A Review on Effects of Personalized Ventilation Systems on Air Quality and Thermal Comfort in Aircraft Cabin Mini-Environments

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Abstract: This study conducts an evaluation of air quality, dispersion of airborne expiratory pollutants and thermal comfort in aircraft cabin mini-environments using a critical examination of significant studies conducted over the last 20 years. The research methods employed in these studies are also explained in detail. Based on the current literature, standard procedures for airplane personal ventilation and air quality investigations are defined for each study approach. Present study gaps are examined, and prospective study subjects for various research approaches are suggested.

Key words: personal ventilation system; computational fluid dynamics (CFD); mini-environment; aircraft; thermal comfort

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0 Introduction

The aviation sector has become one of the most significant fundamentals in today's worldwide market. In 2015, over 3.6 billion people utilized commercial flights as their primary type of long trips, resulting in 9.9 million employment opportunities in airline companies[1]. If necessary precautions are not followed, the environment within an airplane cabin may create favorable conditions for worsening air quality, spreading virus and transmitting infection among passenger. This is due to high passenger density, a wide range of passenger activities, and passengers' inability to leave the enclosed environment for extended periods of time[2]. Disease transmission from one passenger to another can occur off-board an airplane, either before or after a flight. In recent years, air pollution, insufficient air conditioning systems and ineffective pollution prevention strategies have resulted in a variety of symptoms and infectious diseases during and after flights. Vomiting, dizziness, headaches and exhaustion[3] are among the symptoms, as are extremely contagious outbreaks like flu[4], COVID-19[5-6] and tuberculosis[7]. These infections have infected enormous numbers of people, both aboard and off-board airplanes, and have been the primary cause of many deaths in recent years. In comparison to other enclosed environments, the modes of transmission of several infectious diseases aboard aircraft are nearly equal. Influenza, for instance, is identified to be transmitted in three ways: Aerosol, particle, and di-

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rect infection[8-9]. Among these ways, the aerial method has received many considerations in recent air quality studies.

The literature has looked into a number of ways for developing and monitoring air quality in airplane cabins. For the highest possible indoor air, ventilation systems onboard airplanes can control air temperature and velocity distribution. This is to ensure that passengers have a pleasant and comfortable environment by reducing the number of gases and particle pollutants to below permissible limits[10]. In consideration of this, improper use of heating, ventilation, and air conditioning (HVAC) systems might, in some cases, accelerate infection rates[11]. A variety of research have used ventilation systems as an effective control device to improve air quality in airline cabins. Experimental or completely computational opproaches, or a mixture of the two, have been applied for investigation. Many researchers have tried to determine how the kind of air conditioning system affects the transmission of contagious diseases in the air[12-14]. Some research[14-15] examined the use of mixing ventilation system (MVS) with underfloor air and personal ventilation system (PVS) in airline cabins, although such studies lack validation data. Advanced techniques for reproducing pollutant creation, for example, tracer gas and particle originators, have been used to investigate the spread of airborne contaminants in airplane cabins. A typical passenger aircraft's environmental control system is divided into two components. The first is the main air distribution system, which regulates the cabin's overall thermal comfort and air quality[16]. This main air distribution system, however, is unable to meet the thermal comfort and health needs of every passenger, necessitating the use of a personalized air system supply to compensate. The second component uses a personal air supply system to deliver conditioned air to each passenger. Personal supply air systems of this sort are commonly employed. Aircraft manufacturers such as Boeing and Airbus employ this sort of personal systems due to its simplicity of use and control versatility. The personalized air supply system has the benefit of allowing each passenger to manage both the air flow rate and direction to assist them attain their desired atmosphere. Several researchers have been interested in the idea of personalized air delivery systems throughout the last decade. Jacobs et al.[17] developed a novel idea of built-in airplane cabin air-conditioning. Similarly, Zhang et al.[18] developed a personal seatback-enhanced air supply system that distributes clean air directly to a passenger's inhaling areas. Depending on such findings, Ref.[19] proposed that each seat in a commercial airplane was provided with a distinct individual air flow and exhaust, which would help protect passengers from the transmission of airborne infections during flights. You et al.[20] created a personal air distribution system that used air terminals built in chair armrests. This was created and validated by the use of computational fluid dynamics (CFD) modeling and experimental validation. Moreover, Gao et al.[15] investigated the personal ventilation of an air supply channel positioned in each of the passenger's breathing areas using a CFD model and shown that this sort of ventilation may enhance passenger air quality. Thermal comfort and inhaled air quality were investigated by Bolashikov et al.[21] and Melikov et al.[22] utilizing a seat headrest system with personalized ventilation. The primary focus of the airplane mini-environment research is on improving seat position and how this may affect air distribution. The majority of these research focus solely on the effect on air quality in the breathing zone rather than the total effect on passenger thermal comfort. These investigators' advances, though, are still far from completion, and the classic individual nozzle air distribution method is still in use. Only a few of these papers involved experimental studies, with the majority used CFD numerical simulation as the primary study approach.

Numerous researchers have used CFD to simulate particle dynamics[23-24]. The methodologies used to simulate the dynamics of airborne droplets are critical for analyzing their behaviors as well as the impact of the ventilation system on them. In a number of recent experiments, a PVS in the cabin has been found to dramatically enhance air quality and reduce pollutants in the traveler breathing zone[25-27]. There has been considerable studies and literature on the thermal comfort of the interior atmosphere in ground constructions[28-29], but few on the thermal comfort of the airplane cabin environment. Hence, studies on air quality and pollutant control aboard aircraft mini-environment from the last two decades are reviewed in this work. This paper also summarizes studies on human thermal comfort in relation to studies on airplane cabin mini-environment thermal comfort. In addition, recommendations for the most relevant methodologies for air quality study in airplane cabins mini-environments are given, as well as future research opportunities.

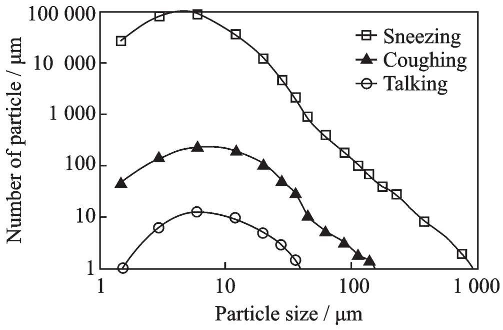
1 Overview of Personal Ventilation System in Aircraft Cabins

One of the most important components of the environmental control system (ECS) is the ventilation system, which is responsible for efficiently dispersing conditioned air to maintain the health and thermal comfort of the occupants. In comparison to other modes of transportation, airplane cabins have a higher occupant density, a more complex internal geometry, a smaller capacity, and a lower fresh air flow per occupant. The overall air exchange ratio in a cabin is substantially higher than that in a building[30], due to the lower air volume and much higher occupant density. As a result, maintaining a healthy and comfortable atmosphere in airplane cabins can be difficult. High-velocity airflow enters the above region and air returns next to the floor, causing air mixing throughout the cabin space. It normally causes small air temperature stratification, but it has the potential to spread infectious pathogens throughout the cabin due to its mixing effect[18, 31]. The PVS has recently been researched in buildings[12,32-34]. The main purpose of the PVS is to provide individual thermal control for passengers while reducing pollutant entrance into the passenger breathing region[35-36]. Though this concept has been adopted successfully in homes[12, 37-38], it has yet to be implemented satisfactorily in airline cabins. The personal airflow outlet, which is common in airplane cabins, is identified by gasper valves, which may not be as operative in encouraging personal temperature control for each person[39]. Finally, CFD simulations[14-15] were utilized to evaluate various conceptual PVS approaches for airplane cabins, indicating improvements of thermal comfort and air-quality when compared to standard MVS. Validation data for those investigations, on the other hand, is limited. Although airplane cabin ventilation is challenging to design, it may be necessary to improve it to provide greater air quality in the breathing region of the occupants without affecting thermal comfort, therefore lowering the risk of inflight cross infection. PVS looks to be a viable choice when used in combination with other ventilation systems. To properly comprehend the impact of PVSs on bio-contaminant dispersion, the state of the art of the methodologies utilized to replicate the energetic of airborne droplets in airplane cabins must be assessed, which is done in the next section.

