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Ventilation strategies and air quality management in passenger aircraft cabins: A review of experimental approaches and numerical simulations

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The cabins of passenger aircraft experience one of the most complex indoor environments among all other means of mass public transportation. Given the large number of passengers that use these aircraft each day worldwide, suitable ventilation strategies for air quality management must be employed to control the spread of airborne contaminants while ensuring passenger comfort. In the current review article, the different ventilation strategies (existing and proposed) used aboard commercial aircraft, and the common airborne contaminants encountered in cabins are discussed through a critical survey of key studies performed mainly in the last two decades. The research methodologies adopted by these studies, which vary from experimental measurements to numerical simulations, are also analyzed in a systematic manner. Based on the available literature, best practices for aircraft ventilation and air quality research are identified for each research methodology. Current research gaps are also discussed and future research topics are suggested for various research methodologies.

Introduction

Air travel has become one of the main pillars of the present globalized economy. It is estimated that more than 3.6 billon people used air travel as their means of long-range transport in 2015 supporting about 9.9 million job opportunities in the aviation sector alone, with projected further annual increases (Air Transport Action Group 2017). The environment inside a commercial aircraft cabin provides a fertile ground for deterioration of air quality, disease transmission, and infection spreading among passengers if proper measures are not taken. This is attributed to the high occupant density, wide range of passenger activity, and the inability of passengers to leave this closed space for prolonged periods of time (ASHRAE 2013). On the other hand, disease transmission from a passenger or group of passengers to others can also occur off-board of aircraft, either before or after flights. This further complicates the task to assess aircraft cabin initiated infections and air quality issues (Mangili and Gendreau 2005).

In recent years, a wide range of symptoms and transmissible diseases due to poor air quality, inefficient ventilation systems, and improper contaminant control measures have been reported during aircraft flights, and sometimes after them. The symptoms and diseases range from nausea, dizziness, headaches, and fatigue (Haghighat et al. 1999) to highly infectious epidemics such as influenza A (H5N1 & H1N1), severe acute respiratory syndrome (SARS), and tuberculosis. These diseases have been responsible for infecting large numbers of people, either aboard or off-board of aircraft and are the main cause of many mortality cases in the past few years (Aliabadi et al. 2011; Olsen et al. 2003; Tellier 2006, 2009).

Different infectious diseases aboard aircraft have almost identical modes of transmission compared to other closed spaces. Influenza, for example, is known to have three main modes of transmission, namely: airborne, droplet, and contact transmission (ASHRAE 2014; Tellier 2006; Weber and Stilianakis 2008). Among these modes, the airborne route has gained a lot of attention in air quality studies in the last two decades. This is mainly attributed to the very small contaminant fragments and expiratory particles that can remain airborne in the space for extended times and distances, which significantly increases the probability of exposure and/or infection when compared to the other modes (Aliabadi et al. 2011).

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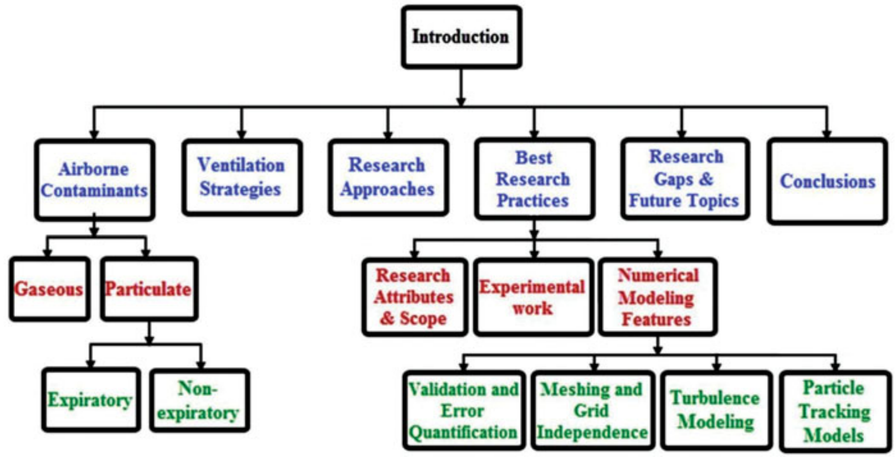

Fig. 1. General outline for the review article.

Many measures for controlling and improving air quality in aircraft cabins have been investigated in the literature. Aboard aircraft, ventilation and air circulation systems are capable of controlling air temperature and velocity, and consequently dispersion, resulting in the best possible indoor air quality. This is to maintain a clean and convenient environment for passengers by decreasing the amount of gaseous and particulate pollutants to under the permitted levels (Liu et al. 2012a). Despite this, infection rates can be accelerated in some cases with the uncontrolled use of heating, ventilation, and air conditioning (HVAC) systems (ASHRAE 2014).

Different research approaches have been used to address air quality in aircraft cabin environments using air distribution systems as a control measure. These approaches range from purely experimental to entirely computational, or combinations of both.

In the present review article, studies concerned with air quality and contaminant management aboard aircraft in the past two decades are investigated. The types of the airborne contaminants studied and the effect of different ventilation techniques adopted in regulating them are among the topics addressed. Additionally, recommendations are provided on the most appropriate approaches for air quality research in aircraft cabins, and future research opportunities are highlighted. Figure 1 depicts the general outline of the current review article.

Airborne contaminants aboard aircraft

The types of airborne contaminants that occupants encounter in aircraft cabins include odors generated from gaseous contaminants, such as galleys and lavatories' effluents, pyrolyzed engine oil and hydraulic fluid, disinsection sprays, and other odorless and volatile organic compounds (VOCs), and particulate contaminants. The particulate pollutants are either generated from human expiratory activities, such as breathing, coughing, and sneezing, or other nonexpiratory sources, such as human skin shedding, dust contamination, and smoking (where permitted). Many studies have investigated the characteristics of particles originated from expiratory human activities and their spread in indoor spaces in the last century (Fairchild and Stampfer 1987; Loudon and Roberts 1967; Nicas et al. 2005; Papineni and Rosenthal 1997; Zhao et al. 2005). Coughing was and still is the most studied source for droplet generation, as it produces large amounts of droplets with elevated discharge velocities (Gupta et al. 2009). In the following subsections, the studies concerned with airborne contaminants in aircraft cabin environments are discussed.

