Recent Progress on Studies of Airborne Infectious Disease Transmission, Air Quality, and Thermal Comfort in the Airliner Cabin Air Environment

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Abstract

Airborne transmission of infectious diseases through air travel has become a major concern, especially during the COVID-19 pandemic. The flying public and crew members have long demanded better air quality and thermal comfort in commercial airliner cabins. This paper reviewed studies related to the airliner cabin air environment that have been published in scientific journals since 2000, to understand the state-of-the-art in cabin air environment design and the efforts made to improve this environment. In this critical review, this paper discusses the challenges and opportunities in studying the cabin air environment. The literature review concluded that current environmental control systems for airliner cabins have done little to stop the airborne transmission of infectious diseases. There were no reports of significant air-quality problems in cabins, although passengers and crew members have complained of some health-related issues. The air temperature in cabins needs to be better controlled, and therefore better thermal comfort models for airliners should be developed. Low humidity is a major complaint from passengers and crew members. Gaspers are used by passengers to adjust thermal comfort, but they do not improve air quality. Various personalized and displacement ventilation systems have been developed to improve air quality and thermal comfort. Air-cleaning technologies need to be further developed. Good tools are available for designing a better cabin air environment.

Practical Implications

By reviewing the most important publications concerning the air environment in commercial airliner cabins, this paper provided a summary of the state-of-the-art on cabin air environment studies. The review also recommended further research needed to improve the cabin air environment.

1. Introduction

According to the International Air Transport Association (IATA 2021), air transportation was a very popular mode of travel in 2019, as 4.5 billion people flew to various destinations around the world. However, the COVID-19 pandemic placed air travel on hold in 2020, when only 1.8 billion passengers flew, a decrease of 60.2% from the previous year. The worst month was April 2020, when airlines experienced a 94% reduction in passenger capacity worldwide (Pavlik et al. 2021). A study by Boeing (Pang et al. 2021) showed that the global risk of COVID-19 transmission during air travel was 1 in 1.7 million. However, other studies have reported an attack rate of 9.7% to 62% (Toyokawa et al. 2020 and Khanh et al. 2020). The flying public has reasonable doubts about the ability of modern airliners to protect them from infection by airborne diseases such as COVID-19.

Airborne infectious diseases are not the only source of concern for the flying public. Cabin air quality has become a very popular topic for research. The National Research Council in the United States

(NRC 2002) conducted a comprehensive review of the airliner cabin air environment and the health of passengers and crew members. The study concluded that although cabin air quality may not be very low, passengers have complained of dry eyes, sore throat, dizziness, headaches, and other symptoms. However, the causes of these symptoms remain unclear (Wolkoff 2016).

In addition, thermal comfort is a very important aspect of the cabin air environment. According to Fanger (1970), thermal comfort is a function of the air temperature, relative humidity, air velocity, and radiant temperature of the environment; clothing level; and metabolic rate. The first four parameters are related to the cabin air environment. Meanwhile, measurements and surveys conducted by Cui et al. (2014) found that the spatial distributions of comfort parameters in cabins were not uniform, and almost 30% of passengers complained that they were too warm.

To solve problems related to infectious disease transmission, cabin air quality, and thermal comfort, government agencies have sponsored several large research projects. For example, the Federal Aviation Administration (FAA) in the United States established a national Center of Excellence (CoE) for Airliner Cabin Environment Research (ACER) in 2004 and conducted a 10-year study on the cabin air environment with more than $20 million in research funding (FAA 2018). The study (FAA 2018) included (1) the effects of the airline cabin air environment on the health and safety of passengers and crew members, (2) the efficiency and effectiveness of aircraft environmental control systems, and (3) emerging technologies with the potential to eliminate bleed air contaminants and purify aircraft air supplies. Meanwhile, the Ministry of Science and Technology in China sponsored a national consortium on Cabin Environment Research for Large Commercial Airplanes from 2012 to 2016 with￥32.86 million in funding (Chen 2016). They studied cabin air distribution, thermal comfort, air quality, design parameters, inverse design methods, and environmental control systems. The research, however, did not find major issues related to health or thermal comfort. The "ideal cabin environment" project sponsored by the European Commission (2013) from 2005 to 2008, with €6 million in funding, used large-scale aircraft cabin environment facilities to determine passenger well-being with validation by in-flight monitoring. The project concluded that flying in current commercial aircraft environments poses no significant health risk to passengers.

The research efforts sponsored by the U.S. government, the Chinese government, and the European Commission have been significant. There have also been numerous projects sponsored by relevant industries, other government agencies, and various foundations. The question is whether we have solved the problems that exist in the cabin air environment. Numerous literature reviews have been published recently on this subject. For example, Fan and Zhou (2019) reviewed models used to predict thermal comfort in airliner cabins. They found large differences between the cabin air environment and buildings on the ground, such that the models for buildings cannot be used for airliner cabins. Chen et al. (2021) examined nearly 50 flights on commercial aircraft in terms of volatile organic compounds (VOCs). They found that the concentrations of VOCs were below the permissible levels, with the exception of benzene. Hayes et al. (2021) reviewed literature on the occupational risks of chemical and radiative exposure in aircraft cabins. They found that the potential for such risks cannot be ruled out. A review of the impact of cabin air quality on the well-being of crew members and passengers by Zubair et al. (2014) discussed the prevalence of dizziness, fatigue, headaches, sinus and ear problems, dry eyes, and sore throats during and after travel and concerns about infectious diseases before the COVID-19 pandemic. Zhao et al. (2019) reviewed the role of interior surfaces in the formation of potentially hazardous microorganisms, which could pose health risks by causing infectious diseases. The objective of a review conducted by Conceição et al. (2011) was to evaluate airborne dispersion of contaminants, especially expiratory droplets, inside aircraft cabins. Leitmeyer and Adlhoch (2016) reviewed influenza virus transmission aboard aircraft and found evidence of such transmission and found that the major limiting factor was the comparability of the studies. Elmaghraby et al. (2018) reviewed different ventilation strategies used in commercial aircraft and the common airborne contaminants encountered in cabins. All the reviews provided very useful information for stakeholders in the aircraft cabin air environment. However, most of the reviews were on one of the subjects of infectious disease transmissions, air quality, thermal comfort, or air distribution. Air quality and thermal comfort are inter-related so they should be considered simultaneously, while air distribution is the fundamental behind. The COVID-19 pandemic brought additional challenges to the flying public, commercial airliner manufacturers, and public officials. The literature reviews have not been conducted for COVID-19 transmissions.

One of the authors of the present review, Qingyan Chen, was the founding co-Principal Director of the FAA CoE for Airliner Cabin Environment Research from 2004 to 2010 and the Chief Scientist for the Chinese consortium for Cabin Environment Research for Large Commercial Airplanes from 2012 to 2016. He has also conducted research on airborne infectious disease transmission and ventilation systems in airliner cabins for the past 17 years. With his experience, this investigation critically reviewed more than 150 peer-reviewed papers from scientific journals published after 2000 that studied the airliner cabin air environment. Prior to 2000, the National Research Council (2002) published a very good book of overview on cabin environment. By using Google Scholar, this investigation found hundreds of articles concern cabin air environment. The 150 papers were selected because they are representative, have high citations, and/or seem to be of high quality. The cabin air environment is created by environmental control systems through air distribution. The air distribution is fundamental to airborne infectious disease transmission, air quality, and thermal comfort in airliner cabins. After reviewing the state of the art in these areas, this paper presents recent efforts to improve the cabin air environment. Finally, this paper describes the research efforts that are still needed for the airliner cabin air environment.