2 Airborne Pollutants Onboard Airplanes

2.1 Expiratory pollutants

Coughing, talking, and sneezing are all examples of how humans atomize droplets. If pathogenic pollutants found in an infected person's expiratory tract are carried outside by these droplets, they can be inhaled and directly transmitted to others, which is one of the most prevalent methods for cross infection to occur. According to Duguid[40], over 95% of expiratory particles are between 2 μm and 100 μm in size, with droplets between 4 μm and 8 μm being the most frequent (Fig.1). Sneezing creates more particles, while coughing occurs more frequently and eventually produces the most particles[41]. Due to gravity, particles larger than 5 μm tend to fall rapidly on surfaces[42]. Smaller particles in the air have a diffusion coefficient comparable to gases[43], which permits them to be transported by



Expiratory activity	Number of particle
1 sneezing	1 000 000
1 coughing with mouth dosed	5 000
Counting loudly 1—100	250

Fig.1 Number of particles generated by human expiratory activity normalized for interval width as a function of particle size[40]

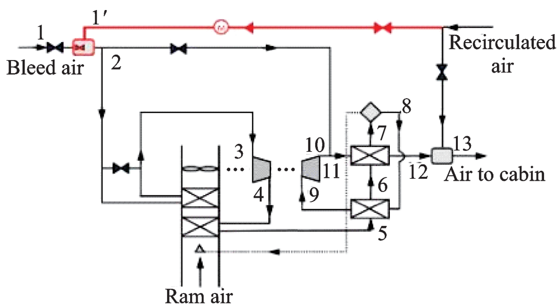
the airflow long enough to vanish and form droplet nuclei as a residue. Consequently, these deposits may be capable of transporting pollutants across greater distances[44].

Smaller aerosols, which have followed the airflow as if they were vaporous particles, prefer to stick to an item's surface after contact, whereas gaseous particles rebound[43]. The droplet concentration emitted every cough, according to Yang et al.[13], is roughly 109 m^{-3}. Based on Duguid's data[40], it is reasonable to estimate that sneezing produces roughly 200 times the amount of particles created by coughing. It is reasonable to anticipate that a sneeze concentration would be on the order of 1 011 m^{-3} if the concentration increased in the same proportion. However, according to a recent study[45], coughing produces droplet concentrations ranging from 2.410 6 m^{-3} to 5.210 6 m^{-3}, nearly three orders of magnitude smaller than that mentioned in Ref.[13]. Table 1 summarizes the research[46-47] related to expiratory pollutant levels that were detected in the literature review. Refs.[52-53] presented a new method named the ultra-high-temperature instantaneous sterilization air conditioning system (UHT-ACS) to sterilize and eliminate viruses in the return air of an air conditioning system, as shown in Fig.2(a). Based on their proposed sys-

Table 1 Characteristics of exhaled droplets

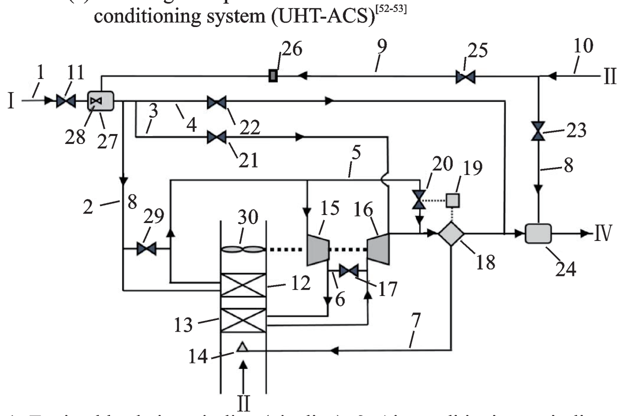
Ref.	Year	Activity of expiratory	Gas/aerosol	Amount	Concentration/ (Droplet•m^{-3})	Size/ (10^{-6} m)	Velocity/ (m•s^{-1})
			Experimental results				
[13]	2007	Cough	Polydispersed/human body	9 • 10^{-4} m^3/s (max)	2.4×10^9 (max)	Heights at 1, 4, 8	
[45]	2009	Breath	Polydispersed/human body		8.4×10^6 (max)	0.3—0.5	
[46]	2008	Breath	Polydispersed/human body		9.9×10^5		
[40]	1946	Speak (count 1—100)	Polydispersed/human body	250/speak		4—8 (most typical)	
		Cough	Polydispersed/human body	5 000/cough			
		Sneeze	Polydispersed/human body	1 000 000/ sneeze			
[47]	1987	Cough	Polydispersed/human body	2 085 (max)/ cough	5.2×10^6 (max)	4—8	11.7
		Speak (count 1—100)	Polydispersed/human body	6 720 (max)/ speak	2.2×10^5 (max)	4—8 (most typical)	3.1
			Numerical results				
[18]	2007	Human breathing	CO_2	5×10^{-6} m^3/s			
[15]	2008	Sneezing	Water, monodispersed	9 600/sneeze		1	20
			Numerical with experimental results				
[48]	2009	Not specified	CO_2	7.5×10^{-5} m^3/s			
[49]	2005	Cough	Water, polydispersed		2.5×10^9	6.75 (medium)	10
[50]	1996	Not specified	latex polystyrene, polydispersed	1.7×10^{-5} m^3/s	3×10^{10}	0.14	
[51]	2009	Not specified	DEHS, monodispersed	7.5×10^{-5} m^3/s	10^{12}	0.7	
			SF6	5×10^{-8} m^3/s			
[4]	2011	Cough	Monodispersed/ water	10^6/cough		8.5	9 (max)
		Breath	Monodispersed/ water	525/breath		0.4	4 (max)
		Talk (for 15 s talking)	Monodispersed/ water	2 250/talk		30	
		Talk	Monodispersed/ water		9.9×10^5		

tem, a simulation of the UHT-ACS is analyzed in various flight states. In the UHT-ACS, the mixing air temperature of return and bleed air can reach temperature up to 148.8 ℃, which is high enough to kill bacilli and viruses in 2—8 s. The supply air temperature of the UHT-ACS in a mixing cavity is about 12 ℃ in cooling mode, both on the ground and in the air. The supply air temperature is about 42 ℃ in heating mode. Compared with the ACS of traditional aircraft, the supply air temperatures of the UHT-ACS in the mixing cavity are in good agreement with those of a traditional ACS with 60% fresh air and 40% return air. Fig.2(b) shows