Gaseous contaminants

Studying the behavior of gaseous contaminants in closed spaces, and especially aircraft cabins, started long after the beginning of the research on dispersion of droplet media in air by medical experts in the mid-1930s and 1940s of the last century (Duguid 1946; Wells 1934; Wells and Stone 1934). This is attributed to the relative simplicity of the investigation tools for particle media. However, the lack of adequate technologies to release and measure trace gases caused a 50-year delay in their technology development (Haghighat et al. 1999; Waters et al. 2002).

The concentrations for various gaseous contaminants found aboard commercial aircraft, such as VOCs, nitrogen oxides, carbon monoxide, carbon dioxide (CO_2), aldehydes, ethanol, ozone, and nicotine were measured in cabins during actual flights by Waters et al. (2002).

Disinsection pesticides are also commonly found as a type of gaseous contaminant aboard many commercial aircraft. Although standard 161–2013 issued by the American Society of Heating, Refrigeration and Air Conditioning Engineers (ASHRAE) strongly recommends the application of pesticides on unoccupied aircraft before boarding (ASHRAE 2013), these pesticides are sprayed in the occupied passenger cabins by several airliners in compliance with the regulations of some countries, such as India, Panama, Madagascar, Uruguay, and Zimbabwe (USDOT 2017).

There are few studies in the literature that have investigated the transport of pesticides in aircraft cabins and their effect on the health of both passengers and crew members. One study was conducted by Isukapalli et al. (2013) who researched the dispersion and deposition of disinsection pesticides in an aircraft cabin using computational fluid dynamics (CFD) simulations. Cabin ventilation was investigated as the sole mechanism for pesticide spread and deposition in the cabin with air exchange rate switched from low to high, and vice versa.

Ethanol, ozone, and ozone-initiated chemistry products are among the toxic pollutants that usually exist in aircraft cabin environments. Ethanol is introduced in the cabin by the wet wipes traditionally presented with meals aboard aircraft. Ozone, on the other hand, is a naturally occurring component in the atmosphere, which increases substantially at higher altitudes typical for commercial aircraft cruises (around 10 km [35,000 ft] or more above sea level).

The most cost-effective method suggested in the literature to reduce ozone-initiated compounds in the cabin is the use of a proper ventilation strategy with some specific ratios of outdoor to recirculated air. More outdoor air may result in more ozone entering the cabin, and consequently more compounds developed from its transformations (Wisthaler et al. 2005). Another effective technique is the use of ozone catalytic units and/or air purifiers. Different types of photocatalytic air purifiers were proved helpful for reducing in-cabin ozone and ethanol concentrations significantly (Bhangar et al. 2008; Wisthaler et al. 2007). It is required by the U.S. Federal Aviation Administration (FAA) that an ozone catalytic converter be equipped by any aircraft flying on routes where ozone exposure is expected to be significant (ASHRAE 2013; U.S. Federal Aviation Administration 1980).

Environmental conditions (temperature, pressure, and relative humidity [RH]) inside airliner cabins have also been investigated for their effects on gaseous contaminant concentrations and related symptoms experienced by occupants. In a study by Strøm-Tejsen et al. (2007) performed in a full-scale Boeing 767 aircraft cabin mock-up, the fresh air supply was varied from 1.4 to 9.4 L s^{-1} (0.05 to 0.33 cubic feet per second [CFS]) per person, leading to a change in RH from 28% to 7%, and a reduction in concentration of gaseous contaminants in the cabin.

Particulate contaminants

Expiratory particulates from human activities

The number of studies that investigated the generation and dispersion of particles originated from human expiratory activities in aircraft cabin environments is limited in comparison to the studies performed in rooms and other confined spaces.

Wan et al. (2005) performed an experimental investigation for the dispersion behavior of expiratory droplets released from a droplet generator (mimicking a coughing person) in a Boeing 767 aircraft cabin mock-up. The researchers found that droplet dispersion was suppressed when the injection point was closer to the cabin wall, and when the ventilation air supply rate was increased at lower RH.

A later experimental study was performed by Sze To et al. (2009) using the same cabin setup to investigate the dispersion of cough droplets and their deposition on the cabin surfaces. For this purpose, the particle image velocimetry (PIV) and the interferometric mie imaging (IMI) techniques were utilized. Following this work, a numerical simulation study (Wan et al. 2009) was performed, which added the infection risk associated with the droplets to the studied parameters. The investigated range of initial droplet sizes before evaporation into nuclei for both studies was between 2 and 225 μm.

Using a different approach, J.K. Gupta conducted a series of studies on expiratory droplets release and transport, their inhalation by passengers surrounding the infected person, and assessment of the airborne infection risk associated in aircraft cabins (Gupta et al. 2011a, 2011b, 2012). Three expiratory activities for the infected person were simulated using CFD methods, namely: breathing, coughing, and talking, with uniform droplet sizes of 0.4, 8.5, and 30 μm, respectively.

Numerous medical studies and reviews also investigated the transmission mechanics of some of the most common infectious diseases by expiratory particles and the associated infection risk in aircraft cabin environments (Mangili and Gendreau 2005; Olsen et al. 2003; Wagner et al. 2009).

Nonexpiratory particulates

Contaminant particulates originated from nonexpiratory sources inside aircraft cabin environments have been considered very rarely in the literature. The main sources of nonexpiratory particles in aircraft cabins are smoking, human skin shedding, and dust contamination released from the clothing of the occupants and the furniture. Skin shedding and dust contamination sources inside aircraft cabins have been overlooked in the literature. On the other hand, smoking, aboard some air flights that still permit so, has been considered by few researchers, and the concentrations of the produced nicotine-containing particles and environmental tobacco smoke (ETS) have been measured.

Dechow et al. (1997) measured the particle concentrations using counters set in the first class, the nonsmokers section, and the smokers section of the economy-class aboard Airbus A310 and A340 aircraft. Nicotine-containing particles, released from smoking, showed some elevated concentrations in the smoking section of the cabin, while it remained at very low levels in the nonsmoking sections. The concentrations also exhibited temporal variations depending on the status of the smokers during the flight (awake, awake and smoking, sleeping, etc.). A similar result was reported by Drake and Johnson (1990) when they conducted some measurements for nicotine and respirable particles aboard four different models of Boeing 747 aircraft during flight using mobile measurement devices. They found that all-daytime flights exhibited a greater concentration of ETS than night-time flights. Waters et al. (2002) measured the concentration of respirable particles and smoking-generated nicotine-containing particles aboard six smoking-permitted flights. They found that the average concentration of all particles in the cabin was higher on smoking-permitted flights than nonsmoking flights.

