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STUDY ON THE AIRWORTHINESS AND COMFORTABLENESS REQUIREMENTS OF AIRCRAFT CABIN AIR CONTAMINATIONS

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Abstract

Airworthiness regulations give the requirements of aircraft cabin air contaminations concentrations (carbon monoxide (CO), carbon dioxide (CO_2), ozone (O_3), etc.), which are the most basic and minimum safety requirements. While, modern civil aircraft design can not only meet the airworthiness regulatory requirements, but also satisfy high level industry standards in order to improving the comfortableness of the cabin. Therefore, according to the influence of cabin air contaminations on the crew and passengers, three limit levels (safety, health and comfortable limits) of cabin air contamination conditions are defined here. Moreover, recommended three limit levels of aircraft cabin air contaminations concentrations are established, by analyzing and summarizing the current effective airworthiness regulations and industry standards requirements on cabin air contamination, such as carbon monoxide (CO), carbon dioxide (CO_2), ozone (O_3), particulate contaminants (PM2.5, PM10), and volatile organic compounds (VOCs). The results of this work can be referenced for the design of air conditioning system as well as cabin safety and comfortableness of modern civil aircraft.

Key words: aircraft cabin air contaminations, airworthiness requirements, safety limits, comfortableness

1. Introduction

The aircraft cabin is a unique and relatively closed space with high occupant density, low humidity, limited ventilation capacity, small range of occupant activity, and different from many other indoor environments (including some other transportation vehicles). Occupants cannot remove themselves from this environment. In addition to temperature and humidity, ventilation, noise and vibration, exposure to cabin pollution will also affect the comfort of occupants. For example, when a passenger suffers from COVID-19, it will cause other occupants to be exposed to COVID-19 virus, which is at great risk of infection. Moreover, cabin ventilation air comes from compressed air in aircraft engines and auxiliary power units, and the bleed air from engines containing compounds may enter aircraft ventilation system and pollute the aircraft cabin air. Therefore, the design of the cabin environment system and the maintenance or operation of the route are designed to provide occupants with a safe, healthy and comfortable cabin environment.

Based on the analysis of the airworthiness technical requirements of aircraft cabin ventilation and air pollutants, and combined with the current effective relevant industrial standards, this paper defines three levels of cabin air quality standards: safety limits, health limits and comfort limits. Then select the cabin ventilation, carbon monoxide (CO), carbon dioxide (CO_2), ozone (O_3), particulate pollution (PM2.5, PM10), volatile organic pollutant (VOCs) concentration and other cabin air quality related parameters, analyze the impact of pollutants on the occupants, and as far as possible according to the requirements of safety, health and comfort, analyze and summarize the reasonable value range of these cabin air quality related parameters corresponding to the three levels. Finally, taking the transport aircraft as an example, the Methods of Compliance (MC) and guidance of the airworthiness requirements of the pollutants in the cabin are given. The research results can provide reference for the design of cabin environment system of transport aircraft (Part 25 aircraft and Part 29 rotorcraft).

2. Analysis of Airworthiness Requirements of Aircraft Cabin Air Pollutants

The possible pollutants and sources of pollutants in the air of the aircraft cockpit are shown in the table below.

Table 1 – Pollutants that may exist in aircraft cabins and their sources

Possible pollutants	Possible sources
CO	The products of incomplete combustion and thermal degradation of fuel and hydraulic oil enter the cockpit through aircraft environmental control system and air-conditioning system.
CO_2	Aircraft kitchen uses dry ice, occupant breathing exhaust, and external air introduction.
O_3	Introduction of high-altitude external air.
PM 2.5	Equipment generation, external air, incomplete combustion of fuel, occupant activity.
PM 10	Equipment generation, external air, incomplete combustion of fuel, occupant activity.
Aldehydes, organophosphates, carboxylic acids, olefins, alkanes, ketones, etc.	Volatilization of fuel oil, lubricating oil, hydraulic oil, hand sanitizer, corrosion resistant paint, or incomplete combustion and thermal degradation products.
Pyrethroid	Insecticide

The airworthiness standard of civil transport aircraft (CCAR/FAR/CS 25) puts forward clear requirements for air ventilation and pollutant concentration in the aircraft cabin. CCAR/FAR/CS 25.831(a) requires that aircraft ventilation systems must provide an adequate amount of uncontaminated air, usually at least 250g (0.55lb) of fresh air per minute for each occupant. Under possible failure conditions (such as the failure of one of the two air conditioning systems), the ventilation system is designed to ensure that there is enough fresh air to prevent the accumulation of polluting gases such as carbon dioxide, and in any case exceeding 5 minutes, the supply of fresh air is not less than 182g(0.4lb) per occupant. A temporary air flow reduction is also acceptable, as long as the environment in the cabin is maintained at a level that is not harmful to the occupants. Temporary air flow reduction means that some aircraft turn off the intake of the environmental control system during take-off in order to gain more thrust and save fuel during take-off. In this short period of time, there is no fresh air supply in the cabin.