1: Bleed air; 1′: Return air; 2: Mixing air; 3: Air inlet of compressor; 4: Air outlet of compressor; 5: Air outlet of the second heat exchanger; 6: Air inlet of condenser; 7: Air outlet of condenser; 8: Air outlet of water separator; 9: Air inlet of turbine; 10: Expansion air of turbine; 11: Air outlet of turbine; 12: Air inlet of mixing cavity; 13: Air to cabin from mixing cavity

(a) Ultra-high-temperature instantaneous sterilization air conditioning system (UHT-ACS)[52-53]



1: Engine bleed air main line (pipeline); 2: Air conditioning main line; 3: Turbine outlet deicing bypass; 4: Supply air temperature regulating bypass; 5: Turbine outlet temperature regulating bypass; 6: Compressor superheated regulating bypass; 7: Water removal; 8: Ordinary recirculated airline; 9: Ultra-high temperature sterilization recirculated airline; 10: Recirculated air main line; 11: Engine bleed air one-way valve; 12: Primary heat exchanger; 13: Secondary heat exchanger; 14: Water sprinkler; 15: Compressor; 16: Turbine; 17: Compressor superheated regulating valve; 18: Water separator; 19: Temperature sensing and regulating device; 20: Temperature regulating valve; 21: Turbine outlet deicing valve; 22: Supply air temperature regulating valve; 23: Ordinary reculated airline valve; 24: Mixing chamber; 25: Ultra-high temperature sterilization recirculated airline valve; 26: Heater; 27: High temperature injection mixing chamber; 28: Injector; 29: Primary heat exchanger bypass valve; 30: Fan

(b) Ultra-high-temperature sterilization air conditioning system (UHTS-ACS)[54-55]

Fig.2 Novel airplane air conditioning systems

a novel high-temperature sterilization air conditioning system for airplanes created in Refs.[54-55]. Their inventions are in the realms of airplane and civil aviation, namely an airborne air conditioning system for airplanes.

2.2 Tracer gas

Nielsen[56] investigated the performance of two types of PVSs often present in airplane cabins: One incorporated into a neck pillow and the other embedded into the seat (Figs. 3(a, b)). To subjectively quantify the PVSs jet entrainment in a person's breathing zone, the authors employed N_2O as a tracer gas and smoke. Larger drops' PVS response is still unknown. Since the testing solutions were not placed in an airplane environment, they did not record the interactions between the PVS and the airplane general ventilation, as well as the effect of other internal barriers like the occupants' bodies and surrounding row seats. The authors discovered that the PVS combined into the neck pillow is more effective than the PVS integrated into the seat at preventing cross infection. Ref.[17] designed a new idea for airplane climatisation in which the passenger's seat served as the primary indoor air quality (IAQ) and temperature control system, with possibilities for local air supply and exhaust (Fig.3(c)).

(a) PV integrated to seat[56]

(b) PV integrated to neck-support pillow[56]

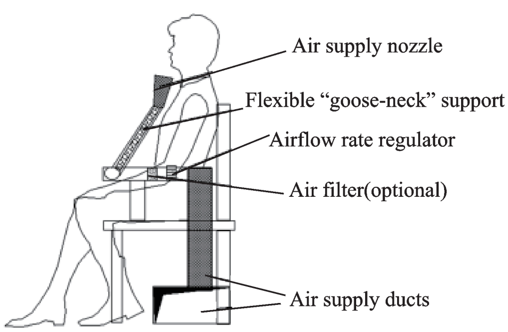
(c) Mock up with the tracer gas probe in breathing zone[17]

(d) Manikin with neck support pillow as personalized ventilation device[14]

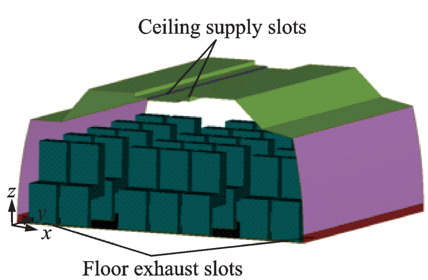
Fig.3 Experimental models of PV[14,17,56]

They measured reductions of contaminant concentration between a factors 2 and 25 by the supply of outside air. Nielsen et al.[14] also developed a personalized ventilation device in the form of a neck support pillow (Fig.3(d)). Their results show that the boundary layer and the process in the breathing zone are rather independent of draught at velocities up to 0.2 m/s.

Ref.[15] compared PVS integrated into the airplane cabin seat armrest (Fig.4) with MVS to a purely MVS while maintaining the same fresh airflow rate in both configurations. A thermal mannequin was taken from an actual, detailed mannequin, as well as pollutants created by the floor and the occupants' skin and noses, were used in the simulation. All of the passengers were given a constant inhalation rate of 1.410 4 m^3/s, with the exception of the index passenger. Infusing CO_2 into an Eulerean frame was used to represent gaseous contaminant dispersion, and both Eulerean and Lagrangean models were used to model aerosol dispersion. The airflow was first calculated using RNG k-turbulence models and typical wall functions. Then, assuming one-way coupling, scattered phase equations were solved. The scattered aerosols were simulated in a Lagrangean frame of reference as spherical particles with a medium diameter of 1 m. These particles were injected at a 20 m/s beginning velocity for 0.5 s in order to simulate horizontal sneezing. The equations used to represent liquid particles were the same as those used to simulate gaseous particles, including the gravitational component, which was neglected in gas simulations. A semi-empirical model with thermophoretic, Brownian, and lift staff forces was utilized to describe the sticking effects of liquid particles on solid surfaces. Expiratory droplets caused by sneezing were observed to traverse more than three rows, though the bulk of them were dropped on interior cabin surface rather than being aired out. PVS combined with MVS was found to conceal up to 60% of the pollutants that would otherwise reach the user in the examined ventilation systems. Ref.[15] and Ref.[18] did not perform any experimental validation.