In its most recent standard, ASHRAE necessitates installing high-efficiency particulate arrestance (HEPA) filters on all recirculated air inlets aboard all operating aircraft, and maintaining them according to the best practices specified by the manufacturer. Those filters can remove expiratory and nonexpiratory particles, viruses and bacteria down to 0.3 μm in size with an efficiency up to 99.97% (ASHRAE 2013).

Aircraft ventilation strategies and their effect on air quality and airborne infection aboard

Different ventilation strategies have been investigated as measures to control infection transmitted via airborne route and other gaseous and particulate contaminants commonly found in the aircraft cabin envelop. Basically, the efficiency of each ventilation system is measured based on the ventilation effectiveness it provides. For aircraft cabins, ventilation effectiveness is defined as the portion of the outside fresh air supplied to the cabin that reaches the breathing zone of the occupants (ASHRAE 2013). In the current section, major studies that examined the effect of one or more ventilation system, such as mixing, displacement, and personalized ventilation, on air quality and disease spread aboard aircraft are discussed. Figure 2 shows schematics for the three main aircraft ventilation systems.

Mixing ventilation is the primary technique used to provide a mixture of outside fresh air and recirculated air from the cabin, with different ratios, to the aircraft occupants after being filtered. Air usually enters at specified volumetric rates from supply inlets located above or below the luggage compartment in the cabin depending on the aircraft type. It then circulates through the cabin under the influence of inertial, viscous, and body (such as buoyancy induced by the thermal plumes from the occupants' bodies) forces (Liu et al. 2013) and exits through the exhaust slots (or return) found at the floor level on the two sides of the cabin. Created by this ventilation strategy, the well-mixed environment helps dilute and disperse infectious organisms and contaminants within the cabin (Zhang and Chen 2007; Zhang et al. 2012).

Zhang et al. (2009) noticed that the mixing air motion generated by the environmental control system (ECS) inside a cabin mock-up affected both the released gaseous and particulate pollutants' movement and enhanced their spread. Rydock (2004) found that the proximity of the infecting person(s) to other occupants has more influence on disease spread than partial air recirculation in the diluted cabin scenario created by the well-mixed condition. A novel localized exhaust technique was proposed by Dygert and Dang (2010) to be used in conjunction with mixing ventilation in the cabin. The setup consists of two air suction ports installed in the back of each seat and around the head of a sitting occupant, and was found to provide an average decrease of 40% to 50% in individual exposure risk to airborne infection from surrounding passengers.

Displacement ventilation was proposed and investigated as an alternative air supply strategy to the overall mixing scenario within the aircraft cabin space. Under-aisle and under-floor ventilation systems are usually used as other names for the displacement ventilation system aboard aircraft. In such systems, air is supplied vertically from an under-floor plenum, usually located under the aisles, through perforated or nozzle vents. Supplied cool air heats as it travels up the height of the cabin due to the surrounding thermal loads primarily released from occupants' bodies. The buoyancy effect causes stratification, and the warm air is eventually removed through the exhaust vents located at the ceiling. Meanwhile, the different contaminants are trapped by this rising warm air in a thick layer close to the ceiling waiting for the next fresh air wave to push them out. Although this ventilation scenario significantly reduces the dilution of pollutants in the cabin air, the trapped contaminants in the upper air layer are not far from the breathing level of occupants and may pose health risks.

An under-floor displacement air distribution system was employed by Zhang and Chen (2007) in a CFD model for a section of a Boeing 767 airliner cabin. It was observed that slight air mixing occurs at the center seats, which indicates that the possibility for contaminant spread and cross-infection exists to some extent with displacement ventilation. Zhang et al. (2010) performed a numerical simulation for an enhanced displacement air distribution system in a section of a wide-body passenger airliner cabin. The novel displacement system was found to decrease the CO_2 concentration in the cabin by 30% and increasing the RH from 10% to 20% by supplying an amount of 0.05 kg h^{-1} (0.11 lb h^{-1}) per person of humidification water only.

As a latest addition to the ventilation technology, personalized ventilation has emerged as a high ventilation effectiveness alternative to the overall mixing and displacement air supply systems in different closed spaces (Melikov 2004). In aircraft cabins, personalized ventilation has been employed in various forms as a measure to protect the micro-environment of occupants from the intrusion of contaminants and infectious organisms. One main advantage of personalized ventilation

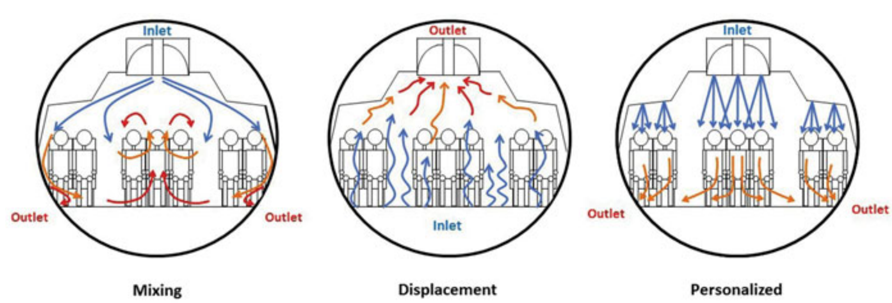

Fig. 2. Aircraft ventilation systems.

over other air supply systems aboard aircraft is that it usually delivers clean outside fresh air directly to the breathing zone of occupants. This helps make the air supplied to occupants free of cabin contaminants.

Aircraft personalized ventilation systems are classified into two categories: proposed and existing systems. Proposed personalized air supply systems had supply inlets installed in each seat armrest (Zhang et al. 2012), in the seat-back in front of each occupant with ceiling exhaust vents (Zhang and Chen 2007), or in the seat-back with localized exhaust opening for each passenger located just below the inlet (Zítek et al. 2010). On the other hand, several studies (Dai et al. 2015; Fang et al. 2015; Li et al. 2015; You et al. 2016) investigated the use of the overhead gaspers, commonly found in different models of passenger aircraft, as effective personalized ventilation supply inlets. Studies agreed on that personalized ventilation provides better air quality and protection against contaminants when operated with the ceiling supply mixing system and/or the displacement system than when those systems operate solely. This comes at the cost of draught risk noticed in some cases, which can be overcome by providing personal control over flow rate, flow direction, and temperature.