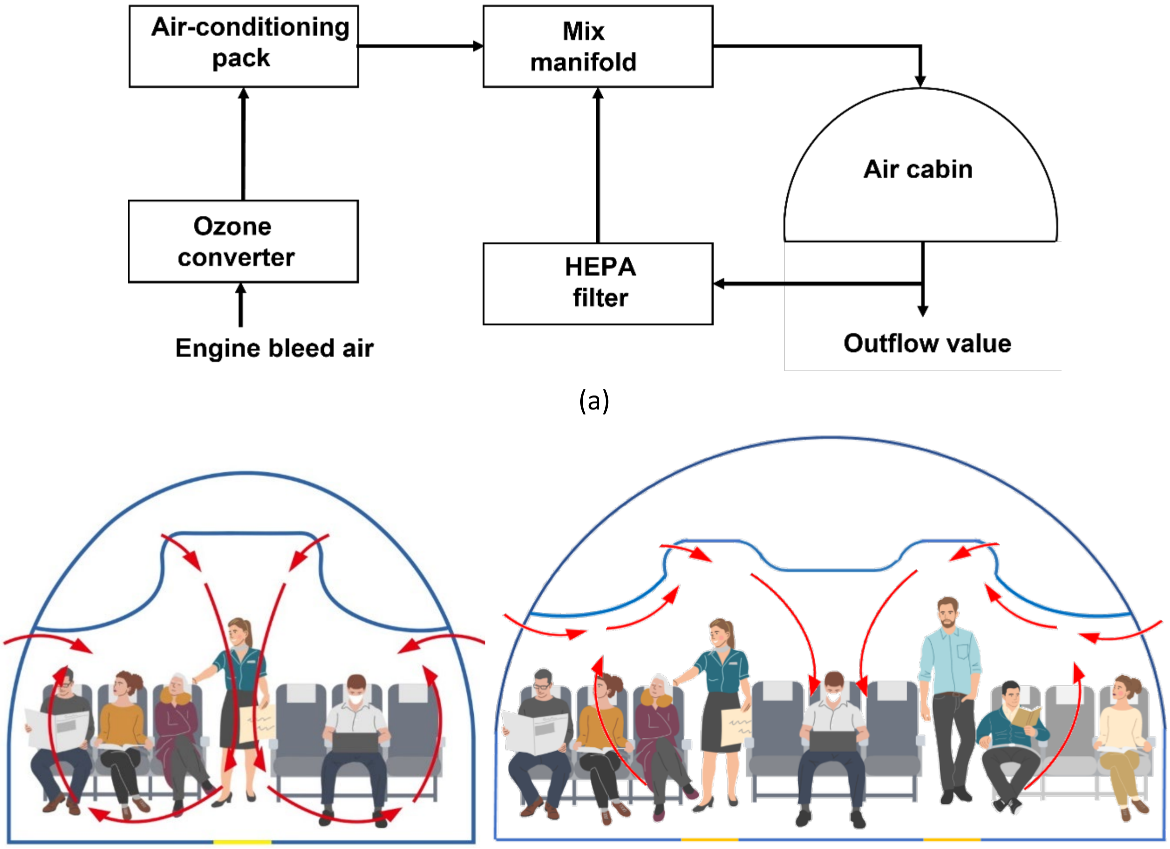
2. State-of-the-art in Cabin Air Environment Design

The air environment inside airliner cabins includes air quality, thermal comfort, and air pressure. Due to the COVID-19 pandemic, the flying public has significant concerns about airborne infectious disease transmission. Since few studies have been published on air pressure, we did not review this topic specifically. On the other hand, air distribution is fundamental to airborne infectious disease transmission, air quality, and thermal comfort. This review began with air distribution systems in airliner cabins.

2.1 Studies on air distribution in current airliner cabins

Background on air distribution in airliner cabins

When an airliner is flying at a cruising height of around 35,000 ft (10,000 m) above sea level, the outside air pressure is about 25 kPa, which is too low to sustain human life. Therefore, airliner cabins must be pressurized to an equivalent height of 8000 ft (2450 m) or lower so that pressure is no lower than 75 kPa, thus ensuring the safety of crew members and passengers (CFR 2022). The air used to pressurize airliner cabins is conditioned for the thermal comfort of the passengers and crew members. The pressurized air or the bleed air is normally from aircraft engine, except B-787 that uses a separated compressor, as shown in Figure 1(a). Typically, airliners use a mixture of 50% outdoor air and 50% filtered return air to reduce energy costs while maintaining acceptable air quality inside cabins (Wang et al. 2008). The supply air should be clean to create a healthy environment inside the cabin. Thus, the return air is filtered by a HEPA filter, while assuming the bleed air is clean at cruising height. At ground level, the outside air is either from an air-conditioning system at jet bridge or from auxiliary power unit. Since thermal comfort is related to air temperature, relative humidity, air velocity, and radiant temperature, airplane manufacturers use mixing ventilation as shown in Figures 1(b) and 1(c). The mixing ventilation system supplies air from the ceiling and/or at upper-shoulder level as illustrated in Figure 2(a). This air mixes with the cabin air to create uniform air temperature inside the cabin. The return air is extracted at floor level on both sidewalls. To minimize contaminant transport in the longitudinal direction, the air supply to each row of seats is equal to the volume of air exhausted at floor level (See Figure 2(a)). Thus, ideal air distribution in airliner cabins should not have evident flow in the longitudinal direction.



(a)

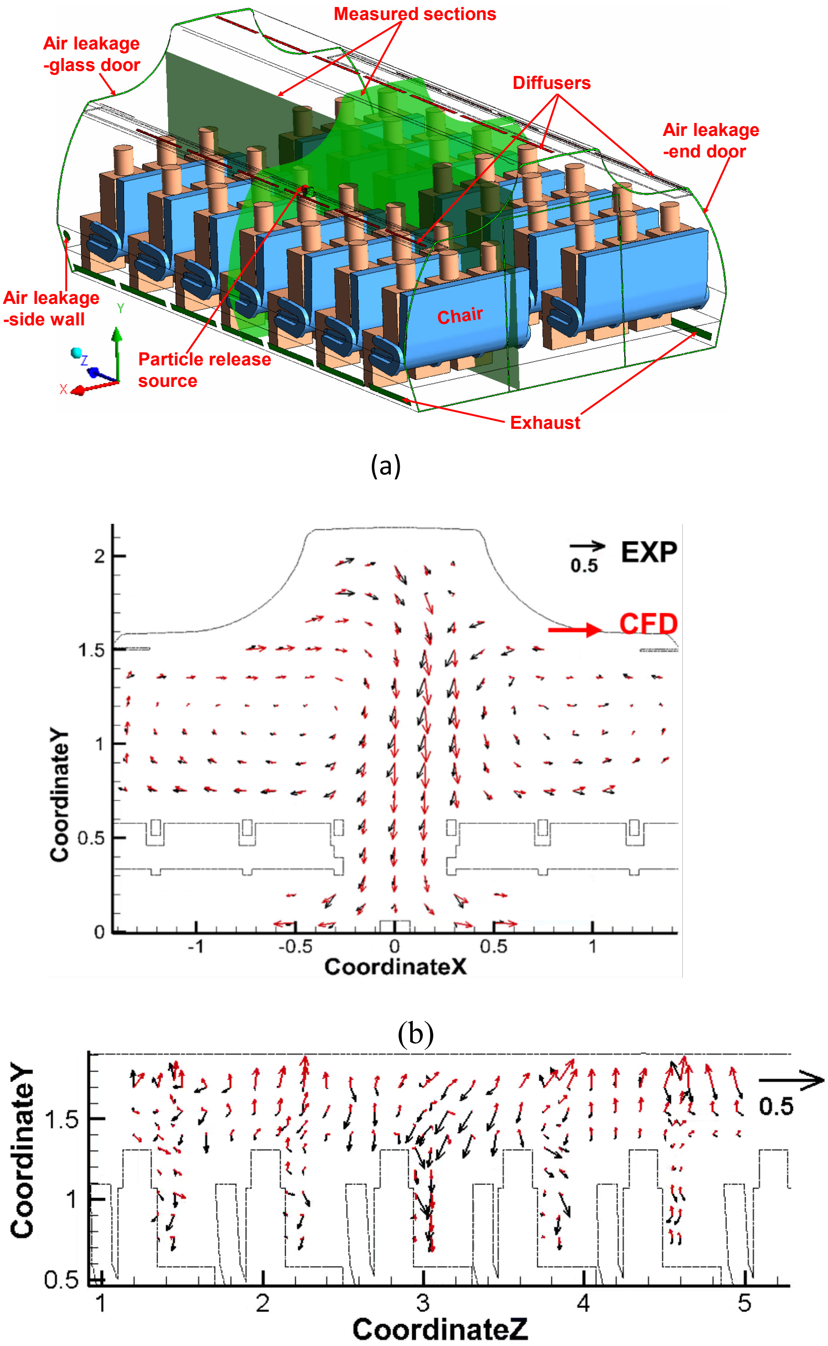
(b)

(c)

Figure 1. (a) Sketch of environmental control system for an aircraft cabin, (b) air distribution at a cross section in a single-aisle cabin, and (c) air distribution at a cross section in a twin-aisle cabin

Research methods for air distributions

Since actual measurements of in-flight air distribution are difficult, the studies of cabin air distribution in airliner cabins in the past two decades can be classified as experimental measurements on the ground using airplanes or cabin mock-ups, and computer simulations. Liu et al. (2012) and Liu and Chen (2013) provided overviews of the research methods. Experimental methods have included scale models, simplified models, full-scale mock-ups, and actual air cabins. Although the experimental measurements are expensive and time consuming, the experimental data have been reliable. The data can be used for validating the simulation results obtained by computational fluid dynamics (CFD) techniques. These overviews also discussed the performance of large-eddy simulations (LES) and Reynolds-averaged Navier-Stokes equation (RANS) modeling. Liu and Chen (2013) found that CFD simulations were mainstream approaches for studying air distributions. For design purposes, they recommended Inverse modeling methods. The review by Liu et al. (2012) concluded that it is necessary to use a full-scale test rig to obtain reliable, high-quality experimental data, and that hybrid CFD models should be used for simulating air distributions in airliner cabins. Figure 2 depicts the airflow distribution in a single-aisle airliner cabin mock-up with seven rows of seats, from a study by Cao et al. (2022). The investigation compared the airflow simulated by CFD with experimental data measured by ultrasonic anemometers.



(a)

(b)

(c)

Figure 2. Air velocity distribution in a single-aisle cabin mock-up with seven rows of seats: (a) schematic of the cabin, (b) comparison of the velocity field predicted by CFD with the corresponding experimental data on a

cross section, and (c) comparison of the velocity field predicted by CFD with the corresponding experimental data on a longitudinal section.