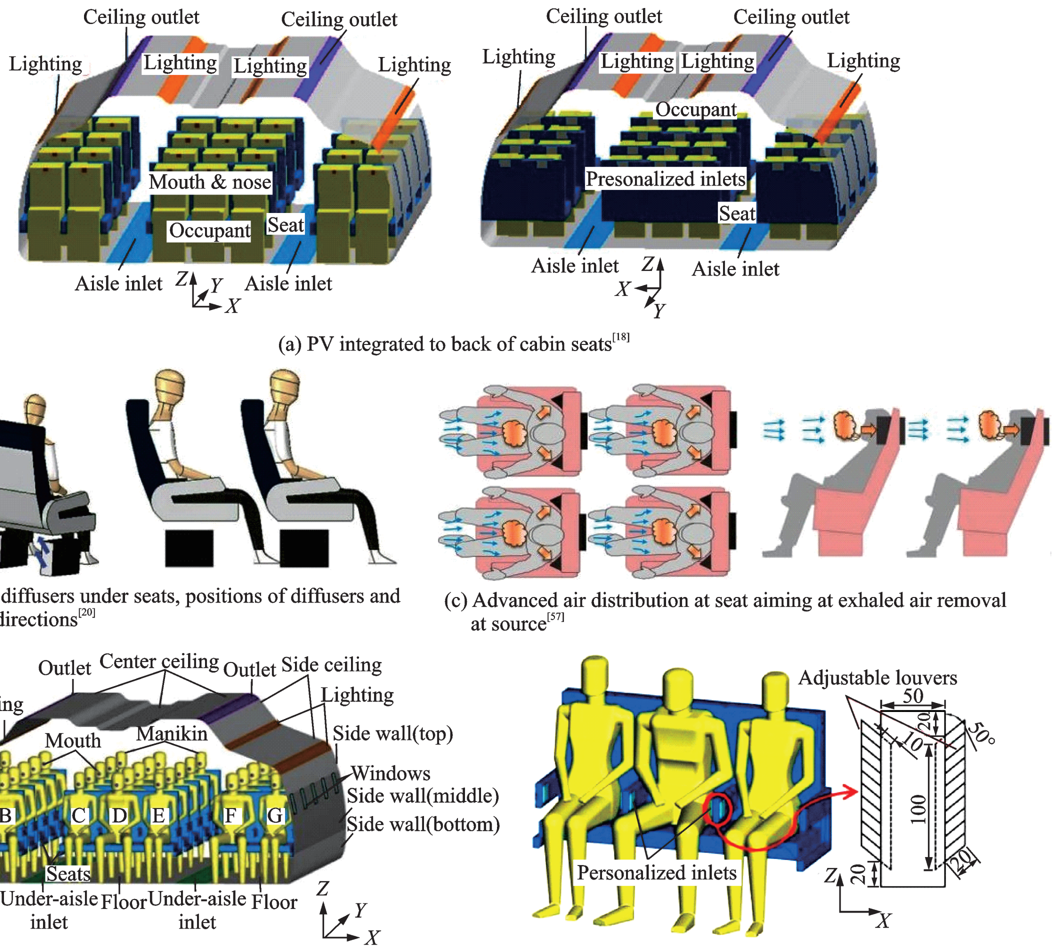
(a) PV installed into armrest of plane's cabin seat



(b) Cabin geometry with supply and exhaust ports in ceiling and floor

Fig.4 Numerical simulation models of PV[15]

Zhang et al.[18] utilized CFD to predict CO_2 dispersion inside airplane cabins, considering for three different forms of ventilation: MVS, DVS, and PVS (Fig.5(a)). Both cabin sides were subjected to a periodicity boundary condition, and the seat was designated as an adiabatic seat, a box-type mannequin with heat dissipation. To make grid generation easier, the cabin was divided into 24 sub-volumes, with hexahedral volumes considered around the passengers. Since the researchers wanted to look at the overall airflow rather than the airflow surrounding the passengers, they used a grid size of about 5 cm. CO_2 was employed as a tracer gas, and the concentration was determined using Euler models after it was constantly delivered at a rate of 5 106 m^3/s/ passenger. Although the authors did not provide experimental confirmation for this study, when compared to MVS, they found that the PVS united with the underfloor air distribution (UFAD) system enhanced passenger air quality. Additionally, You et al.[20] manufactured and installed a proposed ventilation system in an occupied seven-row, single-aisle aircraft cabin mock-up (Fig.5(b)). They discovered that the innovative



(a) PV integrated to back of cabin seats[18]

(b) Individual diffusers under seats, positions of diffusers and air supply directions[20]

(c) Advanced air distribution at seat aiming at exhaled air removal at source[57]

(d) Enlarged view of personal air supply embedded within chair armrests[26]

Fig.5 Different forms of personal air supply in cabin[18,20,26,57]

ventilation system reduced contaminant transport and maintained thermal comfort in the mini-environment cabin. Ref.[57] investigated the effectiveness of individualized ventilation in combination with local suction at each seat in order to reduce airborne cross-infection in the cabin (Fig.5(c)). They discovered a decrease of the tracer gas concentration in the air gasped by the exposed manikin and the exhausted cabin air. Zhang et al.[26] proposed a personal chair-armrest embedded air system (Fig.5(d)). They discovered that the system was robust to prevent the contaminants released at any height to the passenger's breathing region.

3 Methods for Evaluating Thermal Comfort of Airplane Cabins

There are two different models for evaluating thermal comfort in an airplane cabin. The first is a PMV that has been corrected using the human heat balance equation. The second is an adaptive model founded on the departure city's external climate factors. Both models have some restrictions when used to assess the thermal comfort of an airplane mini-environments, despite the fact that they are founded on constant, standard pressure, steady state test information. Low pressure prevails in the majority of airplane cabins. Changes in pressure alter the mass transfer coefficient and convective heat transfer coefficient between the human body and the environment, resulting in changes in the human body's heat dissipation characteristics, for example, variations in convection and skin vaporization[58].

Low air pressure, on the other hand, affects the reduction of air oxygen-pressure, which leads to changes in respiratory function and, ultimately, changes in heat dissipation through breathing. Furthermore, in a small pressure atmosphere, the human body's metabolism, which is a key parameter in these two models, may vary. The accuracy of thermal comfort rating will be severely impacted by changes in metabolic rate.

As a result, these two models can be adjusted based on Refs.[59-60]:

Change the metabolic rate to match the pressure, and Table 2 gives the new equations. In Table 2, at sea level, M_0 indicates metabolic rate at the equivalent level of activity.

Modify the evaporation heat transfer coefficient (h_e) according to pressure

$$h_e = h_{e0}(p'/p'_0)^{-0.45} \tag{1}$$

Modify the convection heat transfer coefficient (h_c) according to pressure

$$h_c = h_{c0}(p'/p'_0)^{0.55} \tag{2}$$

where p'_0 represents the standard atmospheric pressure and p' the ambient pressure. h_{e0} and h_{c0} represent the evaporation and the convection heat transfer coefficients, respectively.

Table 2 Revised calculations of metabolic rate and pressure

Ref.	Impacting factor	Scenario	Fitting formula
[59]	Pressure in atm	Movement	$M = M_0(p'/p'_0)^{-0.76}$
[60]	Pressure in kPa	Seating	$M = -0.005\,09p' + 1.385$

3.1 Corrected PMV model

The PMV equation is[61-62]

$$\mathrm{PMV} = (0.303\mathrm{e}^{-0.36M} + 0.028) \times (M - W - E_{sk} - E_c - E_{lr} - E_{dr} - E_r) \tag{3}$$

where E_{sk} is the heat loss from skin diffusion and perspiration, E_c the convectional heat loss, E_{lr} the heat loss from latent respiration, E_{dr} the heat loss from dry respiration, E_r the heat loss due to radiation, M the metabolic rate, and W the actual mechanical power. The PMV model may evaluate thermal comfort in a location with adequate relative humidity (RH) and sea level pressure, and it predicts PMV using a seven-point thermal sensation scale. However, the cabin pressure and relative humidity of a civil airplane cabin are far lower than those seen at sea level. Numerous terms in the bioheat stability equation will be affected by these lower values. Some terms in Eq.(3) were corrected in Ref.[63] so that it may be used to assess thermal comfort in a cabin mini-environment. They assumed that the air pressure had no effect on the qualities of individual tissues or the insulating properties of worn clothes. Pang et al.[62] just explained how to create a corrected PMV (CPMV) model by correcting several terms in Eq.(3) due to minor cabin relative humidity and pressure.