25.831(b) requires that crew and passenger compartment air must be free from harmful or hazardous concentrations of gases or vapors, and further clarifies that: (1) Carbon monoxide concentrations in excess of 1 part in 20,000 parts of air are considered hazardous. (2) Carbon dioxide concentration during flight must be shown not to exceed 0.5 percent by volume (sea level equivalent) in compartments normally occupied by passengers or crewmembers. The airworthiness standard for civil transport rotorcraft (CCAR/FAR/CS Part 29) also has basically the same requirements, except that 29.831(a) requires that each crew member should be provided with no less than 283L (10 cubic feet) of fresh air per minute, and there is no specific requirement for other occupants.

When the aircraft is cruising at high altitude, the concentration of ozone in the external air is relatively high, which can enter the cabin through the aircraft air conditioning system, which poses a hazard to the occupants. Therefore, CCAR/FAR/CS 25.832 sets out the requirements for the concentration of ozone in the cockpit: (1) 0.25 parts per million by volume, sea level equivalent, at any time above flight level 320; and (2) 0.1 parts per million by volume, sea level equivalent, time-weighted average during any 3-hour interval above flight level 270. Therefore, in order to ensure that the concentration of ozone in the cockpit does not exceed the standard, it is generally necessary to add an ozone conversion device for to remove part of the ozone in the bleed air from engines.

Although the airworthiness standard does not give clear requirements for other pollutants except CO,

CO_2 and O_3, the 25.831(b) "crew and passenger compartment air must be free from harmful or hazardous concentrations of gases or vapors ", presents the all cabin pollutants requirements. The specific safety concentration and other requirements need to be clearly defined when determining airworthiness methods of compliance and criteria.

3. Classification of Aircraft Cabin Air Pollutants Limits

In order to study the effects of cabin ventilation and pollutants on the safety and health of occupants, and to clarify the requirements of aircraft cabin ventilation and allowable concentration of pollutants, the air quality environment of aircraft cockpit is divided into three limit levels: safety, health and comfort, which are defined as follows:

(1) Safety limits: limits for cabin environment parameters that if exceeded would prevent the safe operation of the aircraft. Safety limits is the minimum requirements that the crew can safely operate the aircraft, which can be understood as equivalent to the airworthiness requirement of the aircraft, and must be met.

(2) Health limits: limits for cabin environment parameters that if exceeded would lead to temporary or permanent pathological effects to the occupants. Air quality exceeding the health limit will not only hinder the safe operation of the aircraft by the crew, but may even cause temporary or permanent ill effects on the crew, which shows that the effect of health limit is more serious than the safety limit.

(3) Comfort limits: limits for cabin environment parameters that if exceeded would not achieve an acceptable cabin environment.

Therefore, in general, for the same environmental conditions, the three limit levels are ranked from the lowest to the highest as: health limits < safety limits < comfort limits. For civil aircraft, in order to ensure the safe operation of the aircraft, the requirements of safety limits must be met.

Cabin ventilation, CO, CO_2, O_3, PM2.5, PM10, volatile organic pollutants (VOCs) and other cabin air quality related parameters have been selected; as far as possible according to safety, health, comfort three different limits levels of requirements, by carding analysis and summary of the existing airworthiness standards and industrial standards, the cabin air quality related parameters reasonable ranges have been established.

3.1 Cabin Ventilation

Different standards give different requirements for cabin ventilation, but most of them are based on the requirements of CCAR/FAR 25.831: the minimum amount of ventilation per occupant should be 0.25kg/min (0.55lb/min) in normal operation, and the minimum rate allowed in case of failure is 0.18kg/min (0.4lb/min). According to the air density 1.20kg/m^3 at 20℃, 0.25 kg/min is about 3.5L/s and 0.18 kg/min is about equal to 2.5L/s. These are basically consistent with the requirements of ASHRAE STD 161 and ASHRAE GUIDELINE 28 standards.