Experimental measurements of air distributions

Liu et al. (2012) used an MD-82 aircraft to measure air distribution with ultrasonic anemometers. They obtained high-quality data for validating CFD models. They also found that the flow fields were of low speed and high turbulence intensity and that the flow in the cross section was asymmetric. Meanwhile, experimental measurements in a single-aisle cabin mock-up by Wang et al. (2021) with ultrasonic and hot-sphere anemometers showed airflow and temperature distributions on a cross section to be symmetric. Their measurements detected longitudinal airflows. The measurement technique with these point anemometers was very time consuming, and the measuring resolutions were low. Huang et al. (2015) compared a grid method and a gradient-based method for determining sampling locations and for interpolation of the data to form field distributions. They recommended the gradient-based sampling method to increase the accuracy while minimizing the number of measuring points. To overcome the low resolution of point measurement methods, Mo et al. (2003) used a particle image velocimetry (PIV) system to measure airflow in a cabin mock-up where each measuring area was 0.61 m x 0.61 m. However, if seats or other furniture in the cabin block the laser lights used in the PIV system, the area cannot be measured. The airliner cabin is a very large space, and Li et al. (2015) developed a PIV splicing method that divided a large section into several subsections, thus obtaining continuous flow fields for the large section. With an overlap of 0.1 m between subsections, the measured results were seamlessly linked. Bosbach et al. (2009) combined helium-filled soap bubbles as tracer particles with high-power quality-switched solid state lasers as light sources. The technique allowed PIV to be conducted on scales of several square meters, which was rare according to our literature search. Kühn et al. (2009) used the method to investigate forced and mixed convection in a full-scale passenger aircraft cabin mock-up that represented a cross section of the A380 upper deck. They found that the flow in the aircraft cabin was affected by supply-air jets, negative buoyancy, thermal plumes, etc. Meanwhile, Sun et al. (2005) and Zhang et al. (2005) developed a volumetric particle streak velocimetry (VPSV) method to measure air velocity in a cabin mock-up. The method is non-intrusive, full-scale, three-dimensional, and instantaneous. The only drawback is the need to shine a light on the measurement region; thus, the approach has a very similar disadvantage to that of PIV. There are pros and cons to using the PIV technique. Overall, when the technique is used together with point anemometers, measurements of airflow in airliner cabins can be accomplished with high accuracy.

The PIV technique is most suitable for local flows with easy access by laser lights. For example, by using a cabin mock-up and PIV, Li et al. (2017) found that the thermal plumes from manikins used to simulate passengers were greatly influenced by the cabin geometry. Their study illustrated the complexity of airflow patterns in the cabin. Another group of researchers (Li et al. 2017a) used a cabin mock-up to analyse flow in jet and collision zones. They found very interesting oscillations of large-scale circulation. Although not very popular, the scaled water model has also been used to study global flow in a cabin (Poussou et al. 2010). It was hard to simulate the buoyancy effect, but their measurements were able to detect the downwash flow of a moving body and to observe that a contaminant originating from the moving body could be convected to higher locations. Note that the flow and contaminant transport obtained using the small-scale water model may not be the same as that in a full-scale air cabin because it is difficult to achieve flow similarity (Mazumdar et al. 2011).

Numerical simulations of air distributions

In addition to experimental measurements, numerical simulations of airflow in airliner cabins by CFD are popular. Liu et al. (2013) evaluated the performance of three categories of turbulence models for cabins: the RNG k-ε model, LES, and detached eddy simulation (DES). They concluded that DES yielded acceptable flow fields. LES performed the best, and the results agreed well with the experimental data. This confirmed the earlier investigation by Lin et al. (2005), who compared the Reynolds averaged Navier-Stokes equation (RANS) simulation with LES for airflow in a section of a Boeing 767 cabin. Although LES performed very well when compared with the PIV data (Lin et al. 2006), the computing time for LES was very long. Thus, one faces a dilemma in selecting a suitable CFD model with acceptable computing accuracy and effort. RANS modelling is the most economical, but its accuracy is unsatisfactory. To fix the low-accuracy problem associated with the standard k-ε model, Zhao et al. (2020) made ad hoc modifications to the coefficients in the dissipative equation to achieve closer agreement with the experimental data. These modifications were not based on the principle of solid fluid flow, so the model's performance was case dependent. Meanwhile, several studies have focused on improvements to the turbulence model with theoretical support. For example, Bosbach et al. (2006) tested high- and low-Reynolds number and two-layer RANS models for cabin airflow. They concluded that low-Reynolds number RANS models should be used. In another paper, Günther et al. (2006) confirmed that higher-order, low-Reynolds number models performed well in predicting complex 3D-cabin airflow with separation. The choice of model had a significant impact on the prediction of air distribution, but the use of different CFD programs had only a minor influence. For example, Zou et al. (2018) used STAR-CCM+ and ANSYS Fluent to simulate air distribution in a cabin with the same mesh and boundary conditions and compared the simulated results with each other and with experimental data. The two software programs had the same accuracy, although the wall treatments were different.

Mazumdar et al. (2011) successfully used the re-normalization group (RNG) k-ε model to predict the impact of a moving body on airflow in a cabin. Such a transient result is difficult to obtain experimentally. The numerical modelling was appropriate. Transient simulations may include the interactions between the environmental control systems (ECS) and air distributions in cabins. Yin et al. (2016) developed a model for ECS operation on the ground and in flight in ANSYS Simplorer. The thermal environment in an airplane cabin was simulated by ANSYS Fluent. Coupling of Simplorer and Fluent has made it possible to simulate transient control of the ECS and the cabin air environment.

Our review of air distribution investigations did not find any meaningful inflight measurements, because those measurements were only conducted at very few locations that cannot reveal the spatial difference in a cabin. Airflow in a cabin can be very complex due to the temporal and spatial evolution process of large-scale flow structures with swing motion around the aisle region and large-scale vortices (Yang et al. 2017). Most of the measurements were conducted on the ground in an actual airplane, a section of cabin fuselage, a section of cabin mock-up, or a small-scale water model. The measurements on the ground should be acceptable if the data was used to validate computer models and the validated computer models were used to simulate actual flight conditions by considering different air pressure. The instruments used for the measurements can be point anemometers or laser-based field velocimetry. CFD models can be various RANS turbulence models, LES, or DES. CFD can predict airflow distributions reasonably well in a cabin, but significant discrepancies exist in some regions, as shown in Figure 2.

The best approach for measuring airflow in a cabin should use combined technologies. For example, PIV should be used for the regions where laser light can reach, while point sensors, such as ultrasonic anemometers, should be used in the regions without laser light. For numerical simulation of cabin air distribution, CFD is most popular. Although LES and DES can provide more accurate and informative results than RANS models, RANS modeling is less expensive and faster. Among different RANS models, their performance is case dependent.

2.2 Airborne infectious disease transmission in cabins

As illustrated by Figures 1 and 2, air in both single- and twin-aisle cabins in a cross section is well mixed. The design of the cabins was intended to provide better thermal comfort, but it may facilitate the transmission of airborne infectious diseases. Figure 3 shows that droplets generated by a passenger can be transmitted to the entire cross section and several rows before and after an index patient in a cabin (Cao et al. 2022 and Wang et al. 2022).

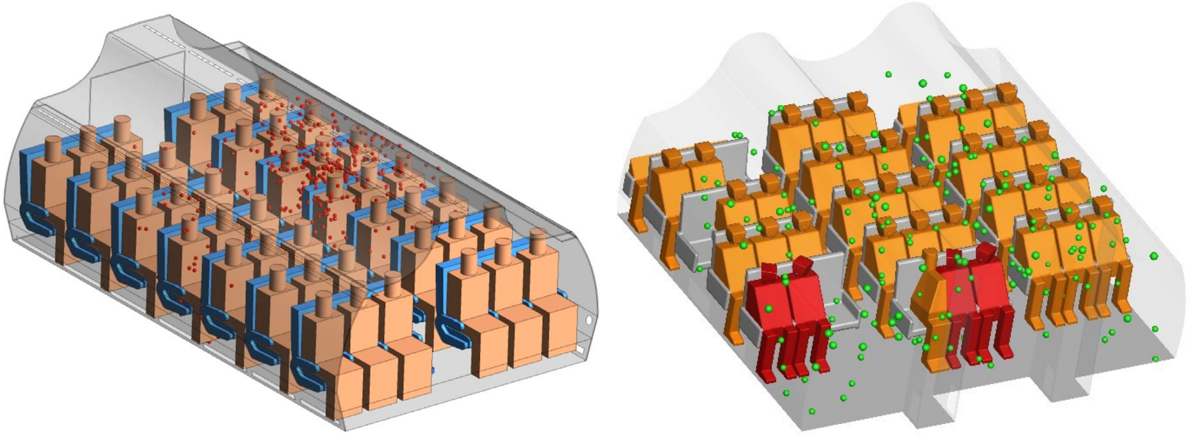


Figure 3. Distributions of droplet nuclei from a coughing passenger (a) in a single-aisle cabin and (b) in a twin-aisle cabin.