3.1.1 Skin wittedness

The evaporative heat loss from the skin, E_{sk}, is calculated using the skin wettedness, w, which can be represented as[64-65]

$$w = \frac{\max\{0.42(M - 58.15), 0\} \times R_e}{5733 - 6.99(M - W) - p_a} + w_b \tag{4}$$

where w_b is the basal wittedness, p_a the ambient pressure, and R_e the water vapor resistance of the clothing[66]. RH on intercontinental flights is usually between 5% and 15%. Low RH is observed to alter the skin's basal wettedness in a very dry environment, leading a normal value of 6×10^{-2} to drop to as low as 2×10^{-2} in a very dry environment. To make w_b dependent on RH, the following linear model is proposed as

$$w_b = \min(0.06, 0.02 + \mathrm{RH} \times 10^{-3}) \tag{5}$$

3.1.2 Lewis ratio

R_e in E_{sk} is calculated using the Lewis ratio, L. It is well-defined as the heat to mass diffusivity ratio and has a value of 0.016 5 ℃/Pa at sea level. This value can be modified in Eq.(6) due to the low pressure in a commercial airplane cockpit in flight

$$\frac{L}{L_0} = \frac{p_0}{p} \tag{6}$$

where p denotes cabin pressure and "0" signifies sea level value.

3.1.3 Convective heat transfer coefficient

Heat losses of E_c and E_{sk} are calculated using the convective heat transfer coefficient, h_c. Eq.(7) is a formula for the pressure dependence of convective heat transfer

$$\frac{h_c}{h_{c_0}} = \left(\frac{p}{p_0}\right)^n \tag{7}$$

With these three revised terms, we can calculate Eq.(7) using the approach described in Ref.[67].

3.2 Adaptive model

One more technique for analyzing thermal feeling is to use an adaptive model of the thermal neutrality temperature, T_n. It evaluates the temperature sensation using the outer climate characteristics of the departing city as input data. Eq.(8) should be used to estimate a comfortable temperature range, assuming that the cabin mini-environment is affectedly preserved and that the thermal neutrality temperature feeling does not alter with pressure[68]

$$T_n = 21.5 + 0.11\mathrm{ET}^* \tag{8}$$

where $T_n \pm 2.5$ ℃ is used as the 90% acceptable level in this case. ET^* is a function of the outdoor temperature and RH.

4 Methodologies for Airflow Distribution and Air Quality in Airplane Mini-Environment

Various methodologies have been used in studies of ventilation system in airplane cabins. In research, numerical simulations are compared against experimental measurements, and combination of the two are also used. Table 3 presents a list of research on air quality and airflow distribution in airplane cabin mini-environments published in the past two decades. Other review studies[8,69] employed similar collective tables, but in this study, only research that focused on air quality and airflow in airplane cabin mini-environment are included, and more attention is focused on the studied characteristics and methodology used. To investigate the properties of airflow and air quality in airplane cabins mini-environment, all viable research methodologies were applied on an equal term. The simulation programs, or software, were mostly commercial, for example Fluent or StarCD, with Fluent being the most popular. The reviewed research used a variety of turbulence models, including RANS, LES, and DES.

Table 3 Significant airflow management and air quality investigations in airplane cabins performed in the past 20 years

Ref.	Year	Configuration of airplane	Investigated factor	Experimentation method	Computational method
[70]	2012	Mock-up of Boeing 767 cabin	Impact of individual gaspers on airflow and pollutants movement	Direct CO_2 measurement utilizing non-dispersive infrared sensors	
[71]	2015	Simple mock-up for airplane cabin with real MD-82 gasper	Velocity and turbulence intensity provided by gasper	Hotwire anemometry	
[72]	2015	Airbus A320 mock-up	Impact of utilizing individual inlet on passenger thermal comfort	Constant thermal sensation surveys and hotwire anemometry	
[73]	2016	Five-row section in real MD-82 cabin	Impact of gaspers on airflow and hazardous contaminant concentration	Photoacoustic multi-gas analysis, hotwire and ultrasonic anemometry	
[74]	2007	Boeing 767-300-CFD cabin model	Impact of innovative VS on velocity and carbon dioxide.		RNG k-ε
[75]	2010	Wide-body-CFD cabin model	Impact of innovative ventilation system on airflow and pollutant concentrations		RNG k-ε
[76]	2016	Airbus A340-600-CFD cabin model	Impacts of utilizing revised MVS and gaspers on passenger thermal comfort		RNG k-ε
[19]	2010	CFD cabin model and mock-up of single-seat experimental	Impacts of a novel PVS on air-velocity and relative humidity (RH)	SAFEX fog was used to visualize airflow and PIV	RNG k-ε
[26]	2012	Twin-aisle airplane cabin mock-up	Impacts of a novel PVS on contamination	Direct CO_2 measurement and ultrasonic anemometry	RNG k-ε
[77]	2016	Mock-up of simple airplane cabin	Airflow and temperature induced by gasper	Spherical anemometry and PIV	RNG k-ε
[78]	2012	MD-82 aircraft cabin	Velocity magnitude, velocity direction, and 30 turbulence intensity	Hot-sphere anemometer (HSA) and ultrasonic 29 anemometers (UA)	

5 Study Progress of Thermal Comfort in Airplane Mini-Environment

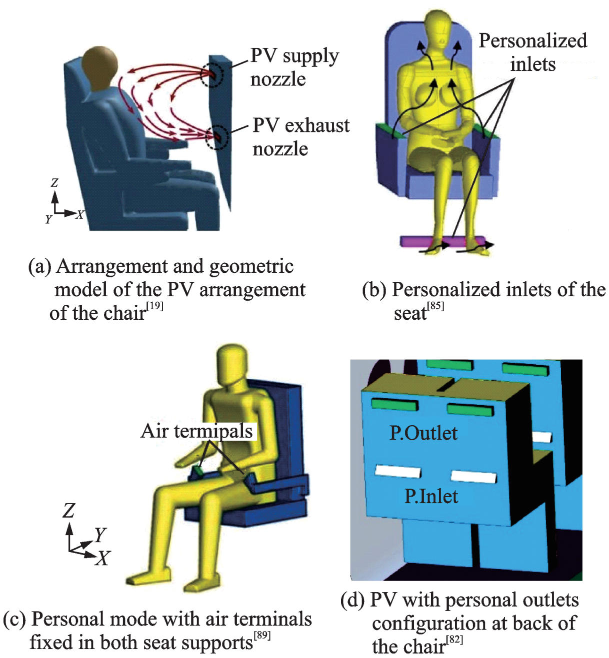
The temperature, relative humidity and air velocity in the aircraft cabin are all controlled through air distribution. As a result, air distribution plays a crucial role in the aircraft's environmental control system (ECS) design. Improved air quality, pollution management, energy savings, and comfort all require effective ventilation and airflow organization. Commercial airplanes frequently employ the mixing ventilation (MV) system. The contaminated air is discharged from the outlet close to the floor[79], while high velocity from the top. High-speed air mixing has an impact on not just air quality and human comfort, but also human health. As a result, numerous academics have examined the MV system and made changes as a result. CFD technology, on the other hand, has become a significant approach to analyze the flow field[80-81] due to its ease and higher precision, and it also shows a significant part in the research of airplane cabin flow field. In order to depict the distribution of indoor airflow, a numerical study of airflow might take into account a variety of internal disturbances, boundary conditions, and starting circumstances. As a result, determining the appropriate air supply and then guiding the strategy to realize good ventilation is simple.