Research approaches for studying airflow distribution and air quality in aircraft cabins

Studies concerned with air distribution and quality in aircraft cabins have adopted various approaches. Research approaches range from pure experimental work to numerical simulations validated against experimental measurements, or combinations of both. Table 1 shows a list of 38 studies performed on airflow distribution and air quality in aircraft cabin environments in the last 20 years. Similar collective tables have been included in other review studies (Conceição et al. 2011; Liu et al. 2012a), but in the current investigation more studies are considered, and more emphasis on the studied parameters and the techniques adopted is given.

Out of the 38 studies, 17 studies had only experimental work performed, while 9 had pure numerical simulations validated by experimental data from other studies. Twelve studies did experimental measurements or analytical calculations to validate the numerical models created by one or more of the authors. All possible approaches of research have been used on equal basis to investigate airflow characteristics and air quality in aircraft cabins.

Most studies that mimicked aircraft cabins, either in the form of experimental mock-ups or numerical models, used the actual dimensions and configurations for cabins as much as possible. However, it is essential to compare the airflow patterns between a mock-up or model and a real cabin to assess the differences caused by simplifications (Chen et al. 2017).

Numerous experimental measurement techniques have been employed in the surveyed studies. Those techniques can be classified into two main categories: (1) flow measurement techniques; and (2) species or contaminants measurement techniques. Examples for the first category are: PIV, planar laser-induced fluorescence (PLIF), and fog or dye visualization. For the second category, detectors, lab analysis methods, such as chromatography and mass spectrometry, proton-transfer-reaction mass spectrometry (PTR-MS), and the IMI techniques are some examples.

Conversely, the numerical simulation techniques and tools used for airflow and air quality investigations in aircraft cabins were limited. The codes, or software, used for simulations were mainly commercial, such as Fluent or Star-CD, with Fluent being used more commonly. Different turbulence models have been employed in the surveyed studies, such as Reynolds-Averaged Navier-Stokes (RANS), large eddy simulation (LES), or detached eddy simulation (DES) models.

Best practices for aircraft airflow and air quality research

There is no unique research approach, or set of research practices, that is most suitable for all aircraft airflow and air quality studies. This is attributed to the distinctive characteristics that each aircraft airflow and/or air quality research study possess.

In the current section, the factors that influence the selection of a specific research approach, are discussed. Moreover, recommendations for research practices extracted from the available literature are presented.

Attributes and scope of the research

Airflow and air quality research in airliner cabin environments can range in spatial scale from a single seat, or group of seats, to a full-scale section of the cabin, or a whole cabin in some cases. The parameters that can be considered for study are numerous; such as airflow velocity, air temperature, RH, buoyancy effects, air turbulence and vorticity effects, gaseous and/or particulate contaminant dispersion, particulate contaminant deposition, and more. In addition, the general theme of the study can vary significantly. For instance, thermal comfort, comparison of ventilation systems' performance, effect of moving bodies on airflow patterns, influence of ventilation on contaminant dispersion and/or deposition rates, and infection risk assessment are among many research topics found in the literature.

Experimental work difficulties and advantages

The complexity in the aircraft cabin environment makes the experimental quantification of physical phenomena, such as buoyancy effects or simultaneous cabin-wide flow behavior, a very challenging task. Additionally, using experimental measurements to validate similar numerical models or experimental prototypes is extremely demanding (Zhang et al. 2009). Table 2 lists some of the most commonly used experimental measurement techniques for airflow and air quality studies in aircraft cabins. The measured quantity, cost, pros, and cons are highlighted for each.

Despite the difficulties encountered with performing experimental work in aircraft cabins, the experimental approach has many advantages. First, performing systematic experimental measurements inside cabins gives an assurance of

Table 1. Summary of the key airflow distribution and air quality studies performed in aircraft cabins in the last two decades.

Study	Aircraft setting	Studied parameter(s)	Experimental technique	Numerical technique/Tool
EXPERIMENTAL				
Haghighat et al. (1999)	Actual in-flight aircraft (Airbus A320, Airbus A340, Boeing 767, DC9)	Temperature, RH and Carbon dioxide concentration	On-board measurement using a portable air sampler	—
Waters et al. (2002)	Actual in-flight aircraft (eleven different types)	Temperature, RH and contaminant levels	Direct-reading data logging (DRDLI)	—
Rydock (2004)	Actual in-flight Airbus A340	Concentration of tracer gas (SF_6) released as a cough puff	Sample collection using syringes for later analysis	—
Wisthaler et al. (2005)	Mock-up for a Boeing 767 aircraft cabin	Ozone-initiated products concentrations	Proton-transfer-reaction mass spectrometry (PTR-MS)	—
Strøm-Tejsen et al. (2007)	Mock-up for a Boeing 767 aircraft cabin	Effect of RH% on contaminant levels and flight symptoms	In-cabin detection, gas chromatography and mass spectrometry	—
Wisthaler et al. (2007)	Mock-up for a Boeing 767 aircraft cabin	Effect of using air purifiers on the levels of gaseous pollutants	Proton-transfer-reaction mass spectrometry (PTR-MS)	—
Bhangar et al. (2008)	Actual in-flight aircraft (seven different types)	Ozone concentration in cabin during flight	In-flight sampling with an ozone photometer	—
Wang et al. (2008)	Mock-up for a Boeing 767-300 aircraft cabin	Ventilation effectiveness factor (VEF) and local mean age of air	Volumetric particle tracking velocimetry (VPTV) and gas sampling	—
Kühn et al. (2009)	Mock-up for an Airbus A380 upper deck cabin	Airflow velocity and temperature fields for two cases of convection	PIV and temperature measurement by Type K thermocouples	—
Sze To et al. (2009)	Mock-up for a Boeing 767 aircraft cabin	Airflow and cough particles dispersion and deposition	PIV and Interferometric Mie Imaging (IMI)	—
Anderson (2012)	Boeing 767 aircraft cabin simulator (mock-up)	Effect of using personal gaspers on airflow and contaminants transport	Direct sampling of CO_2 using non-dispersive infrared sensors	—
Liu et al. (2012b)	Actual parked MD-82 aircraft	Airflow velocity field and cabin geometry to be used for CFD validation	T-scan laser tracking, hot-sphere anemometry, and ultra-sonic anemometry	—
Li et al. (2014)	Actual parked and insulated MD-82 aircraft	Concentrations of gaseous (SF_6) and particulate (DEHS) contaminants	Photoacoustic multi-gas analysis and optical particle sizing	—
Zhai et al. (2014)	Actual in-flight Boeing 737–800 aircraft	Concentrations of particles and CO_2 in cabin air supply and return	Direct measurement using an airborne particle counter and CO_2 detector	—
Dai et al. (2015)	Simplified mock-up for an aircraft cabin with an actual MD-82 gasper	Gasper-induced airflow velocity and turbulence intensity	Hot-wire anemometry	—
Fang et al. (2015)	Mock-up for an Airbus A320 aircraft cabin	Effect of using personal air supply ports (gaspers) on thermal comfort	Hot-wire anemometry and regular thermal sensation questionnaires	—