Different routes of infection

According to simulation results reported by Lei et al. (2018), airborne, close contact, and fomite routes accounted for 21% (95% CI: 19%-23%), 29% (95% CI: 27%-31%), and 50% (95% CI: 48%-53%), respectively, of SARS CoV transmission in cabins. The researchers determined that passengers sitting within two rows of an index patient had a significantly higher infection risk. Jayaweera et al. (2020) reviewed a large number of transmission cases in healthcare facilities. They concluded that nosocomial transmission by airborne SARS-CoV-2 virus-laden aerosols was plausible. However, some others, such as Schwartz et al. (2020), have asserted that the lack of secondary cases after prolonged air travel exposure supports droplet transmission, not airborne transmission, as the likely route of spread for COVID-19. A total of 239 scientists from 32 countries (among them, co-author Chen) appealed to the medical community and to the relevant national and international bodies to recognize the potential for airborne spread of COVID-19 (Morawska and Milton 2020). Now, the Centers for Disease Control and Prevention (CDC 2021) in the United States has stated that “COVID-19 is spread in three main ways:

- Breathing in air when close to an infected person who is exhaling small droplets and particles that contain the virus.
- Having these small droplets and particles that contain virus land on the eyes, nose, or mouth, especially through splashes and sprays like a cough or sneeze.

- Touching eyes, nose, or mouth with hands that have the virus on them.”

The first bullet point indicates airborne transmission. The World Health Organization (WHO 2021) has given similar reasons for COVID-10 spread.

Non-uniform distribution of infection

Mahmoud et al. (2019) showed that the airflow pattern plays a major role in gaseous contaminant concentration level. The concentration level at some seats may be higher than at the source seat. Although the airflow in a cross section of a cabin may be well mixed, Yan et al. (2017) found that particles from a coughing passenger at a window seat travel much further than at other seats. However, Khatib et al. (2020) found that proximity to an index patient was more important than seat type or location. Gupta et al. (2012) studied influenza transmission in an airliner cabin by using deterministic and probabilistic approaches to quantify the risks based on the number of inhaled influenza virus RNA particles and quanta, respectively. They found that influenza can be easily spread in the cabin.

Influencing factors on infection

In regard to air distribution in existing airplanes, Yan et al. (2020) found that the jet generated by a passenger’s cough could break up thermal plumes formed by passengers and induce local air recirculation. A contaminant could stay in the breathing zone for a long time, thus increasing the infection risk. Kotb and Khalil (2021) simulated cough droplets from an infected moving passenger and found that the droplets could spread to a distance of more than 4 m (about 4 rows away) along the cabin and affect many passengers. The average infection risks for seated passengers were 0.2015 for no human movement, and 0.2051 and 0.2096 for moving speeds of 0.5 m/s and 1.0 m/s, respectively, according to a study by Han et al. (2014). Their results indicate that passenger movement may increase the average infection risk in the cabin, especially for the passengers seated three rows in front of and one row behind the index patient.

Evidence of infection in airliner cabins

Yang et al. (2020) studied several flights with COVID-19 cases in the early days of the pandemic. They concluded that there was potential COVID-19 transmission in airplane cabins. Toyokawa et al. (2020) studied passengers and flight attendants exposed to COVID-19 during a flight on March 23, 2020. By using whole-genome sequencing of SARS-CoV-2 to identify the infectious linkage, they found a secondary attack rate of 9.7%. They asserted that the lack of face-mask usage in the airplane was a risk factor for contracting COVID-19. Very similarly, Choi et al. (2020) studied four individuals with COVID-19 infection from a flight from Boston to Hong Kong. They discovered identical and unique virus genetic sequences that belonged to a clade not previously identified in Hong Kong. Therefore, the results of the study strongly suggested that the virus was transmitted during air travel. Khanh et al. (2020) studied a flight from London to Hanoi in March 2020 and found an attack rate of 62% for passengers seated in business class along with the only symptomatic person. They did not find evidence supporting alternative transmission scenarios. Hoehl et al. (2020) discovered two likely instances of SARS-CoV-2 transmission on an international flight with seven index cases. Although the transmissions may have occurred before or after the flight, the two passengers were seated within two rows of an index patient.

On the other hand, a study by Boeing (Pang et al. 2021) found a very low risk of COVID-19 transmission during air travel (1 in 1.7 million). Harries et al. (2021) also reported that SARS-CoV-2 transmissions on airliner cabins were limited. Nevertheless, they still recommended that masks be worn in cabins. Khatib et al. (2020) stated that the use of face masks had significantly reduced onboard transmission. Hostman and Rahai (2021) used a COVID-19 case in which four index patients had infected two others as an example. They found that mask wearing could dramatically reduce the risk of airborne infection. Similarly, Wu et al. (2021) suggested that using even low-effectivity masks on airplane would reduce SARS-CoV-2 spread by 11%. The use of high-effectivity masks, such as N95 masks, would significantly reduce the spread of airborne infectious disease (Gupta et al. 2012). Nir-Paz et al. (2020) studied a 13.5-hour flight during which all passengers wore surgical masks, removing them only for eating and drinking. The tests on the passengers found no SARS-CoV-2 transmission, even though there were two index patients on board. Recently, Wang et al. (2022) studied two transmission cases on flights. They simulated the dispersion of droplets of different sizes generated by coughing, talking, and breathing activities by an infected person in the business-class cabin during a flight from London to Hanoi (Khanh et al. 2020). The results show that the index patient can infect 12 fellow passengers, and the researchers' method correctly predicted 84% of the infected/uninfected cases. On the second flight, only one passenger was confirmed to have been infected by four index patients around the infected passenger. The passenger did not wear his/her mask for a period of one hour. Wearing mask is very important in airplane cabins where social distancing is difficult. Deng and Chen (2022) found that wearing surgical masks can reduce the necessary social distance from 2 m to 0.5 m.

The literature has documented airborne transmissions of SARS-CoV-2 in airliner cabins, although airplane manufacturers seemed to downplay the significance. The spread was probably caused by the mixing ventilation used in current air cabins. However, the spread seems limited to the proximity of an index patient since the environmental control systems try to minimize the longitudinal flow. Thus, the above review demonstrates that the current cabin air environment does little to prevent airborne infectious disease transmission among passengers and crew members. In some cases, the environment would even enhance transmission. Very few instances of SARS-CoV-2 transmission in airplanes have been reported, probably due to the wearing of masks by passengers and crew members. The studies on SARS-CoV-2 transmissions in air cabins are very few. It is important to conduct more controlled studies in the future.

2.3 Cabin air quality

Health symptoms related to cabin air quality

According to a review by Zubair et al. (2014), crew members and passengers report dizziness, fatigue, headaches, sinus and ear problems, dry eyes, and sore throats during and after travel, in addition to persistent concerns about infectious diseases such as influenza, tuberculosis, and measles. Lindgren et al. (2000) reported complaints about the work environment. Air crew experienced more frequent drafts, stuffy air, dry air, static electricity, noise, inadequate illumination, and dust than office workers. This finding was confirmed by a report on self-assessed occupational health and working environment (Sveinsdóttir et al. 2007), which found that cabin crew had worse gastrointestinal, sound-perception, and common cold symptoms than nurses and teachers. In general, such symptoms can be attributed to inorganic chemicals (CO_2, CO, O_3, particular matters (PM), etc.) and organic chemicals (VOCs, SVOCs, microbial volatile organic compounds, etc.).

Weisel et al. (2017) affirmed that some specific classes of chemicals present in aircraft cabins could contribute to the complaints reported by passengers. The complaints included not only negative perceptions of air quality but also persistent symptoms. However, those symptoms were not of a magnitude requiring medical intervention and did not lead to persistent health effects. Some have suspected that VOC, SVOC and tricresyl phosphate concentrations from bleed air have an adverse health impact. Schuchardt et al. (2019) studied air quality data from 177 flights, including B-787 flights. They concluded that "smell events" classified as oil leakage with odor perception were false positives, and that VOC and tricresyl phosphate concentrations presented no threat to human health.

Chemicals in cabin air

Giaconia et al. (2013) found that the concentration of CO_2 on 14 short-haul (flying time less than 1.5 h) domestic flights in Italy can reach 2000 ppm in aircraft cabins. MacGregor et al. (2008) measured concentrations of CO, CO_2, $PM_{2.5}$, O_3, VOCs, and semi-volatile organic compounds (SVOCs) during boarding, takeoff, cruise, and descent. They did not find significant problems when compared with the existing standards. Very similarly, Yu et al. (2021) conducted measurements during four flights and found that the CO_2 concentration was 1440 ± 111 ppm, CO concentration was 1.2 ppm, and relative humidity ranged from 13.8% to 67.0% with an average of 31.7%. Cao et al. (2017) found that the PM_{10} concentration could be 40 $\mu g/m^3$ in the cabin when the aircraft was on ground, and below 20 $\mu g/m^3$ when the aircraft was in the air. The higher value was due to heavy outdoor air pollution at the two airports in the study. Results from Yu et al. (2021) were similar, and they observed that older aircraft had higher PM concentrations. According to tests on 26 Chinese domestic flights and 20 international flights (Chen et al. 2019), the maximum concentration of ozone in the cabin was less than 20 ppb, and the average O_3 concentration less than 10 ppb. The O_3 level was significantly lower than the limit specified in the relevant airworthiness standard (100 ppb). However, ozone byproducts such as nonanal were still at relatively high levels (averaging 11 $\mu g/m^3$), and their effect on passengers' perception must not be ignored. Bekö et al. (2015) concluded that exposure to ozone during a flight may lead to discomfort and associated symptoms related to the eyes and upper respiratory system. They measured ozone concentrations on 83 US domestic and international flights at cruising altitude and found that the average concentrations were relatively low (median: 9.5 ppb). Bagshaw and Illig (2019) found that passengers and crew members were the primary sources of microorganisms in aircraft cabins and were also the reservoirs of infectious agents on aircraft.