As a result, several aircraft cabin thermal comfort studies have been conducted using CFD and related commercial software, as shown in Table 4. Additionally, certain new ventilation techniques, like the DVS and the PVS, have been proposed to increase the cabin's thermal comfort. The DVS is more successful at removing contaminants than standard airliner airflow[86]. The use of a DVS in the cabin was proposed by Zhang et al.[18] The air inlet was under the passageway, while the outlet was at the ceiling. The energy consumption of the DVS is lower than that of the MVS, and its installation is useful to improving the aircraft's energy efficiency. However, one of the DVS's most common problems is that it is possible to induce temperature discomfort and stratification[87]. Maier et al.[88] found that with modest air velocities, DVS might create a suitable climatic environment in the airplane passenger cabin. Despite the fact that the known disadvantages of MVs were validated, they have no impact on the subjects' satisfaction ratings. The PVS may effectively remove pollutants by supplying fresh air straight to the traveler's breathing region. Zhang et al.[89] recommended that a PVS was installed in the cabin. For the PVS, a personalized inlet was fitted in the back of the passenger seat. The PVS can reduce air mixing, which is particularly good for pollutant emissions in the area of passengers. Ref.[19] suggested another PV system

Table 4 Summarization of flow field study in airplane cabin mini-environment

Ref.	Year	Study method	Airplane cabin	Study contents	Process	Assessment method of thermal comfort	Other parameter
[82]	2021	Fluent	Boeing-767	MV, DV and PV system	Steady	PMV, PPD	Relative humidity, velocity, temperature distribution and age of air
[20]	2018	Fluent/Experimentation	Boeing-737	MV, DV and PV system	Steady	PMV, PPD	Air temperature distributions, SF6 concentration distribution
[83]	2015	Fluent	Boeing-767	MV, DV and PV system	Steady	PMV, PPD	Relative humidity, velocity, temperature distribution and age of air, draft (DR) and CO_2 concentration
[84]	2013	Fluent	Boeing-737	MV and PV system	Steady	PMV, PPD	Velocity and temperature distribution
[85]	2014	Fluent	Single-aisle cabin	PV and MV system	Steady	PMV, PPD	DR
[19]	2010	Fluent	Boeing-767	PV and MV system	Steady	Not accounted for	Relative humidity distribution
[18]	2007	Fluent	Boeing-767	MV, DV and PV system	Steady	Not accounted for	CO_2 concentration

that took into account the issue of humidifying cabin air. The passenger's personal inlet was fitted at the rear of the seat in front of him/her, as illustrated in Fig.6(a), and an air outlet was placed slightly below the inlet. In addition, Ref.[85] created a novel PVS type as indicated in Fig.6(b), At the armrest and the bottom of the customized seat, there were full fresh air supply vents added, as well as an air input for circulating air. The PVS, on the other hand, could cause temperature stratification[15]. Zhang et al.[89] also proposed personal mode with air terminals fixed in both seat supports as can be seen in Fig. 6(c). Ref.[82] studied the passenger thermal comfort in a new proposed personal mode with personal outlets configuration in front of the passenger (directly to the face) as can be seen in Fig.6(d). Their study found that the proposed system provided an acceptable thermal environment aircraft cabin. This review discovered that the majority of thermal comfort studies on airplane cabins were concentrated on small single-channel airliners based on literature research. Wide-body airplanes, on the other hand, will be the primary development direction for airplane cabins in the future. The flow field in a wide-body airplane will be very difficult, therefore optimizing the wide-body airliner's air supply system will be a major concern.



(a) Arrangement and geometric model of the PV arrangement of the chair[19]

(b) Personalized inlets of the seat[85]

(c) Personal mode with air terminals fixed in both seat supports[89]

(d) PV with personal outlets configuration at back of the chair[82]

Fig.6 Different forms of personal air supply of seat[19,82,85,89]

6 Characteristics and Limitations of Numerical Modeling

6.1 Grid independence study, validation and identification of errors

The initial and boundary conditions are the most significant limitations, which many people ignore. The boundary and initial conditions are instances of the exact time and space solution. If a researcher does not have access to an experimental setup, CFD is an option to investigate some parameters, and numerical simulation may be used to validate some experimental outcomes. One of the primary foundations of numerical simulation is the confirmation and evaluation of computations generated using a given code or approach. Only a fraction of the code's computations for a case study may be validated, hence a numerical code cannot be validated in its entirety[90]. A variety of methods are used to quantify the difference between experimentally measured and numerically estimated values. The most popular way to quantify and communicate the amount of error between observed and predicted results is to use simple or root mean square(RMS) error percentages. However, in other circumstances, such as ventilation, airflow, and air quality investigations, this method may produce inflated, non-representative, and imprecise error predictions. The mean fractional bias (FB) and the normalized mean square error(NMSE) are two good indicators established by Hanna[91] to describe the inaccuracy in atmospheric air quality models between observed and anticipated concentrations. Calculated error in FB and NMSE differs from absolute error percentages in a few ways. The FB characterizes the discrepancy between experimental and expected values, whereas the difference between observed and expected values is denoted by the NMSE. The FB and NMSE can be used in air quality studies with any physical amount[92].

Another important component for numerical simulations is meshing, or discretization, of a CFD model domain. The quantity of grid elements, or nodes, that can be generated in a single domain varies significantly relying on the domain's size and grid elements. Since each element or node in the constructed grid receives a numerical solution of the governing equations, the number of elements or nodes in the grid, as well as their placement in the grid, can have a significant impact on the numerical findings' correctness. Another significant factor in the computing cost and accuracy of CFD simulations is the number 72 of cells. Numerous CFD studies have performed grid independence tests (GITs)[93]. GIT, a precise method for verifying the numerical solution's degree of independence from grid size and configuration changes, was required. This test is commonly used to determine the coarse, medium, and fine refinement levels of a grid. Grid independence testing was previously accomplished by comparing the generated solution for each grid level to the other two levels on a constant spatial part within the domain, for example a line or surface. For subsequent use, the grid level whose solution has appropriate grid independency is chosen. The grid convergence index (GCI) was established by Roache as a more demonstrative statistic for grid refinement experiments. Using an asymptotic method, the GCI calculates the level of uncertainty in grid convergence[90]. GCI, like the GIT, uses the solution on three separate grid levels and these grids may be built using grid coarsening instead of grid refinement[90]. GCI is a numerical value that indicates how near the solution is to convergence between two grid levels, or between the coarsest grid level, which serves as a guideline, and each of the additional grids. GCI has been utilized to quantify grid convergence in many air-flow and air-quality research, whether in airplane cabin[94], or other enclosed spaces[95]. It is vital to remember that grid convergence is not always applicable to incomplete models like the LES model. If none of the constituent equations in a model are flow dependent, it is said to be complete. Examples of such requirements include material properties, beginning and boundary conditions, and numerical discretization. GCI may not equal zero or even be reduced by successive mesh refinement, as it is with models redefined at a certain length scale. For example, the LES model formulates and solves a large number of partial differential equations at above-grid and sub-grid scales[90].

