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Influencing Factors of Carbonyl Compounds and Other VOCs in Commercial Airliner Cabins: On-board Investigation of 56 Flights

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Abstract

Volatile organic compounds (VOCs) as a non-negligible aircraft cabin air quality(CAQ) factor influence the health and comfort of passengers and crew members. On-board measurements of carbonyls and other volatile organic compounds (VOCs) with a total of 350 samples were conducted in 56 commercial airliner cabins covering 8 aircraft models in this study. The mean concentration for single carbonyl compound was normally between 0.3–8.3μg/m^3, (except for acrolein & acetone, avg.=20.7μg/m^3), similar to the mean concentrations of highly-detected VOC (97% of which ranged in 0-10μg/m^3) in aircraft cabin. Formaldehyde, with major sources as construction materials, its concentration in flights were significantly lower than in residential buildings. Acetone, as a characteristic VOC from human emission, its concentration in flights were similar to that in other transportation vehicles with high occupant density. The variation of VOC concentration in different flight phases of long-haul flights was the same as that of CO_2 except for the meal phase, which indicates the importance of cabin ventilation in diluting the gaseous contaminants; while the sustained and slow growth of the VOC concentrations before descent phase in short-haul flights indicated that VOC in cabin air mainly came from cabin interiors during the cruising phase. Overall, the mean concentration during cruising phase for benzene series, aldehydes, alkanes,

other VOCs (DR>50%), carbonyls were 44.2μg/m^3, 17.9μg/m^3, 18.6μg/m^3, 31.5μg/m^3, 20.4μg/m^3 lower in long-haul than in short-haul flights respectively. Carbonyls and D-limonene showed a significant correlation with meal service ($p<0.05$). Unlike the new decorated rooms or new vehicles, the inner-materials were not the major emission sources in aircraft cabin.

Keywords

Cabin air quality(CAQ); Ventilation; Aldehyde; Flight duration; Meal service

1. Introduction

Aircraft cabin air quality (CAQ) has been paid more and more attentions with the develop of aviation industry. Volatile organic compounds (VOCs) as a non-negligible air quality factor influence not only the air quality perception of passengers and crew members, but also their health and wellbeing in commercial airliner cabins [1-4]. There are multiple special VOCs sources in airliner cabins, including in-cabin materials, cabin services (meal and cleaning services), human activities (inhalation/exhalation, body emissions), airborne chemical reactions, as well as evaporation and combustion of jet fuel, engine oil, etc. entering through environmental control systems (ECS) [5]. The multiple sources make it difficult to use one or several VOCs to represent the overall characteristics of cabin VOCs. Therefore, understanding the current cabin air quality status is essential for exploring effective control methods for cabin VOCs pollutions.

In the past 20 years, there has been a number of studies on VOCs concentrations in aircraft cabin. Some studies focus on multi-parameter measurements of aircraft cabin environment to evaluate CAQ, or investigating the characteristic of a specific source [6-10]. Nagda and Rector [11] conducted a review on cabin VOCs and SVOCs concentrations for six studies conducted before 2001, and found that the concentrations of ethanol and acetone were significantly higher in cabins than in building indoor environment, while other tested VOCs levels are comparable to those in buildings. These studies were highly targeted but normally in small sample size (about 2-5 flights), which make it difficult to represent the general conditions of commercial airliner cabins. A few research teams have carried out on-board VOC measurements on relatively large number of test flights: Waters et al. [12] tested 36 flights on 11 aircraft types and found the predominant VOC was ethanol, followed by toluene and limonene, and mentioned formaldehyde were detectable but too low to be quantified. The team of Cranfield University sampled 5 target VOCs on 100 flights with 5 different aircraft types, and found that the most abundant VOCs were limonene and toluene [13]. Guan et al. [14-15] conducted in-flight measurement in 107 flights, and proposed 41 VOCs with high detection rate (>50%) as key compounds in cabin. However, carbonyls were not included in the study. The above studies mostly used Tenax-TA tube for VOCs sampling [12-15], which could obtain the quantitative data of long-chain VOCs (C_6-C_{16}), but few measurements were carried out for small molecule VOCs (short-chain VOC), such as carbonyls. Spengler et al. [16] conducted the measurements of VOCs including 5 carbonyls on some of the 83 tested flights. Systematic measurement on carbonyls were only founded from Hannover Medical School's studies [17-19] which more focus on

its relationship with "smell events".