Chemical reactions in cabin air

Tamás et al. (2006) used a simulated aircraft to study ozone removal in cabins and found that 60% of the ozone was removed by passengers. Respiration accounts for only about 4% of the removal. The rest was removed by the aircraft seats, HEPA filter, and other surfaces. It was very interesting to learn that a T-shirt worn overnight by a person can remove 70% ozone around the person, indicating the importance of skin oils in ozone removal. Rai et al. (2013) found that ultrafine particles could be generated by ozone reactions with a soiled T-shirt. These reactions were identified as another potential source of ultrafine particles indoors. Coleman et al. (2008) discovered that ozone reactions with surfaces can substantially reduce the ozone concentration in cabins, but also that the reactions generate volatile by-products that may negatively affect the health and comfort of passengers and crew.

Comparison of cabin air quality with air quality in buildings

An earlier review by Nagda and Rector (2003) demonstrated that chemical contaminant levels in aircraft cabins were similar to those in residential and office buildings, except for the levels of ethanol, acetone, chlorinated hydrocarbons, and fuel-related contaminants. Rosenberger et al. (2016) attempted to measure airborne aldehydes in aircraft but did not find noticeable levels. Guan et al. (2014) detected an average of 59 VOCs (median value) on each flight, with a total of 346 VOCs on 107 flights, but none of the VOC levels was particularly alarming health-wise. Chen et al. (2019) measured VOC in 46 flights and found that the median concentrations of VOCs on Chinese domestic flights were mainly in the range of 0–20 μg/m^3, higher than those on international flights (0–10 μg/m^3), similar to those in Chinese residences, and far lower than the limit set in the available aviation standards. They also found that the overall VOC concentrations in single-aisle aircraft were slightly higher than those in twin-aisle aircraft; the fluctuation range of VOC concentrations in business class was small. The concentrations of VOCs are lower during the cruising phase than in other phases. The influences of dynamic and intermittent VOC sources such as meal/drink services on short-haul flights cannot be ignored. Yin et al. (2022) compared VOC levels from 251 occupied residences to those from 56 commercial flights. Their calculations indicated that cancer/non-cancer risks to crew members and passengers due to VOCs were below the assessment criteria. Meanwhile, according to measurements by Fu et al. (2013), the concentration of microbial volatile organic compounds in cabin air was 3192 ng/m^3, which was 3.7 times higher than that in homes ($p < 0.001$), and 2-methyl-1-butanol and 3-methyl-1-butanol concentrations were 15–17 times higher than in homes ($p < 0.001$). The researchers concluded that textile seats were much more contaminated by pet allergens and fungal DNA than leather seats.

Multiple articles reported health-related issues by passengers and crew members. Crew members experienced more health symptoms than other workers. Several studies attempted to link the symptoms to chemicals in air cabins. Many chemical data obtained from cabins were available and their reactions in cabins were also studied. The data was within the thresholds of standards and regulations and was comparable with that in buildings. Thus, more studies are needed to identify the causes of the health symptoms.

2.4 Thermal comfort in cabins

As mentioned in the previous section, the environmental control systems of airliners supply air to cabins to create a well-mixed condition in a cross section and to minimize airflow in the longitudinal direction. Figure 4 shows the air temperature distributions computed by CFD in a cross section and a longitudinal section (see section locations in Figure 2). The air temperature distributions were fairly uniform, although thermal plumes were generated by the heated manikins that were used to simulate passengers. In the longitudinal direction, the amount of air supplied to and returned from each row was the same, and the thermal load in each row was also the same. One would expect uniform air temperature as well. The mixing air distribution system should also generate a uniform distribution of relative humidity. However, as shown in Figure 2, the air velocity was not uniform. In some seats, passengers might experience a draft. In addition, the surface temperatures of the walls, ceiling, and floor of the cabin during cruising were different from the temperatures of the air and passenger clothing. Therefore, radiant temperature asymmetry exists in airliner cabins.

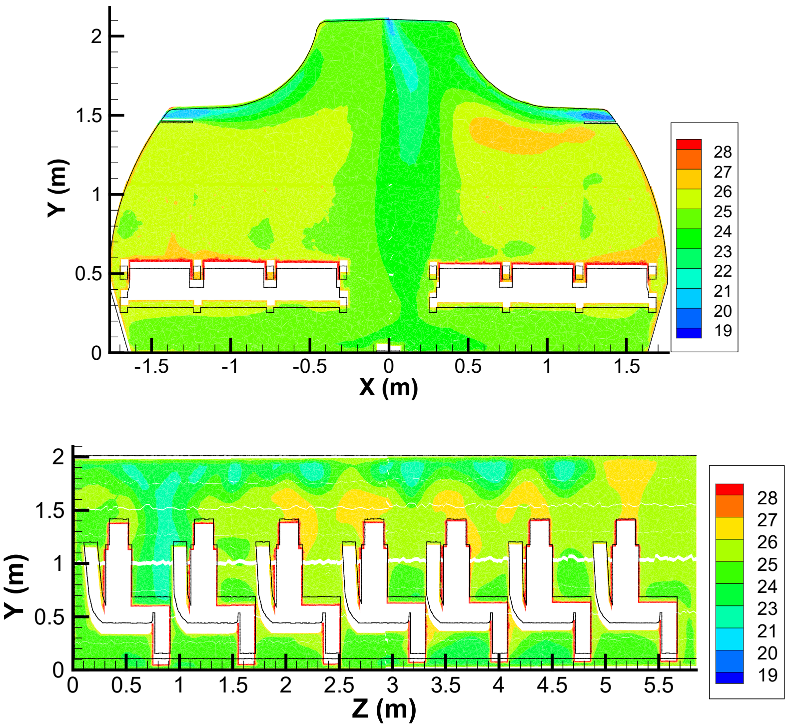


Figure 4. Air temperature distributions in a single-aisle cabin mock-up with seven rows of seats (a) in a cross section and (b) in a longitudinal section.

Air temperature and relative humidity in airliner cabins

Chen et al. (2019) measured air temperature in 46 flights and found that the air temperature during the flights ranged from 21 to 30°C. Higher cabin temperatures were usually found on Chinese domestic flights, and lower temperatures on international flights. Apparently, the flight crew did not set a comfortable temperature for some of the flights. The relative humidity on international flights was maintained at a relatively low level (10–25%), except for the first two hours of the flights. The average relative humidity on domestic flights was slightly higher (averaging 28%). More than 90% of the passengers reported that the cabin air quality and thermal environment were acceptable, while the most frequent complaints according to subjective perception were odor (more than 50% of passengers perceived an intensity above “slight”), irritation (more than 25% of passengers perceived an intensity above "slight"), and dryness (more than 25% of passengers perceived the cabin air as “very dry”). According to experimental measurements during 14 short-haul domestic flights in Italy by Giaconia et al. (2013), relative humidity ranged from 17.9% to 27.0%, which was similar to the observation in the study by Chen et al. (2019). Earlier, Cui et al. (2014) studied thermal comfort in 14 Boeing-737 airplanes from seven airlines and found that air temperature was between 24 and 29°C, relative humidity between 5% and 30 %, and air velocity under 0.2 m/s. They also found a 1.4 K difference between air temperature and black globe temperature, which indicates a difference between air temperature and radiant temperature. The air temperature at head level was higher than that at foot level by less than 2 K. Cui et al. concluded that the passengers were thermally satisfied, and no difference was found between fore and aft. However, in another study by the same team (Cui et al. 2014a) on 10 aircraft in China, they found that the spatial distribution in the cabins was uniform, with a higher average temperature of 26.2°C in the middle section. About 30% of passengers complained of being too warm. A numerical simulation by Desai et al. (2021) also found different comfort levels in different sections, especially during long-haul intercontinental flights such as those on Airbus-380 and Boeing-747 aircraft. Winzen and Marggraf-Micheel (2013) studied thermal comfort at two different air temperatures (21.5°C and 23.0°C) and found that people prefer warmer conditions. The study sought to identify the lower temperature boundary for thermal comfort.