6.2 Turbulence modeling

Since present computer capacity and speed are insufficient to simulate the characteristics of turbulence flow in an airliner's cabin, turbulence models must be used in CFD simulations of air distributions in airliner cabins. Liu et al.[96] suggested large-eddy simulations (LES) and detached-eddy simulations (DES) among numerous turbulence models for airflow studies in airplane cabins. On the other hand, these models need a long computation time and a high mesh density. The LES model, according to Ref.[97], gave the most precise flow features, whereas the v2f and renormalization RNG k-ε models might produce satisfactory outcomes with significantly less computing period. The RNG k-ε model was used to simulate cabin flows because it is one of the most widely utilized turbulence models in design practice. Because the airflow in an airplane cabin can be transitory, the researchers modeled the flow as transient or unsteady in their simulation. The RNG k-ε model's governing equations can be expressed in a general form for both steady and transient flows.

$$\rho\frac{\partial\bar{\phi}}{\partial_t}+\rho\bar{u}_i\frac{\partial\bar{\phi}}{\partial_t}-\frac{\partial}{\partial_{xi}}\left(\Gamma_{\phi,\mathrm{eff}}\frac{\partial\bar{\phi}}{\partial_{xi}}\right)=S_\phi \tag{9}$$

where ϕ represents the pollutant concentration, S_ϕ the mass flow rate of the source (per unit volume) and Γ_ϕ the diffusion coefficient. When $\phi=1$, Eq.(9) becomes the continuity equation. Furthermore, CFD models have a tendency to resolve the partial differential equations that govern flow and dispersion at a local level in the simulated area. The nature of the induced flow turbulence, on the other hand, is nonlocal, and even the tiniest alteration at one location might influence the flow faraway in the domain[98]. As a result of this, different numerical turbulence models use different methodologies to simulate flow turbulence with varying accuracies and proportionate processing costs. An evaluation of the four basic groups of turbulence models is shown in Table 5.

Table 5 Types of numerical turbulence models used in the literatures for airflow and air quality researches

Turbulence model	Concept of modeling	Utilization complications	Conclusions based on research	Ref.
DNS	All turbulent eddies and length/time ranges are precisely and accurately simulated	Simulations of ventilation are quite difficult	For indoor flow simulation, the DNS model is unsuitable	[99]
LES	Smaller eddies are modelled, whereas larger eddies are analyzed in detail	To resolve large eddies, the entire domain requires a very fine mesh	LES is best suited to natural convection flows with a low Rayleigh number and induced convection flows with low turbulence.	[98]
			In a room, for forced or mixed convection airflow, the LES-DSL is the ideal option.	[100]
			In computing mixed convection flow in full airplane cabins, the LES outperforms the DES and RNG k-models.	[101]
			For residential and environmental airflows, including heat transmission, LES outperforms RANS models.	[102—106]
DES	Hybrid modeling uses both LES and RANS models at the same time	Most ventilation models make it difficult to apply	In empty airplane cabins, DES is useful for projecting mixed convection airflow.	[101, 107]
RANS	Separately, the fluctuation and time-averaged elements of the flow are solved	Because accuracy is low, selecting the best RANS model for the simulated situation is difficult	In a model for an arena, the standard RNG k-ε model accurately estimates airflow.	[96, 108]
			For simulations of interior airflow, the RNG k-ε model surpasses the normal k-model.	[109]

6.3 Models for particle tracking

A particle tracking model is necessary for air quality models that include particulate pollution dispersion. There are two types of numerical particle tracking models: Eulerian and Lagrangian. The Eulerian models treat the particles as a continuous phase, similar to the fluid in which they disperse, and use a control volume technique to solve their governing equations. Lagrangian models, which solve equations for particle motion to create unique trajectories, treat particles as discrete phases[74, 99]. The discrete random walk (DRW), which demonstrates that the fluctuating components of velocities follow a Gaussian probability distribution, is the most often used Lagrangian particle tracking model[100]. The Eulerian particle tracking strategy is represented by the single fluid model, mixture model, and drift flux model, whereas the Eulerian particle tracking technique is represented by the single fluid model, mixture model, and drift flux model. Several studies carried out during the last two decades compared the predictions of several numerical particle tracking models in closed environments to experiments[74, 110-111]. The DRW model was recommended for the Lagrangian technique and the drift flux model for the Eulerian approach during the experiments[112-113]. While Lagrangian models are widely utilized in particle tracking simulations and are included in the majority of commercial CFD software[114], Hybrid models that combine Eulerian and Lagrangian approaches have attracted the interest of numerous scholars. The solved equations in such models are divided into two categories: Adjective and diffusive. The adjective component is solved as a symmetric diagonally dominating system, which eliminates associated numerical mistakes and allows large Courant numbers for the flow[115-116].

7 Impact and Recommendation of Aircraft Ventilation Systems on COVID-19 Transmission Onboard

It is vital to identify cost-effective intervention techniques to limit COVID-19 transmission aboard planes, especially as new SARS-CoV2 variants arise. Different ventilation approaches have been examined as COVID-19 transmission control measures on planes. Essentially, each ventilation system's efficiency is determined by the amount of ventilation it provides. The fraction of the outside fresh air provided to the cabin that reaches the occupants' breathing zone is referred to as ventilation efficacy in aircraft cabins[11]. After being filtered, mixing ventilation is the major technique for providing a mixture of outside fresh air and recirculated air from the cabin to the aircraft occupants in various ratios. Depending on the aircraft type, air enters at specific volumetric rates from supply inlets situated above or below the luggage compartment in the cabin. It then circulates through the cabin under the influence of inertial, viscous, and body forces[101] before exiting through the exhaust slots on both sides of the cabin at the floor level. Talaat et al.[117] compared aerosol transmission in three models created by this ventilation strategy: (a) A full-capacity model (60 passengers), (b) a reduced-capacity model (40 passengers), and (c) a full-capacity model with sneeze guards/shields between passengers. They employed Lagrangian simulations to describe aerosol movement with particle sizes ranging from 1 to 50 μm, which includes aerosols produced by breathing, speaking, and coughing. The study by Talaat et al.[117] was focused with relative comparisons of various models and intervention measures. In all of the models, the authors did not draw any conclusions about the expected number of infections, necessitating characterization of the probability density functions of viral shedding rates and the infectious dosage of SARS-CoV-2. The usage of sneeze shields/guards was recommended based on a comparison to the commonly used intervention technique of lowering passenger capacity by vacating middle seats. Yan et al.[118] used a computer model to study the transmission of COVID-19 by cough-induced particles in a Boeing 737 cabin section. In each case, one passenger coughed, and cough particles with measured size distributions were released and tracked using the Lagrangian framework. Their findings demonstrated that cough flow emitted by passengers might quickly build into a strong turbulent cough jet, causing the local airflow field to break up.

Yan et al.[118] observed that cough particles generated by the middle-seat passenger were easily confined in his or her own local environment due to ventilation design and seating arrangement. Cough particles emitted by passengers in aisle seats posed the least risk of exposure to adjacent passengers. Zee et al.[119] studied the track particles exhaled by a passenger assigned to different seats on a Boeing 737 airplane to describe the transfer of respiratory infections during commercial air travel. Zhang et al.[120] built and designed a cabin model of a seven-row Airbus A320 airplane to simulate SARS-CoV-2 transmission in the cabin with a virus carrier using the CFD modeling tool in their study. Their findings demonstrated that the virus spreads to the cabin ceiling within 50 s of the virus carrier breathing normally. When one coughed, the virus spread to the front three rows, where the mass proportion was larger.