(*Continued on next page*)

Table 1. (Continued)

Study	Aircraft setting	Studied parameter(s)	Experimental technique	Numerical technique/Tool
Li et al. (2015)	Five-row section within an actual parked MD-82 aircraft	Effect of using gaspers on airflow and gaseous pollutant concentration	Hot-wire and ultra-sonic anemometry and photo-acoustic multi-gas analysis	—
		NUMERICAL		
Lin et al. (2005)	Numerical model for a Boeing 767-300 cabin section	Airflow patterns and air velocity magnitudes	—	RANS and LES simulations using Fluent code
Zhang and Chen (2007)	Numerical partial model for a Boeing 767-300 cabin	Effect of novel ventilation systems on air velocity and CO_2 concentration	—	RANS (RNG k-ε) simulations using Fluent
Wan et al. (2009)	Numerical model for a Boeing 767 cabin section	Airflow and expiratory aerosols dispersion and deposition	—	RANS (RNG k-ε) simulations using Fluent with Lagrangian particle tracking
Dygert and Dang (2010)	Numerical model for a Boeing 767 cabin section	Effect of localized exhaust on airborne contaminant removal	—	RANS (Realizable k-ε) simulations using a commercial solver
Zhang et al. (2010)	Numerical partial model for a wide-body aircraft cabin	Effect of a new air supply system on airflow and contaminant concentration	—	RANS (RNG k-ε) simulations using Fluent
Gupta et al. (2011b)	Numerical partial model for a twin-aisle aircraft cabin	Airflow velocity field and transport of expiratory droplets	—	RANS (RNG k-ε) simulations using Fluent with Lagrangian particle tracking
Gupta et al. (2012)	Numerical partial model for a twin-aisle aircraft cabin	Risk of infection due to influenza outbreak in a 4-h flight	—	RANS simulations using Fluent and a model for infection risk assessment
Liu et al. (2013)	Numerical model for a MD-82 aircraft first-class cabin (empty or occupied)	Prediction of airflow pattern and turbulence by three turbulence models	—	RANS (RNG k-ε), LES and DES simulations using Fluent
Hassan (2016)	Numerical partial model for an Airbus A340-600 aircraft cabin	Effect of using modified mixing air supply and gaspers on thermal comfort	—	RANS (RNG k-ε) simulations using Fluent
		NUMERICAL WITH EXPERIMENTAL OR ANALYTICAL VALIDATION		
Garner et al. (2004)	Actual parked Boeing 747-100 aircraft	Airflow distribution and velocity	Three-dimensional sonic anemometry	Developed PICMSS code and the commercial Fluent code
Bosbach et al. (2006)	Mock-up for a part of a real aircraft cabin	Airflow turbulence and velocity fields	Particle image velocimetry (PIV)	RANS simulations with three turbulence models using Star-CD
Günther et al. (2006)	Mock-up for a part of a real cabin and a single-person sleeping bunk	Airflow turbulence and velocity fields	PIV and thermography	RANS simulations with three turbulence models using Star-CD

(*Continued on next page*)

Table 1. (Continued)

Study	Aircraft setting	Studied parameter(s)	Experimental technique	Numerical technique/Tool
Yan et al. (2009)	Mock-up for a Boeing 767-300 aircraft cabin	Airflow pattern and airborne pollutant dispersion	VPTV and CO_2 sampling using infrared sensors	RANS (Standard k-ε) simulations using Fluent
Zhang et al. (2009)	Mock-up for a half-occupied aircraft cabin	Air velocity and temperature, and gaseous and particulate pollutants dispersion	Ultrasonic anemometry, photoacoustic analysis and optical particle sizing	RANS (RNG k-ε) simulations using Fluent with Lagrangian particle tracking
Poussou et al. (2010)	One-tenth scale aircraft cabin mock-up	Effect of a moving body on airflow and contaminant transport	PIV and Planar Laser-Induced Fluorescence (PLIF)	RANS (RNG k-ε) simulations using Fluent
Zítek et al. (2010)	Single-seat experimental mock-up and a sectional CFD Cabin model	Effect of a new personal ventilation system on air velocity and RH	PIV and airflow visualization using SAFEX fog	RANS (Standard k-ε) simulations using Fluent
Gupta et al. (2011a)	Numerical partial model for a twin-aisle aircraft cabin **(semi-analytical validation)**	Transport and inhalation of droplets generated from different expiratory events	—	RANS (RNG k-ε) simulations using Fluent with Lagrangian particle tracking
Zhang et al. (2012)	Mock-up for a twin-aisle aircraft cabin	Effect of a new personal ventilation system on cross-contamination	Ultra-sonic anemometry and direct CO_2 sampling	RANS (RNG k-ε) simulations using Fluent
Isukapalli et al. (2013)	Mock-up for a Boeing 767 aircraft cabin	Dispersion and deposition of disinsection pesticides in cabin	Gas chromatography and mass spectrometry	RANS (RNG k-ε) simulations using Fluent
Li et al. (2016)	Numerical partial model for a Boeing 737–200 aircraft cabin	Effect of airflow vortex structure on airborne contaminant transport	PIV, hot-wire and ultra-sonic anemometry, and infrared thermal imaging	RANS (RNG k-ε) simulations using Fluent
You et al. (2016)	Simplified aircraft cabin mock-up	Gasper-induced airflow velocity and temperature distributions	PIV and hot-sphere anemometry	RANS (RNG k-ε and SST k-ω) simulations using Fluent

certainty about the quantified parameters. Second, true technological advancement comes because of the emerging and everlasting need for more accurate experimental measurement techniques. Finally, numerical and computational models need validation and verification, which makes the availability of high-resolution experimental measurements of critical importance.

