the aircraft ventilation system and others might have become nonviable before they reach the more

distant parts of the cabin. Other reasons would be the possibility that the collection plates, used to sample the bacteria, could have picked only large droplets depending on their orientation and distance. The larger droplets may settle out of the airflow before they reach the more distant parts of the cabin. Nevertheless, these data combined give a reliable quantification of the field dispersion of contaminants and provide a basis for developing or validating dispersion models.

The summarized studies give some insight into the behavior in the near (two seats or fewer from the point of release) and far fields. Evidence of large flow structures is evident in most studies. Also, there is evidence that these structures are chaotic. For example, the tracer gas data showed poor repeatability in the vicinity of the injection, but they had good repeatability at other locations. This chaotic nature makes it difficult to model and predict concentrations in the near-field region.

Tracer gas, PIV, and particle tracing are valuable experimental tools to predict the airflow characteristics and behavior. The results associated with these tools provide significant boundary conditions to validate and develop computational simulations and codes. Experimental and simulation investigation for the airflow inside aircraft passenger cabins can help in predicting the dispersion of unwanted particulates, viruses or bacteria in aircraft cabins and would help the development of appropriate decontamination methods and tools. This would help decrease the health hazardous and risks onboard these special environment compartments.

## Conflict of interest

The authors do not have any conflicts of interest.

## Nomenclature

| | |
|---|---|
| ft | feet |
| m | meter |
| in. | inch |
| HEPA | high-efficiency particulate air |
| CFM | cubic feet per minute |
| GC/MS | gas chromatography-mass spectrometry |
| PIV | particle image velocimetry |
| CFD | computational fluid dynamics |
| LES | large eddy simulation |
| SPIV | stereoscopic particle image velocimetry |
| RANS | Reynolds Averaged Navier-Stokes |
| nm | nanometer |
| µm | micrometer |

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