Therefore, summing up the above relevant standard requirements, it is recommended that the reasonable range of values for the three levels of safety, health and comfort limits for cabin ventilation are shown in the following table:

Table 2 – Recommended safety, health and comfort limits for cabin ventilation

Level	Requirements	Notes
Safety limits	The minimum amount of ventilation per occupant should be 0.25kg/min (0.55lb/min) in normal operation, and the minimum rate allowed in case of failure is 0.18kg/min (0.4lb/min)	CCAR/FAR/CS 25.831 SAE AIR4766 ASHRAE STD 161, GUIDELINE 28
Health limits	The minimum amount of ventilation per occupant should be 0.25kg/min (0.55lb/min, 3.5L/s)	ASHRAE STD 161, GUIDELINE 28
Comfort limits	The minimum amount of ventilation per occupant should be 9.4L/s	

3.2 CO

For the concentration of cabin CO, most standards adopt the requirements of CCAR/FAR/CS 25.831(b)(1): carbon monoxide concentrations in excess of 1/20,000 of air (i.e. 50ppmV) are considered hazardous. Therefore, this requirement can be regarded as a safety limit for the concentration of carbon monoxide in the cabin.

Therefore, summing up relevant standards such as ASD-STAN TR 4618, it is recommended that the reasonable range of values for the three levels of safety, health and comfort limits for cabin CO are shown in the following table:

Table 3 – Recommended safety, health and comfort limits for cabin CO

Level	Requirements	Notes
Safety limits	581mg/m^3 (50ppmV), peak value	CCAR/FAR/CS 25.831(b)(1)
Health limits	29.1mg/m^3 (25ppmV) TWA 1h 11.6mg/m^3 (10ppmV) TWA 8h	WHO/LQL
Comfort limits	——	CO is colorless and tasteless, and generally does not considered to be one of comfort indexes.

3.3 CO_2

For the concentration of cabin CO_2, most standards adopt the requirements of CCAR/FAR/CS 25.831(b)(2): carbon dioxide concentration during flight must be shown not to exceed 0.5 percent by volume (sea level equivalent) in compartments normally occupied by passengers or crewmembers. 0.5 percent by volume is equal to 5000ppmV.Therefore, this requirement can be regarded as a safety limit for the concentration of CO_2 in the cabin.

Therefore, summing up relevant standards such as ASD-STAN TR 4618, it is recommended that the reasonable range of values for the three levels of safety, health and comfort limits for cabin CO_2 are shown in the following table:

Table 4 – Recommended safety, health and comfort limits for cabin CO_2

Level	Requirements	Notes
Safety limits	9130mg/m^3 (5000ppmV)	CCAR/FAR/CS 25.831(b)(2)
Health limits	36520mg/m^3（20000ppmV） （15 minutes exposure）	EU TLV, ‘Technical rules for hazardous substances (TRGS) 402 and 900, Germany
Comfort limits	3650mg/m^3 (2000ppmV)	ASHRAE 62 N, etc.

3.4 O_3

For the concentration of cabin O_3, most standards adopt the requirements of CCAR/FAR/CS 25.832: (1) 0.25 parts per million by volume, sea level equivalent, at any time above flight level 320; and (2) 0.1 parts per million by volume, sea level equivalent, time-weighted average during any 3-hour interval above flight level 270. The requirements of 25.832 for ozone concentration limits are defined as health limits in ASD-STAN TR 4618.

Therefore, summing up the relevant standards and requirements, it is recommended that the reasonable range of values for the three levels of safety, health and comfort limits for cabin O_3 are shown in the following table:

Table 5 – Recommended safety, health and comfort limits for cabin O_3

Level	Requirements	Notes
Safety limits	Flight altitude 9,750m: 0.5mg/m^3 (0.25ppmV) Flight altitude 8,230m: 0.5mg/m^3 (0.1ppmV)	CCAR/FAR/CS 25.832
Health limits	0.5mg/m^3 (0.25ppmV), peak value 0.20mg/m^3 (0.1ppmV)，TWA 3h TWA 8h < 0.12mg/m^3 (0.06ppmV)	CCAR/FAR/CS 25.832 CCAR/FAR/CS 25.832 WHO guidelines/ EC directive
Comfort limits	——	

3.5 Particulate Pollutions (PM2.5, PM10)

The requirements for the concentration of cabin particulate pollutions are not clearly stipulated in the airworthiness regulations, but is mentioned in the standards or regulations of other environmental organizations or associations, and then cited by SAE, ASTM, ASD-STAN and other relevant standards.