Thermal comfort model for airliner cabins

Pang et al. (2018) studied thermal comfort on 30 flights in China and found that a neutral cabin temperature can satisfy 90% of passengers. The neutral cabin temperature is a function of outdoor effective temperature (ET*) and was determined by a corrected predicted mean vote (Pang et al. 2013). After measuring and controlling the cabin equivalent temperature, Curran et al. (2010) recommended using equivalent temperature to control thermal comfort in cabins, although the equivalent temperature is not the same as the neutral cabin temperature. However, thermal comfort is not a uniform sensation for a given passenger. According to Park et al. (2011), passengers usually find that the upper part of the body is too warm while the lower part is too cold. The predicted mean vote (PMV) from Fanger (1970) can predict the overall thermal sensation in a cabin relatively well. The percentage dissatisfied due to draft (PD) was higher than the predicted percentage dissatisfied (PPD) for the whole-body thermal comfort that was determined from the PMV. Maier and Marggraf-Micheel (2015) developed a statistical model for thermal comfort in cabins. The results indicated that subjective ratings explained more variance than did objective measurements. Among thermal comfort parameters, air temperature was the most important, but relative humidity and air velocity were also significant to comfort. This was confirmed by an investigation by Jia et al. (2018) that compared different air parameters.

Relative humidity and health symptoms

Relative humidity is important not only to thermal comfort but also to health. An overview by Wolkoff (2018) revealed that complaints of sensory irritation in eyes and upper airways were generally among the top two symptoms in office environments, together with the perception of “dry air”. Lindgren and Norbäck (2005) found that the most common symptoms among airline crew were fatigue (21%), nasal symptoms (15%), eye irritation (11%), dry or flushed facial skin (12%), and dry/itchy skin on hands (12%). The most common complaint was dry air (53%). Tesón et al. (2013) exposed 16 tears inflammatory mediators of dry eye patients to an environment of 23°C, 5% relative humidity, localized air flow, and 750 millibars of barometric pressure. Compared to the control group, the dry eye patients became more symptomatic, suffering a significant ($P \leqslant 0.05$) decrease in tear stability and volume. In contrast, Grün et al. (2012) were not able to establish a relationship between perceived symptoms and dryness or between subjective assessment of dryness and low relative humidity. However, more studies have pointed in the other direction. For example, Lindgren et al. (2007) used a humidifier in a Boeing 767 cabin during eight intercontinental flights. They found that the cabin air quality was perceived to be better with the air humidification, and they did not observe an increase in microorganisms in the cabin air. Nagda and Hodgson (2001) demonstrated experimentally that a modest increase in relative humidity seemed to alleviate a great number of symptoms. They suspected that some symptoms experienced by flight attendants and passengers stem from low humidity on flights lasting three hours or longer.

Air temperature in air cabins was not controlled with thermal comfort standard. The variation can be 10 K. Existing PMV model can be used for predicting and controlling thermal comfort in air cabins, although there were other alternatives developed recently. Relative humidity in air cabins was usually very low, especially in inter-continental long-haul flights. Many health related symptoms seem to be related to relative humidity. Humidification technology is being applied to some of the airplanes.

3. Efforts to Improve the Cabin Air Environment

According to the above review of the state of the art in the airliner cabin air environment, the environmental control systems in airliner cabins are effective in maintaining a reasonable thermal comfort level. However, the rate of dissatisfaction with thermal comfort remains high (Park et al. 2011, Cui et al. 2014 and 2014a). The systems also seem to provide adequate amount of outside air to maintain reasonable air quality. Although the measured chemical levels seem to be acceptable, passengers and crew members experience symptoms that cannot be explained. In particular, the relative humidity in cabins is low, which may cause some health-related issues. The environmental control system cannot provide adequate protection to passengers and crew members from airborne infectious diseases such as COVID-19. The low infection rate in airplane cabins seems to be attributable to mask wearing by passengers and crew. Since these problems are not new, what has the research community done to improve the cabin air environment in the last two decades? This section provides a critical review of their efforts.

3.1 Using gaspers to improve thermal comfort and air quality

In commercial airplanes, a system of gaspers, which are small, circular, and adjustable vents above the seats, provides personalized ventilation for the thermal comfort of each passenger. Although the gasper system has been used for decades, very few assessments of its performance were conducted before 2000.

Using gaspers to improve thermal comfort

Cui et al. (2017) investigated gasper systems in 10 commercial airliners with the use of questionnaires. They found that about two thirds of the passengers used gaspers to increase their comfort. Du et al. (2017) tested gaspers in a cabin mock-up and found that to maintain a good thermal sensation and air movement sensation, the flow rate and air temperature through gaspers should be 0–0.86 L/s at 24°C, 0.12–1.09 L/s at 26°C, and 0.26–1.30 L/s at 28°C. In a study of passengers' use of gaspers to improve thermal sensation, Fang et al. (2019) observed that half of the passengers chose to cool their upper bodies, and very few directed air flows toward their heads. Wu et al. (2017) found that subjects were very sensitive to the thermal environment in the aircraft cabin, and a higher draft rate at the face occurred under some conditions. They developed a new model to calculate draft rate.

Using gaspers to improve air quality

Since a gasper system supplies clean air to passengers, some researchers have studied the impact of gasper flow on cabin air quality. Lin et al. (2016) measured air quality in an MD-82 aircraft cabin with gaspers on. They found that the gasper flow had a substantial impact on contaminant transport in the cabin, but turning on the gaspers may not improve air quality. If a patient with an airborne infectious disease were present in a cabin, You et al. (2017) determined that the distribution of opened gaspers would influence the infection risk for passengers. However, the total infection rate with gaspers on was similar to that with gaspers off. Li et al. (2018) used PIV to obtain detailed measurements of the flow from a gasper. They observed that only 6% of the air delivered to the breathing zones of passengers was clean air from the gaspers, and the rest was entrained ambient air.

Studies of gasper flow

The airflow from a gasper is complex. Tang et al. (2017) measured gasper flow with a high-frequency hot-wire anemometer and found that the mean velocity, velocity gradient, and energy spectra in the near fields of jet flows depended on nozzle geometry, and beyond the attachment point the flow exhibited self-similarity. On the other hand, it is not easy to predict airflow from a gasper. Studies by Shi et al. (2016) and You et al. (2016) show that the SST k-ω turbulence model could predict gasper-induced jet flows better than the RNG k-ε model. In other regions, the RNG k-ε model was better. Thus, it is necessary to use the two models together for predicting cabin airflow with gaspers on (You et al. 2017). Because the gasper has an extremely small geometry, the prediction would require tens of millions of grid cells. Therefore, You et al. (2016a) proposed an approach to accurately predict airflow from a gasper with a limited number of grid cells in CFD.

A half of passengers would turn on gaspers to improve thermal comfort. Since gasper provides local cooling, corresponding thermal comfort models were developed. However, the air quality at the breathing zone did not improve with gaspers on, because the entrainment from the jet introduced contaminants as well. To accurately study the gasper flow would need specific RANS turbulence model.

3.2 Advanced ventilation systems

Overview of advanced ventilation systems

Elmaghraby et al. (2018) gave an overview of different ventilation strategies developed in the past. This section highlighted some original work on this subject. To prevent SARS-CoV-2 from spreading in air cabins, Mboreha and Kuman (2020) suggested novel personal ventilation for creating a micro-environment for each passenger as well as a novel seat arrangement. In fact, researchers have been making such efforts for a long time. For example, Zhang and Chen (2007) was probably one of the earliest to develop advanced ventilation systems for airliner cabins, including a personalized supply of air from the seatback of the seat in front. Compared with other advanced systems, the personalized ventilation system provided the best air quality without a draft risk. Gao and Niu (2008) proposed a system to deliver clean air directly to the breathing zone. According to their results, the system can prevent inhalation of up to 60% of air pollutants by a passenger. Zítek et al. (2010) proposed a similar personalized ventilation system that supplied and exhausted personal air on the back of the seat ahead. Their conclusions were similar to ours. Melikov et al. (2012) developed a seat headrest-mounted air supply terminal device. They observed a dramatic improvement in inhaled air quality and a decreased risk of airborne disease infection. You et al. (2019) recommended a personalized displacement ventilation system installed on the cabin floor. In comparison with others, their system seems to be the most effective in maintaining cabin thermal comfort and reducing airborne infectious disease transmission in cabins. Mboreha et al. (2021) suggested several personalized ventilation systems and found that they can provide an acceptable thermal environment in aircraft cabins.

Performance of the advanced ventilation systems

When proposing personalized system, Zhang and Chen (2007) also developed an underfloor displacement ventilation system that supplied air at floor level along the aisles. The latter system provided much better air quality than mixing ventilation and was easy to install. Bosbach et al. (2012) were the first to test a displacement ventilation system with air supply from the side walls under flight conditions in an A-320 passenger aircraft cabin. They found that the system provided low air velocity and turbulence. They also tested a hybrid system that used both lower and upper side-wall supplies. Both systems provided acceptable thermal comfort. Recently, Liu et al. (2022) experimentally compared the effectiveness of displacement ventilation and mixing ventilation in removing an airborne virus generated by a passenger in a cabin mock-up. They determined that the risk of COVID-19 infection for passengers under the displacement ventilation without mask wearing was equivalent to that with the traditional mixing system with masks. This result shows the importance of air distribution in virus transmission. However, displacement ventilation may create a draft because low-temperature air is supplied at foot level. To overcome this, Maier et al. (2018) proposed a ceiling-based cabin displacement ventilation system that supplied air at a higher level together with displacement ventilation under the passenger seats. The system reduced energy use and maintained good thermal comfort. Fišer and Jícha (2013) proposed a modified mixing ventilation system that supplied air at shoulder level. A portion of the air was supplied upward and the other downward. They found that the system provided the lowest age of air, compared with other systems they studied. The system was even more effective than underfloor displacement ventilation.