Numerical modeling characteristics and requirements

Validation and error quantification

One of the main pillars of numerical simulation is the validation and verification of the calculations performed using a specific code or technique. One cannot validate a whole numerical code, but only a specific set of calculations for a case study performed using the code (Roache 1997).

Error quantification between the experimentally measured and the numerically predicted quantities is performed in various ways. Most commonly, the simple or root mean square (RMS) error (difference) percentage is quantified and used to report the amount of error between the measured and predicted values. However, this method may yield some exaggerated, unrepresentative, and undefined error estimates in some cases, especially for ventilation, airflow, and air quality studies. Alternatively, Hanna (1989) proposed two performance measures to express the error between the measured (observed) and predicted concentrations in atmospheric air quality models: the mean fractional bias (FB), and the normalized mean square error (NMSE).

Unlike the absolute error percentage measure, FB and NMSE define some specific attributes for the calculated error. The FB represents the shift between the observed and predicted values, while the NMSE gives the spread between

Table 2. Experimental techniques commonly used for aircraft cabin airflow and air quality measurements.

Technique	Measured quantity	Measurement method	Cost*	Pros	Cons
Particle Image Velocimetry (PIV) /Volumetric Particle Tracking Velocimetry (VPTV)	Flow velocity magnitude and direction through flow visualization (2D or 3D)	Flow seeding using tracer particles, illuminated by laser sheet(s), and flow images are recorded by video cameras	Very high	Provides real-time flow field and velocity measurements	Small measurement area, seeding particles/fluid incompatibility issues
Planar Laser-Induced Fluorescence (PLIF)	Species transport and concentration in a background medium (2D or 3D)	Specific dye substances are illuminated using laser sheets. Dye flow in the background medium is recorded by video cameras	Very high	Can work with PIV to yield velocity and concentration profiles	Requires special dyes with specific optical resonance wavelengths
Fog/Dye Flow Visualization	Flow direction and velocity(2D or 3D)	Flow visualization by injecting specific types of fogs or dyes, such as SAFEX fog, into the flow	Low	Quick and easy way to determine flow direction and pattern	Fog or dye injection method may affect the accuracy of flow velocity quantification
Hot-Sphere Anemometer (HSA) /Hot-Wire Anemometer (HWA)	Gas flow velocity (1D, 2D, or 3D)	Flow velocity is inferred from the amount of cooling of the electrically-heated sphere/wire probe placed in the gas flow through Newton's law of cooling	Low to moderate	Fast response and high spatial resolution	Need frequent calibration, hot-wires break often
Ultra-sonic Anemometer (UA)	Gas flow velocity (1D, 2D, or 3D)	Flow velocity is interpreted from the time the generated sonic pulses take to travel between transducer pairs	Low to moderate	Suitable for extended time measurements, infrequent maintenance	Flow distortion can be caused by the structure supporting the transducer(s)
Gas Direct Sampling	Trace gas (contaminant) concentration in a background gaseous medium	In-cabin direct gas concentration measurement using portable or fixed samplers, sensors or photometers	Low to moderate	Simple and instantaneous species concentration quantification	Limited accuracy, inefficient for unsteady measurements in large spaces
Gas Chromatography	Concentrations of trace gases, such as VOCs, in a prepared mixture specimen	Different compounds in a mixture are separated and detected after dissolving them in a "mobile phase" due to different travel speeds and retention times	Moderate to high	High accuracy in determining trace gas concentrations even in very small amounts	Preparing a mixture specimen from the cabin can be difficult in some flow cases
Photoacoustic Spectrometry	Concentrations of trace gases in air with very high accuracy up to parts per billion or parts per trillion level	Gas sample is illuminated by a high-intensity laser or infrared light which allows the gas constituents to absorb different wavelengths of the light and generate sounds (photoacoustic spectrum) proportional to the light intensity. This spectrum is used to determine the absorbing constituents of the gas sample	Moderate to high	Evaluates samples in their original, in situ form without chemical or physical interference	Prepared gas mixture specimen is needed, gas constituents can be confused if similar light wavelengths are absorbed

(*Continued on next page*)

Table 2. (Continued)

Technique	Measured quantity	Measurement method	Cost*	Pros	Cons
Mass Spectrometry	Mass concentration of VOCs in a prepared complex mixture specimen	Different compounds in a mixture are ionized and sorted according to their mass-to-charge ratio. Separated compound are then identified by comparing the mass spectra to known masses	Moderate to high	Highly accurate, can be used for any type of trace gases	Prepared sample is required, full mass spectra analysis can be difficult if multiple mixture components have the same mass
Proton-Transfer-Reaction Mass Spectrometry (PTR-MS)	Mass concentration of VOCs in air or fluid through online (real-time) monitoring	H_3O^+ ions, produced from ionizing supplied distilled water, react with VOC trace constituents through proton transfer reactions, and their absolute concentration is calculated directly without prior calibration	Moderate to high	No prepared specimen is needed, provides real-time measurements	Not all trace gas molecules are detectable, the maximum quantifiable concentration is limited (≈10 ppmv**)
Optical Particle Counting (OPC)	Number and size of liquid or solid particles in air through standard particle size bins	Each particle is illuminated by a high intensity light (laser or halogen light), and its size is inferred using either light scattering, light obstruction, or direct imaging methods before being counted and added to its respective size bin	Low to moderate	Easy to use, provides fast and detailed particle bin size distribution	Detectable particle size range can be limited, counters can be damaged by incompatible particle
Interferometric Mie Imaging (IMI)	Size of transparent and spherical liquid droplets scattered in air (cough or sneeze droplets). Velocity of droplets can also be measured if the system is integrated with a PIV system	The width of the interference fringes, resulted from the merged scattered light from two glare points on each droplet's surface, in addition to the refractive index of the droplet material and the view angle of the receiver are analyzed together to calculate the droplet size	Very high	Handles a wide range of droplet sizes, provides accurate droplet positioning	Limited to transparent and spherical liquid aerosols only

*Costs are given in ranges that use the following criteria: "Very high" for techniques that cost more than U.S. $100,000, "High" for the cost range from U.S. $10,000 to U.S. $100,000, "Moderate" for the range from U.S. $1,000 to U.S. $10,000, while "Low" is for the techniques that cost less than U.S. $1,000. Those cost ranges are approximate and differ from one manufacturer to the other.\
**ppmv = parts per million volume.

observed and predicted values. The FB and NMSE can be used with any physical quantity in air quality studies (Hanna and Chang 2012).