As an alternative to the general mixing scenario within the airplane cabin space, displacement ventilation was proposed and researched. Air is supplied vertically from an under-floor plenum, usually beneath the aisles, through perforated or nozzle vents in such systems. The surrounding thermal loads, largely released from occupants' bodies, heat the supplied cool air as it goes up the height of the cabin. The buoyancy effect promotes stratification, which allows the heated air to escape through the ceiling exhaust vents. However, the various pollutants are held in a thick layer at the ceiling by this rising warm air, waiting for the next fresh air wave to force them out. Although this ventilation scenario improves pollutant dilution in the cabin air, retained toxins in the upper air layer are close to the passengers' breathing level and may pose health hazards. Zhang et al.[18] used a displacement ventilation system in a CFD model for a part of a Boeing 767 airplane cabin. It was discovered that slight air mixing occurred at the center seats, implying that with displacement ventilation, the risk of pollutant dissemination and cross infection exists to some extent. In aircraft cabins, personalized ventilation systems showed the highest promise for improving air quality and reducing cross-infection[15,18,82]. As a result, greater research should be focused on the potential of personalized ventilation systems in limiting COV-

ID-19 transmission in the sick person's microenvironment. These actions are known as shielding effects. For instance, the shielding effects of personalized ventilation can be examined using innovative, but in reality, cabin seat configurations with air inlets near the occupants' faces, or changed overhead gasper arrangements can improve their protective efficiency. Investigation of the used ventilation systems aboard such unique airliners, as well as the resulting airflow patterns in each deck's cabin, is necessary with the development of new aircraft types and designs, such as the double-decker and multi-deck aircraft. A new study direction like this could open the way for multi-cabin COVID-19 dispersion experiments in the near future.

8 Future Research Ideas and Research Gaps

8.1 Determination of pollutant levels and characteristics in mini-environment airplane cabin

Researchers should analyze or investigate a novel personnel ventilation system and a new environmental control system with purification equipment, such as the airplane ultra-high-temperature sterilization air conditioning system and sterilization method[52,54], to maintain the air quality in the cabin healthy for passengers, particularly during an epidemic like SARS-CoV-2. Future studies can use gas sampling trees with developed spatial resolution and better sensor placement in the cabins to attain the best concentration measurement accuracy possible. Another factor to consider is the necessity for further in-depth research into the spreading and removal features of some hazardous gaseous substances, for example disinfection pesticides, which are now widely used on many commercial airplanes. Some research[26,121-122] that investigated gaseous pollutant concentrations in airplane cabin mini-environments used portable and "hand-held" air or gas samplers and "photometers", which had limited precision and could not determine a wide concentration in vast areas. A steady collection of sensors or well-applied sample lines are necessary for decreasing human sampling errors. Some scientists utilized a data acquisition (DAQ) system to assess gas concentrations in airplane cabins using a fixed-sensor technique[70,123-124]. Passengers inhaling pesticides may entail health hazards that have been missed in the literature and should be investigated further. More focus can be placed on leading onboard live testing for the infectivity and survival of the microorganisms included in the droplets for particle pollutants aboard airplanes, particularly those created from expiratory activities.

8.2 Approaches to air quality study in suggested mini-environment aircraft cabins

Culture methods like culture dishes can be employed onboard airplanes to investigate the viability and infectivity of airborne viruses. Using culture dishes or media plates to collect airborne pathogen samples and allowing them to incubate, or grow, in cabin temperature, relative humidity, and air composition conditions can provide a more realistic picture of the true risk of infection. Laboratory procedures like as polymerase chain reaction (PCR) and plaque assay methods[125] can be employed to improve and confirm the results of the plane culture methods. Custom wall functions can provide more accurate numerical predictions for numerical modeling methodologies of airflow and pollutant movement, either by altering current functions or adopting new rules for the wall. Another option is to use other transport models with the traditional Navier-Stokes equations. The Lattice-Boltzmann method (LBM) is an example. Rather than the usual continuum-based Navier-Stokes model[126], it is founded that on complicated fluid flow fields, mesoscopic equations, and "microscopic collision" models were suitable[127]. LBM models have also been found to be faster than Navier-Stokes models when using parallel computation.

9 Conclusions

The present study conducts a systematic evaluation of air quality, dispersion of airborne expiratory pollutants and thermal comfort in aircraft cabin mini-environments using a critical examination of significant studies conducted over the last two decades.

Expiratory activities such as coughing, breathing, and sneezing produce the most common particle pollutants, with coughing obtaining the most research attention. It was discovered that, due to a lack of suitable methods to release and analyze trace gases in the mid-nineteenth century, research on particle pollutants was 50 years ahead of that on gases. Mean radiant temperature, colored light, low relative humidity, human metabolic rate, and gender are all elements that influence the thermal comfort of a human body in an airplane cabin mini-environment, with the first three being environmental factors and the other two being human characteristics. Some studies have attained good agreement levels in the pollutant concentration fields.

The main equipment required to investigate the spread of airborne expiratory contaminants inside airplane cabins could be identified based on the presented paper, and a discussion about a mechanism for evaluating airline personal ventilation technologies for indoor air quality may begin. Mixing, displacement and customized systems are the three basic types of airflow distribution that are used in airplane ventilation systems. Although scientists continue to argue the benefits and drawbacks of operating systems like MVS and DVS, there is general agreement that PVSs deliver better air-quality for passengers than traditional ventilation systems.

Studies of air-flow and air-quality in airplane cabin mini-environment have used a number of study methods, ranging from purely experimental to completely numerical, or a combination of both. According to the literature, every conceivable study methodology has been used to evaluate air-flow and air-quality in the mini-environment of airplane cabins on a nearly equal basis. In fact, the numerical approaches employed were limited. For all airplane air-flow and air quality studies, no single study method or collection of study observes is the most appropriate. As a result, specific best practices for airplane air-flow and air-quality research have been suggested, based on the literature and dependent on the study possibility and research approach.

Finally, study gaps are mentioned in relation to each of the article's investigated concerns. Future study should include developments and innovative methods in experimental and numerical studies. Scientists should look into a novel personal ventilation system as well as a new environment control system with purification equipment, such as the aircraft ultra-high-temperature sterilization air conditioning system and sterilization method. Future experimental investigations should focus on culture methodologies and spatially distributed measurements. More complex wall functions, LBM, and turbulence models may be useful in future numerical CFD investigations.

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个性化空调系统对飞机座舱微环境空气品质和热舒适性的影响综述

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摘要:对近20年来的飞机座舱空气调节方法进行了综述。首先,对飞机座舱微环境下的空气质量、污染物扩散、热舒适性等进行了分析评估。然后,阐述了飞机座舱空气环境研究的实验和数值方法。最后,进一步分析了相关研究方法的优缺点,并对不同研究方法的前瞻性研究对象和新一代环控系统进行了展望。

关键词:个性化空调系统;计算流体力学;微环境;飞行器;热舒适性