Therefore, summing up the relevant standards and requirements, it is recommended that the reasonable range of values for the three levels of safety, health and comfort limits for cabin particulate pollutions are shown in the following table:

Table 6 – Recommended safety, health and comfort limits for cabin particulate pollution

Level	Requirements		Notes
	PM2.5	PM10	
Safety limits	——	——	
Health limits	100μg/m^3 (TWA 1 h) 40μg/m^3(continuous)	150μg/m^3 (TWA 24h)	Health Canada ANSI/ASHRAE 62-1999
Comfort limits	——	——	

3.6 VOCs

The requirements for the concentration of cabin volatile organic pollutants (VOCs) are not clearly stipulated in the airworthiness regulations. Only ASTM D6399 and ASD-STAN TR 4618 have clear concentration limits for these organic pollutants. ASTM D6399 summarizes the standard requirements of other relevant organizations and associations, and gives the concentration requirements of organic compounds pollution, which is the general requirement, regardless of the types of organic pollutants. On the other hand, ASD-STAN TR 4618 subdivides all kinds of organic pollution components, such as stupid and formaldehyde, and gives the concentration limits of each component.

Therefore, summing up the above relevant standards and requirements, it is recommended that the reasonable range of values for the three levels of safety, health and comfort limits for cabin VOCs are shown in the following table:

Table 7 – Recommended safety, health and comfort limits for cabin VOCs

Level	Requirements	Notes
Safety limits	< 100ppmV	OSHA PEL (Title 29 CFR 1910)
Health limits	< 0.01ppmV	ASTM D6399 SMACs[9] ATSDR[10]
Comfort limits	< 0.01ppmV	

Due to the wide variety of cabin organic pollutants, each kind of organic pollution has different effects on human health and comfort. The above table only gives the limit requirement of concentration of total volatile organic compounds (TVOC), which is a total concentration requirement of VOCs when the concentration of each pollutant does not exceed the standard. For the concentration limits of each component of VOCs, you can refer to ASD-STAN TR 4618.

4. Airworthiness Compliance analysis of Civil Aircraft Cabin Air Pollutants

Taking the civil transport airplane as an example, the airworthiness regulation requirements of cabin air pollutants are mainly CCAR/FAR/CS 25.831(a), (b), (c), and 25.832. Based on the safety, health and comfort limits levels indexes of cabin ventilation and pollutant, the acceptable means of compliance (MC) and limit level standards for these airworthiness provisions are given, as shown in the table below.

Table 8 – Airworthiness compliance explanation of cabin air pollutants

Regulations	Means of compliance (MC)	Explanation of compliance	Acceptable level and reference standards
25.831 (a)	MC1: explanation MC2: analysis / calculation	Prepare the air conditioning system design report with description of the configuration and principle of the system, and then through the flow calculation shows that the system can meet the ventilation requirements stipulated in 25.831(a), and provide enough fresh air per unit time. For reasonably possible failure states, the system can provide at least 0.4lb/min air for everyone. Reasonable possible failure states mainly include fan, valve or pipeline failure, resulting in subsystem failure, or single air conditioning system failure.	Cabin ventilation: safety limits and health limits. Reference standards: ASHRAE STD 161 SAE AIR4766 ASD-STAN TR 4618
	MC5: ground tests MC6: flight tests	Through the ground tests and flight tests of the air conditioning system, verify the accuracy of ventilation analysis and calculation under normal condition and reasonable possible failure state.	
25.831 (b)	MC1: explanation MC2: analysis / calculation	Prepare the air conditioning system design report and analyze possible air pollution sources. According to the data of engine manufacturers and the design of air conditioning system, evaluate the most serious air pollution condition. According to the pollution condition, calculate the most serious pollution state in the cabin and determine whether the concentration of pollutants such as CO and CO_2 exceeds the standards. CO_2 concentration analysis needs to consider the CO_2 exhaled by personnel at full capacity of the aircraft.	CO: safety limits CO_2: safety limits Reference standards: ASHRAE STD 161 SAE AIR4766 ASD-STAN TR 4618
	MC5: ground tests MC6: flight tests	Conducting the air conditioning system ground tests and flight tests and measuring the concentration of cabin air pollutants during the tests, to verify the accuracy of the above-mentioned pollutant concentration analysis and prediction, and to meet the requirements of 25.831(b).	
25.831 (c)	MC2: analysis / calculation MC3: system safety analysis	Through the system safety analysis, the reasonable and possible faults or functional failures of ventilation, heating, pressurization and related systems are given. Based on the corresponding design compensation measures, it is analyzed and calculated that the concentration of CO and CO_2 in the cabin meets the requirements of 25.831 (b) in the case of failure.	
25.832	MC1: explanation MC2: analysis / calculation	Through the design description (especially the ozone conversion device) and the analysis & calculation of ozone conversion efficiency, it is shown that the ozone concentration entering the aircraft cabin after treatment meets the requirements of 25.832. Analytical methods are also available to calculate the ozone concentration in the cabin (see AC120-38- FAR document).	O_3: safety limits and health limits Reference standards: ASD-STAN TR 4618
	MC9: equipment	Through the evaluation of the conversion performance of the	