Meshing and grid independence

Meshing, or discretization, of a CFD model domain is another crucial component for numerical simulations. The number of grid elements, or nodes, which can be created in one domain may vary significantly depending on the sizes of that domain and the grid elements. As the numerical solution of the governing equations is obtained for each single element or node of the created grid, the number of elements or nodes and the way they are arranged in the grid can notably affect the accuracy of the numerical results. For this reason, an accurate procedure has been necessary for quantifying the degree of independence of the numerical solution from the grid size and configuration changes, which is called grid independence test (GIT). This test is usually performed for three different levels of grid fineness: coarse, medium, and fine. The methodology that was used for grid independence testing in the past consisted of a comparison between the obtained solution (velocity, temperature, concentration, etc.) on a continuous spatial segment, such as line or surface within the domain, for each grid level (coarse, medium, and fine) with the other two levels. The grid level that exhibits enough grid independency of its solution (shows no significant change in the solution with the change in mesh size to a finer level) is chosen for further use.

A more representative measure for grid refinement studies was proposed by P.J. Roache, called grid convergence index

(GCI). The GCI uses an asymptotic approach for calculating the amount of uncertainty in grid convergence (Roache 1994). Similar to the simpler GIT, the GCI makes use of the solution on three different grid levels; such grids that can be created through grid coarsening and not necessarily by grid refinement (Roache 1997). The GCI reports a numeric value that shows how much convergence is achieved in the solution between two successive grid levels, or between the coarsest grid level, taken as a reference, and each one of the two other grids. The GCI has been employed in many airflow and air quality studies to quantify the grid convergence, either in aircraft cabins (Wan et al. 2009), or other closed spaces (Aliabadi et al. 2014).

It must be noted that the concept of grid convergence does not always apply to models that are not complete (or incomplete), such as the LES model. A model is termed complete if its constituent equations are free from flow-dependent specifications. Such specifications include material properties (density and viscosity), initial and boundary conditions, and numerical discretization. In such a case, a GCI may not necessarily approach zero or even reduce by further refining the mesh, which is the case for models that are redefined at a specific length scale. For example, the LES model formulates and solves different sets of partial differential equations at above-grid and subgrid scales (Roache 1997).

Turbulence modeling

Accurate CFD modelling of airflow and air quality cannot be performed without defining a suitable turbulence model for the simulated type of flow. This is the case since turbulence cannot be exactly simulated economically for most practical applications. Additionally, CFD models tend to solve the partial differential equations that govern the flow and dispersion (continuity, species, energy, etc.) locally at a point in the simulated domain. On the other hand, the nature of the generated flow turbulence is nonlocal, and the smallest change occurring at one point can affect the flow far away in the domain (Spalart 2015). Due to this nature, different numerical turbulence models adopt various strategies in simulating the flow turbulence with distinguished accuracies that come at proportional computational costs. Table 3 shows a comparison among the four main categories of turbulence models.

Particle tracking models

For air quality models that have particulate contaminant(s) dispersion, a particle tracking (transport) model is required. The numerical particle tracking models are classified into two main categories: Eulerian models and Lagrangian models. The Eulerian models consider the particles as a continuous phase, similar to the fluid in which they disperse, and solve their governing equations using a control volume scheme. The Lagrangian models, on the other hand, treat the particles as a discrete phase, and equations are solved for the motion of particles to yield individual trajectories (Zhang and Chen 2007; Zhao et al. 2008). The most common Lagrangian particle tracking model is the discrete random walk (DRW) model, which considers that the fluctuating components of velocities obey a Gaussian probability distribution (Zhao et al. 2008). On the other hand, the single fluid model, the mixture model, and drift flux model represent the Eulerian particle tracking approach.

In the last two decades, many studies have investigated the performance of different numerical particle tracking models in closed spaces, and compared their predictions to experimental data (Nijdam et al. 2008; Zhang and Chen 2007; Zhao et al. 2008). Studies agreed on promoting the use of the DRW model for the Lagrangian approach, and the drift flux model for the Eulerian approach.

Although, the Lagrangian models are currently widely adopted in the numerical particle tracking simulations and are included in most of the available commercial CFD packages (Lai and Cheng 2007), new mixed Eulerian-Lagrangian models are beginning to attract the attention of many investigators. In those models, the solved equations are split into two parts: advective and diffusive. The advective component is solved using the Lagrangian step to reduce the associated numerical errors and allow large Courant numbers (Co) for the flow, whereas the diffusive component can be solved easily as a symmetric diagonally dominant system (Cheng et al. 1996; Dimou 1992).

Research gaps and future research topics

Determination of contaminant levels and properties in aircraft cabins

Some of the studies that measured the concentrations of gaseous contaminants (real or surrogates) in aircraft cabin environments used portable and hand-held air or gas samplers and photometers (Bhangar et al. 2008; Haghighat et al. 1999; Zhang et al. 2012) with limited accuracy and deficiency in determining a wide range of concentrations in large spaces. Alternatively, a fixed set of sensors or well-implemented sampling lines are more desirable for eliminating human errors in sampling. Some researchers used the fixed-sensor (sampling tree) approach for quantifying gas concentrations inside aircraft cabins through a data acquisition (DAQ) system (Anderson 2012; Strøm-Tejsen et al. 2007; Wang et al. 2008; Yan et al. 2009). For future studies, and to attain as much concentration measurement accuracy as possible, gas sampling trees can be employed with higher spatial resolution and better sensor positioning in the cabin space.

Another side to consider is the need for more detailed studies on the dispersion and deposition characteristics of some harmful gaseous compounds, such as disinsection pesticides, which are very common aboard many airliners today. The inhalation of pesticides by passengers may pose health risks that are overlooked in the literature and could be worthy of investigation.

For particulate contaminants aboard aircraft, and especially those generated from expiratory events, more emphasis can be directed toward conducting on-board live tests for the viability and infectivity of the micro-organisms contained in the droplets.