Tools for developing advanced ventilation systems

In order to develop more innovative ventilation systems, Chen et al. (2017) proposed the use of inverse modeling methods based on the CFD technique. These methods set the characteristics of the desired environment, such as PMV, percentage dissatisfied due to draft, and local age of air, as the design objective and inversely determine the air supply inlets and parameters. The researchers have successfully used the methods to design the airflow distribution in an airliner cabin. The inverse modeling methods include the CFD-based genetic algorithm method (Xue et al. 2013), the CFD-based adjoint method (Liu et al. 2015), the CFD-based artificial neural network method (Zhang and You 2014), and the CFD-based proper orthogonal decomposition method (Wei et al. 2016).

Advanced ventilation systems have been developed in the past 20 years. The systems include displacement ventilation systems, under-floor air distribution systems, personalized ventilation systems, and a combination of two of those systems. The studies have shown the advantages of those systems in providing high air quality and may reduce airborne virus level in breathing zone with acceptable draft level. Inverse modelling tool can be used to develop more advanced ventilation systems.

3.3 Air cleaning technologies

Air cleaning is another important technology for improving air quality and reducing airborne infectious disease transmission in airliner cabins. Wang et al. (2007) found that VOCs in cabin air can be removed by means of photocatalytic oxidation (PCO) and that TiO_2 is the most popular photocatalyst; this approach is efficient and cost-effective. However, the reactions produce intermediates that can be more toxic to human health and should be removed or further oxidised to CO_2. Sun et al. studied air purification devices with PCO technology. The devices can decompose ethanol, isoprene, and toluene but can also produce formaldehyde and acetaldehyde. They observed both positive and negative effects when using the PCO units in subjective assessments. The results look very similar to those of an earlier preliminary study by Ginestet et al. (2005), who designed a modular PCO unit with four UV lamps sandwiched between two interchangeable titanium dioxide coated panels. Air cleaning with charcoal is a more mature technology than PCO. Rosenberger (2018) used a charcoal filter in addition to the standard high-efficiency particulate air (HEPA) filter in an Airbus-321 aircraft. He observed a reduction of approximately 30% for SVOCs and VOCs in air. Wu et al. (2019) designed a once-through ozone removal unit. Their results demonstrated a 99% removal rate with a pressure drop of only 1.9 kPa at the reaction temperature of 200°C.

3.4 Prediction of airborne infectious disease transmission

Studies of droplets generated through respiratory activities

The incidence of airborne infectious disease transmission tends to rise and fall over time. Since 2000, we have experienced several major outbreaks, such as SARS in 2003, H1N1A influenza in 2009, and the on-going COVID-19 pandemic. Because of the evidence of SARS and H1N1A influenza transmission in airliner cabins, many studies in the last two decades have sought to understand the transmission mechanism in cabins. The viruses of those diseases were airborne because they were generated by human respiration activities. Chao et al. (2009) conducted a highly accurate investigation on droplets produced by coughing and speaking. According to their measurements, the geometric mean diameter of the droplets expelled during coughing was 13.5 μm, and during speaking the diameter was 16.0 μm. Fabian et al. (2008) measured the droplet size from the breathing of patients with influenza and grouped the droplets into mean diameters of 0.4 μm, 0.75 μm, and 2.5 μm. Wang et al. (2009) found that aerosols with initial sizes under 28 μm in diameter can stay airborne for a long time. Using influenza data as an example, they estimated that the risk of infection through inhalation of the airborne virus was at least two orders of magnitude higher than the risk of infection through contact. Therefore, many investigations focused on airborne aerosols, particles, or droplets.

Droplet deposition in airliner cabins

To et al. (2009) experimentally studied dispersion and deposition of expiratory aerosols in aircraft cabins. Their results indicate that 60–70% of expiratory aerosols by mass were deposited in close proximity to the source, but airborne transmission is possible. A study by Powell et al. (2014) determined that particle deposition on a horizontal surface in a cabin mock-up was 10 times higher than on a vertical surface. Wang et al. (2021) found that the droplets from a cough in a cabin deposited mainly on the seat and seatback of the seat in front. Meanwhile, particle deposition onto surfaces depends on particle size, particle release mode, and the airflow pattern in an airliner cabin, according to Wang et al. (2011). They found that 35% of small (0.7 μm) particles, 55% of medium (10 μm) particles, and 100% of large (100 μm) particles from breathing deposited onto the cabin surfaces, and the rest were removed by the cabin ventilation. The proportions of small, medium, and large deposited particles changed to 48%, 69%, and 100%, respectively, in the case of coughing. You and Zhao (2013) discovered that the passenger occupancy rate in a cabin did not greatly influence the particle deposition rate. There may be concerns that particles deposited on a surface could be resuspended due to airflow, but Zhai et al. (2014) found that resuspension is not an important factor, especially as time elapses.

Transmissions of fine droplets in air cabins

Although large particles can be easily deposited on various surfaces in a cabin, small particles that are not heavy but are very large in number can be airborne. Many viruses, including SARS, H1N1A influenza, and SARS-CoV-2, are smaller than 0.3 µm in diameter. The fine droplets produced by breathing, speaking, coughing, and sneezing can cause people who inhale them to become sick through air transport, even though modern airplanes were designed not to have flow in the longitudinal direction. Beneke et al. (2011) measured a roughly 37% decrease in particle concentration with each successive row in the longitudinal direction from the source in a cabin mock-up. In a cross section with very strong mixing, experimental measurements by Li et al. (2021) in a cabin mock-up found that the particle exposure for the passenger in the window seat was always the lowest, regardless of the particle source location. The researchers also found that particles from a passenger can be transported across at least four rows of seats in the longitudinal direction, which was much farther than the distance of two to three rows stated in earlier literature.

Computer models for studying fine particle transmissions in air cabins

Since experimental studies are expensive and time consuming, many more investigations have used CFD modeling to predict particle dispersion and transportation in airliner cabins. Particle transport can be predicted by the Lagrangian method, which tracks the motion of individual particles, or by the Eulerian method, which treats particles as a continuum in CFD simulations. Chen and Zhang (2005) found that the two methods yielded nearly identical results. Zhang et al. (2009) determined that sub-micron-sized heavy particles behaved like a passive gas contaminant in a cabin mock-up. Li et al. (2014) measured very similar distributions of 3 µm-diameter particles and a tracer gas released in the same location in a first-class cabin. Meanwhile, Zhang et al. (2009) demonstrated that the RNG k–ε model can predict particle transmission in a cabin mock-up with reasonable accuracy. For better accuracy and simulation of transient particle transport, a hybrid DES-Lagrangian and RANS-Eulerian model should be used (Chen et al. 2013). To reduce the computing costs of DES and RANS modeling, Chen et al. (2014) introduced the Markov chain method, which can provide faster-than-real-time information about particle transport in a cabin.

Human respiration activities, such as coughing, talking, breathing and sneezing, can generate many droplets in different sizes with virus. Large particles would deposit to different cabin surfaces due to inertial force and gravity. While fine droplets can remain airborne and be transferred to different parts of air cabin. Since the air cabin has limited longitudinal flow, the virus would still be confined in the proximity of the source. CFD with Lagrangian method was most popular, while other methods were also available to improve accuracy or to reduce computing costs.

4. Discussion

Challenges in simulating cabin air environment

Airflow in an airliner cabin is very complex. The main driving forces for the air motion are jets from the environmental control system and thermal plumes from passengers and crew. The inertial forces from the jets and the buoyancy forces from thermal plumes are comparable. As a result, the flow in the cabin is unstable. Yao et al. (2015) proved theoretically that the topological structure of flow in a cabin is absolutely unstable and is low on anti-jamming. Correct prediction of cabin airflow by CFD is difficult. To simulate the flow in a seven-row cabin that did not have gaspers, Yao et al. (2015) used RANS models with 20 million grid cells. Meanwhile, You et al. (2016) used 1.58 million grid cells to simulate one gasper and took 2 days on a workstation to complete the simulation. If LES or DES were used for a whole air cabin with half of the gaspers on, the number of grid cells needed would be on the order of billions. Thus, simulation of such a flow will remain a challenge for the foreseeable future.

Recommendations on simulating cabin air environment

On the other hand, it may not be necessary to simulate the flow in a whole cabin with many gaspers on. Whether the simulation is conducted for design purposes or for evaluating airborne infectious disease transmission, air quality and thermal comfort, one can study the flow characteristics in a row or two with no more than 100 million grid cells. This is affordable with a computer cluster if LES or DES is employed. If an understanding of global flow in a whole cabin is needed, the cabin can still be divided into several zones, such as the first-class cabin, business-class cabin, economy-class cabin, and service areas. This would require prescribing the flow and thermal conditions between zones. One solution is to use a zonal model to estimate the conditions, as demonstrated by Chao et al. (2014). In addition, not all simulations need to be highly accurate. For example, during the conceptual design of a cabin flow, the designer may only need to know the general flow features. In that case, RANS modeling is appropriate. Even adaptive coarse-grid-generation methods together with fast fluid dynamics (Liu and Chen 2018) may be sufficient.