Regulations	Means of compliance (MC)	Explanation of compliance	Acceptable level and reference standards
	qualification	ozone conversion unit (including equipment design, manufacture and performance tests), it is shown that the ozone concentration to the cabin after conversion meets the requirements of 25.832.	

During the above tests, it is necessary to determine the concentration of pollutants such as CO, CO_2 and O_3 in the cabin air. The acceptable concentration measuring methods and the accuracy of measuring equipment are as follows:

(1) CO & CO_2

- Measurement: Non-dispersive infrared adsorption.
- Quantification limit: ≤ ±2% related to upper limit of measurement.
- Accuracy: ≤ ±2% related to upper limit of measurement.

(2) O_3

Measurements of O_3 concentration should be taken in the cabin air, not in the incoming air.

Method 1:

- Measurement: Chemiluminescence method;
- Quantification limit: 0,0015 ml/m^3;
- Accuracy: ±20% related to upper limit of measurement.

Method 2:

- Sampling: Impinger containing Indigocarmin;
- Measurement: VIS - Spectrometer (623nm);
- Quantification limit: 0.011 mg/m^3 (sampling volume: 80L);
- Accuracy: ±21%.

5. Conclusions

By analyzing the airworthiness requirements and industrial standard requirements related to cabin air pollution of civil aircraft, according to the different demand levels of safety, health and comfort limits, the reasonable value range of air pollutant parameter indexes in airworthiness requirements and industrial standards are analyzed and summarized, the definition of air pollution parameter value range is studied, and the safety, health and comfort limit levels requirements of various cabin air quality parameters are given. The final summary is shown in Table 9 below. Taking the transport airplane as an example, the means of compliance and guidance of the airworthiness requirements of the cabin pollutants are given. The research results can provide reference for the design and verification of cabin environment system of transport aircraft.

Table 9 – Recommended safety, health and comfort limits for cabin air quality parameters

	Safety limits	Health limits	Comfort limits
Cabin ventilation	The minimum amount of ventilation per occupant should be 0.25kg/min (0.55lb/min) in normal operation, and the minimum rate allowed in case of failure is 0.18kg/min (0.4lb/min)	The minimum amount of ventilation per occupant should be 0.25kg/min (0.55lb/min, 3.5L/s)	The minimum amount of ventilation per occupant should be 9.4L/s
CO	581mg/m^3 (50ppmV), peak value	29.1mg/m^3 (25ppmV) TWA 1h 11.6mg/m^3 (10ppmV) TWA 8h	——
CO_2	9130mg/m^3 (5000ppmV)	36520 mg/m^3 (20000ppmV) (15minutes exposure)	3650 mg/m^3 (2000ppmV)
O_3	Flight altitude 9,750m: 0.5mg/m^3	0.5mg/m^3 (0.25ppmV), peak value	——

	Safety limits	Health limits	Comfort limits
	(0.25ppmV) Flight altitude 8,230m: 0.5mg/m^3 (0.1ppmV)	0.20mg/m^3 (0.1ppmV)，TWA 3h TWA 8h < 0.12mg/m^3 (0.06ppmV)	
PM2.5	——	100μg/m^3 (TWA 1 h) 40μg/m^3(continuous)	——
PM10	——	150μg/m^3 (TWA 24h)	——
VOCs	< 100ppmV	< 0.01ppmV	< 0.01ppmV

Abbreviations

CO	carbon monoxide
CO_2	carbon dioxide
O_3	Ozone
VOCs	Volatile organic pollutant
CCAR	China Civil Aviation Regulations (CAAC)
FAR	Federal Aviation Regulations (FAA)
CS	Certification Specification (EASA)
TWA	Total Weight Average
WHO/LQL	World Health Organisation Guidelines for Air Quality, Geneva, 2 000
ppmV	parts-per million by Volume
MC	Means of Compliance
TVOC	Total volatile organic compounds

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