Aircraft ventilation strategies

Personalized ventilation systems provided the most promising results for air quality enhancement and cross-infection

Table 3. Categories of numerical turbulence models used for airflow and air quality studies in literature.

Modeling philosophy	Computational time/Cost	Usage problems	Studied models and conclusions
Direct Numerical Simulation (DNS)			
Detailed and direct simulation of all turbulent eddies and length/time scales	Years/Extreme	Very complex for ventilation simulations	DNS model is impractical for indoor flow simulation (Zhai et al. 2007)
Large Eddy Simulation (LES)			
Large eddies are solved in detail, but smaller eddies are modelled	Months/High	Highly fine mesh is required for the whole domain to resolve large eddies	• LES is best suited for natural convection flow with low Rayleigh (Ra) number, and for forced convection flow with low turbulence (Zhang et al. 2007) • LES-DSL is the best for forced convection or mixed convection airflow in a room (Wang and Chen 2009) • LES is better than DES and RNG k-ε (RANS) models for predicting mixed convection flow in occupied aircraft cabins (Liu et al. 2013) • LES is better than RANS models for urban and atmospheric airflows with heat transfer (Aliabadi et al. 2017; Li et al. 2008, 2010, 2012; Nazarian and Kleissl 2016)
Detached Eddy Simulation (DES)			
Hybrid modelling using LES (core) and RANS (near boundaries) models simultaneously	Weeks/Moderate	Hard to apply in most ventilation models	DES is good for predicting mixed convection airflow in unoccupied aircraft cabins (Liu et al. 2013)
Reynolds-Averaged Navier-Stokes (RANS)			
Fluctuating and time-averaged components of flow are solved in a separate manner	Days or hours/Affordable	Accuracy is less, choosing the most suitable RANS model for the simulated case is challenging	• Standard k-ε model predicts airflow well in a model for an auditorium (Launder and Spalding 1974; Nielsen 1973) • The RNG k-ε model is better than the standard k-ε model for simulations of indoor airflow (Chen 1995)

mitigation in aircraft cabins (Gao and Niu 2008; Zhang and Chen 2007; Zhang et al. 2012, 2013). Therefore, more research effort should still be placed on the potential of the personalized ventilation systems in preventing harmful contaminants from reaching the occupants, and in containing infectious particles in the microenvironment of the infecting person. Such actions can be called "shielding effects." For example, the shielding effects of the personalized ventilation can be investigated through new, but realistic, configurations for cabin seats with air inlets near the faces of the occupants, or modified arrangements (ergonomics) of overhead gaspers that can increase their protection effectiveness.

With the development of new aircraft models and designs, such as the double-decker and multi-deck aircraft, investigation of the employed ventilation strategies aboard those novel airliners and the resulting airflow patterns in each deck's cabin is required. Such a new research direction can pave the way for multi-cabin contaminant dispersion studies soon.

Suggested air quality research approaches in aircraft

Using culture methods, such as culture dishes, the viability and infectivity of airborne pathogens can be measured aboard airliners. The use of culture dishes or media plates (e.g., agar gel plates) to collect samples of airborne pathogens during flights, and allowing them to incubate, or grow, in the cabin temperature, RH, and air composition conditions can provide more accurate indication of the true airborne infection risk in cabins. Despite this, laboratory techniques, such as polymerase chain reaction (PCR) and plaque assay methods (Aliabadi et al. 2011) can still be used to complement and verify the results from the culture methods aboard aircraft.

For the numerical simulation techniques of airflow and contaminant transport, the use of custom wall functions, either through modifying existing functions or considering new laws for the wall, can provide more accurate numerical predictions. Another suggestion is the application of alternative transport models to the common Navier-Stokes equations. One example is the Lattice-Boltzmann Method (LBM), which is based on complex fluid flow fields on microscopic collision models and mesoscopic equations instead of the familiar continuum-based Navier-Stokes model (Chen and Doolen 1998). LBM has been reported in the literature for successfully simulating a wide range of complex flows, either bounded flows (Fakhari and Lee 2015), or unbounded atmospheric and urban flow fields (Chen 2016). Moreover, LBM models have been shown to run faster than Navier-Stokes models using parallel computations.

Summary and conclusions

In the current article, ventilation and air quality in aircraft cabin environments are reviewed systematically through a critical survey of key studies performed in the last two decades.

The main gaseous contaminants considered are ozone, carbon oxides, disinsection pesticides, ethanol, and VOCs produced in the cabin environment. The main particulate contaminants are those originating from expiratory actions, such as breathing, coughing, and sneezing, with coughing being considered the most in literature. The nonexpiratory particulates, on the other hand, are produced from smoking, skin shedding, and dust contamination. It was noticed that the lack of adequate technologies to release and measure trace gases in the middle of the last century made the research on particulate contaminants precede that on gases by 50 years. It was also found that the number of studies that investigated the generation and dispersion of expiratory particulates in aircraft cabin environments was significantly less than those performed in rooms (buildings) and other closed spaces in the last years.

The available aircraft ventilation systems are based on the main three categories of airflow distribution that include mixing, displacement, and personalized systems. While the scientific community continues to debate the pros and cons of operational systems, such as mixing and displacement, there is consensus that the recently emerged personalized ventilation systems provide improved air quality for the occupants in comparison to the traditional ventilation systems.

The research approaches for airflow and air quality studies in aircraft cabins have varied from fully experimental to fully numerical, or combinations of both. Considering the literature, all possible research approaches have been used on almost equal basis to investigate airflow patterns and air quality in aircraft cabins. Many experimental measurement techniques have been used in the surveyed studies, which can be classified into two main categories: (1) flow measurement techniques; and (2) species or contaminants measurement techniques. Conversely, the numerical techniques used were limited in comparison.

Generally, there is no unique research approach, or set of research practices, that is most suitable for all aircraft airflow and air quality studies. Consequently, some of the best practices for aircraft airflow and air quality research have been proposed based on the literature, and depending on the research scope and the chosen research approach.

Finally, research gaps relevant to each of the investigated topics in this article were discussed. The recommendations for future research are concerned with improvements and transformative approaches in experimental and numerical investigations. Culture methods and spatially distributed measurements are highly encouraged for future experimental investigations. Future numerical investigations based on CFD can benefit from more advanced wall functions, turbulence models, and Lattice Boltzmann Methods (LBM).

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