Studies needed for inter-continental, business-class cabins

Most of the flow studies have focused on single-aisle, economy-class cabins, according to our literature review, since such flights are the most common. Some researchers have investigated single-aisle, first-class cabins. However, very few studies have addressed intercontinental twin-aisle cabins. The most popular twin-aisle airplane was the Boeing 767, which is not a very large airplane and is often used for both domestic and international flights. Considering the long duration of international flights, more studies are needed for large airplanes, such as the Boeing-777 and Airbus-350. Since passengers pay a hefty price for the business-class cabin on inter-continental flights, airplane manufacturers need to demonstrate that they can provide better environmental conditions. Our review did not find any studies on the cockpit or service areas. These spaces are mainly occupied by the flight crew, but some of the spaces have potential contaminant sources, such as the ovens and dry ice used in galley areas. The air quality and thermal comfort in these spaces should be investigated.

Prevention of infectious disease transmissions in future commercial aircraft

Traditional airplane design has not taken airborne infectious disease transmission into account. The past two decades have taught us that such transmission occurs from time to time. The airplane manufacturing industry cannot continue to ignore the issue. During the COVID-19 pandemic, some manufacturers and top airline executives released misleading information. For example, they claimed that because commercial airplanes used HEPA filters, the cabins were very clean. It is true that HEPA filters can filter out the majority of viruses. Unfortunately, our literature review identified infection by means of passenger-to-passenger transfer within a cabin, before the air was filtered by the environmental control system. The CDC (2021) and WHO (2021) asserted that transmission mainly occurred in close proximity to an index patient. The supply of clean air on airplanes is essential. Our literature review did not find evidence that air-conditioning systems can transport SARS-CoV-2 in buildings or airplanes. In addition, the airplane manufacturers and airliner executives claimed that the high air exchange rate in airplanes made the air quality in a cabin is better than that in an office. If it is the number of viruses inhaled that determines whether or not a person becomes sick, the number can be calculated as

Number of viruses inhaled (#) = Inhalation rate (L/s) x Duration of exposure (s) x Virus concentration in air (#/L)

Virus concentration (#/L) = Number of viruses generated by infected individuals (#/s) / Ventilation rate (L/s)

The air exchange rate, which is not in the above two equations, is defined as

Air exchange rate (#/h) = Ventilation rate (L/s) x 3600 (s/h) / Air cabin volume (L)

Thus, the smaller the air cabin volume, the higher the air exchange rate. Since the volume of space occupied by a passenger is much smaller than that occupied by an office worker, the air exchange rate in a cabin should be much higher than that in an office. Instead, the air supply rate to an office for each worker is much higher than that to a cabin for each passenger, and thus the virus concentration in an office is lower than that in a cabin. At present, the low infection rate found on airplanes seems to be attributable to the wearing of masks by passengers and crew members. Studies of transmission in cabins have been very limited, although good tools are available, such as CFD modeling of particle dispersion and transport in cabins and experimental techniques for measuring sources and transmission. To date, investigations of SARS-CoV-2 transmissions in cabins have been inconclusive. Very different views exist in the literature, because it is hard to prove that a given passenger was infected by COVID-19 in a cabin, at an airport, or inside ground transportation during travel.

If SARS-CoV-2 transmission occurs mainly through close contact, social distancing in airliner cabins may not be feasible because it is expensive. The airlines want to be profitable, while passengers are reluctant to pay high ticket prices. Current seat design in airplanes did not account for transmission by contact. Redesign of seats in all cabin classes is possible for airlines. However, the redesign should prioritize safety, especially in the case of evacuation during an emergency landing. Improvements to the seat design would require efforts by structural, mechanical, and ergonomic engineers. Investigations on large, semi-airborne particles with diameters of 10–50 μm should also be pursued under various seat designs and perhaps screen/shield options.

More studies needed on health symptoms and cabin air quality

Our review has shown that cabin crew members experience worse gastrointestinal, sound perception, and common cold symptoms than nurses and teachers. Passengers and crew exhibited numerous health symptoms during air travel. However, the review did not find concrete evidence that the symptoms are linked to chemical exposure in air cabins. Is the low outdoor flow rate of 5 L/s per passenger a problem? The CO_2 concentration in many cabins was well above the 1000 ppm that is specified for buildings. but well below the 5000 ppm set by air-worthiness regulations. Is the high CO_2 level a problem? So far, no one has answered this question with scientific evidence. Guan et al. (2014) found a total of 346 VOCs on 107 flights. Many VOCs and other chemicals have not been measured. The list of chemicals present on flights may not have been exhausted. The PCO technology used to convert VOC-generated secondary products and their toxicity has not been well studied. Studies on the link between exposure to VOCs and other chemicals and health issues require considerable resources as well as research teams with multidisciplinary knowledge. At present, only dryness is an obvious factor in passenger and crew complaints, and some studies have attempted to rule out a link between complaints and health issues. Therefore, it is necessary to continue the efforts to determine whether the health issues and complaints of passengers and crew are linked to cabin air quality.

Impact of cabin pressure on cabin environment

The air pressure in an airliner cabin at cruising height is lower than the atmospheric pressure at sea level. Cui et al. (2017) found that the respiratory flow rate decreased as pressure dropped, while the O_2 consumption and CO_2 production increased. They also observed a significant increase in the respiratory quotient. The widely used model for predicting PMV does not apply to air cabins. In addition, Wu et al. (2017) found that the draft model cannot be employed in air cabins, especially with the use of gaspers. The special thermal environment in airliner cabins poses a unique thermal comfort problem that requires further study and development of suitable comfort and draft models.

Advanced design tools needed to solve problems in air cabins

To completely solve the problems related to airborne disease transmission, air quality, and thermal comfort in airliner cabins, designers of environmental control systems need to think outside the box. Many efforts have focused on personalized ventilation, displacement ventilation, underfloor air distribution, and so on, which are traditionally used in buildings. The airliner cabin is a distinct environment with specialized geometry, high occupant density, low pressure, low relative humidity, use of specific materials for seats and cabin walls, limited outside airflow rate, high outdoor ozone level, and increased thermal load from electronics. In addition, the visual environment, vibration, turbulence, high noise level, jet lag, and other factors make the situation even worse. The available inverse modeling methods (Chen et al. 2017) are interesting, as they can set PMV and local age of air as design objectives. If additional design objectives were included, the computing efforts for most of the methods would increase exponentially. Wearable technologies, artificial intelligence, and big data analytics may be introduced in the design process, although this literature review did not find any research on these subjects for the airliner cabin air environment.

5. Conclusions

This paper presented a comprehensive and critical review of scientific literature published since 2000 on airborne infectious disease transmission, air quality, and thermal comfort in the commercial airliner cabin air environment. More than 150 journal papers from were selected for the review. This investigation led to the following conclusions:

- Air distribution in an airliner cabin is a fundamental parameter governing the cabin air environment. Many studies have sought to understand the air distribution in terms of airflow, air velocity, air temperature, and turbulence. Experimental measurements have used ultrasonic, hot-wire, and hot-sphere anemometers, PIV, and the like. Computer simulations by CFD have been very popular. Most of the CFD simulations were compared with or validated by experimental data. LES and DES yielded more accurate results than RANS modeling but required a much longer computing time.

- Studies on the transmission of airborne infectious diseases, especially SARS-CoV-2, in airliner cabins have been inconclusive because there were too few well-defined cases in which infection was proven to occur in the cabin rather than elsewhere in the travel process. At the same time, it has been difficult to prove that airliner cabins are safe for passengers. The low infection rate observed at the present time may be due to the wearing of masks by passengers and crew members.
- Comprehensive experiments have been conducted to measure the concentrations of inorganic and organic chemical compounds on hundreds of flights with very detailed results. The ozone level was found to be low, and there has been no evidence of contaminated bleed-air. In general, few of the chemicals are considered a threat to health. The review did find numerous papers reporting health-related issues among passengers and crew members during air travel. However, no concrete evidence has been published that would establish a link between the health issues and the detected chemicals.
- The air temperature distribution in airliner cabins was found to be uniform. Air temperature varied greatly, which led to some complaints. Low relative humidity was a major complaint of passengers and crew, but several studies indicated that it was not a problem. Due to low cabin pressure, the thermal comfort models used in buildings may not be suitable for air cabins.
- The use of gaspers can improve thermal comfort, as many passengers have found, but the flow from gaspers cannot improve air quality in the breathing zone due to high entrainment. The development of personalized and displacement ventilation systems for airliner cabins has yielded some promising results in improving air quality and preventing infections. However, none of these ventilation systems has been used in practice. Meanwhile, air cleaning with the use of PCO technology may generate secondary products that could have an adverse impact on health; therefore, more studies are needed.
- Many good experimental and computational tools have been developed to measure and calculate airborne infectious disease transmission in airliner cabins. Large particles are deposited on various surfaces in a cabin, but small particles can be airborne, increasing the risk of transmission.

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Conflict of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Author Contribution

Feng Wang: Literature search and analysis, Paper draft
Ruoyu You and Tengfei Zhang: Conceptualization, Further analysis, and Paper editing
Qingyan Chen: Project administration, Paper structure design, Supervision, Review and final edits.

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