Carbonyl compounds in cabin environment is necessary for quantitative research due to the following reasons. First, formaldehyde and acetaldehyde have clear health hazards according to the International Agency for Research on Cancer [20], in which formaldehyde is in Group 1 (carcinogenic to humans), and acetaldehyde is in Group 2B (possibly carcinogenic to humans). Formaldehyde is commonly emitted from cabin inner materials, paint, adhesives [21-22], and is also generated by human body through exhale and skin emission [23-24], therefore quantitative evaluation of formaldehyde pollution in cabin environment which has large surface area and high occupant density is needed. Smoking is also an important source of formaldehyde, therefore the researches involving formaldehyde measurement in aircraft cabins were mainly conducted in the 1990s ([6, 7, 25, 26] when smoking in cabin was not completely prohibited. Furthermore, aldehydes and other carbonyl compounds, such as malondialdehyde and acetone, could serve as biomarkers of oxidative stress which may affect the concentration of carbonyls in cabin [27-28]. Additionally, bleed-air could be a source of aldehydes as overheating of the jet oil could release aldehydes [29-30]. Aldehyde (RCHO) are also the typical reaction products in the presence of O_3 which is commonly existed in cabin environment [10, 31]. Finally, as aldehydes accounted for a significant fraction of cooking VOCs [32-34], may also be typical VOCs during meal/drink service phases in aircraft cabin. And the carbonyls may be related to people's complaints on “smell events” in cabin [17, 19] due to the low human olfactory threshold of some aldehydes [35-37]. As matters stand, the research on aircraft cabin environment involving carbonyls tests is few and lack of in-depth analysis.

In this study, on-board measurement in 56 commercial flights was carried out to obtain carbonyl compounds (short-chain VOCs) pollution status in aircraft cabins, to illustrate its correlation with long-chain VOCs for different flight phases, flight duration, and aircraft age, and to explore the interaction of emission sources and ventilation on VOCs pollution in cabin.

2. Methods

2.1 The tested flights and condition

The on-board measurements of carbonyls and VOCs were conducted in 56 commercial aircraft from May 2018 to June 2019. Flight selection was random, but intended to have broader coverage of aircraft model, age, and duration (*Table 1*). The 56 tested flights covered eight aircraft models, 28 short-haul flights (i.e. Chinese domestic flights) and 28 long-haul flights (i.e. international flights) of which 82% distributed in 10 to 14 hours. The flight age refers the time starting from the first date in service, and ranged from 0 to 20 years.

Table 1. Distribution of the tested flights.

		Number of flights	Percentage
Aircraft model	A320 series	6	11%
	A330 series	7	13%
	A350 series	3	5%
	B737 series	16	29%

	B747 series	1	2%
	B777 series	14	25%
	B787 series	8	14%
	E190 series	1	2%
Flight duration	1h-4h	28	50%
	4h-10h	5	9%
	10-14h	23	41%
Flight age	<1 year	4	7%
	1-3 year	10	18%
	3-5 year	11	20%
	5-10 year	19	34%
	>10 year	12	21%

For single tested flight, one to five samples were taken covering various flight phases including boarding, taking-off, cruising, meal/drink servicing, and descent. Boarding phase was defined as the time period before the flight started taxiing, with 10 flights were tested; take-off phase was defined to include taxi-out, take-off, and partial climb time, with 19 flights were tested; cruising phase was defined as level flight stage without any special personnel activities, with all 56 flights were tested; and 30 flights and 14 flights were sampled during meal/drink servicing and descent phases, respectively. All samplings were taken without interference of the cabin ventilation settings, including the use of environmental control system (ECS) and the use of personal gasper.

The samples were taken at breathing zone by placing the sampling device on the seat table or seat back pocket without blocking air sampling port. Meanwhile, key environmental parameters including temperature, relative humidity, and carbon dioxide in cabin were recorded during the whole flight duration by using a HOBO data logger (HOBO MX1102A, ONSET, USA). TVOC concentration as toluene equivalent was automatically recorded by a portable PID VOC monitor ppbRAE 3000 (RAE Systems, USA) in eight flights to monitor the change of TVOC concentration during the whole flight duration. These instruments were ensured to able to work in cabin environment with low humidity and low pressure (working condition: RH 0-95%, insensitive to pressure changes in 0.8-1.0 atm).

2.2 Sampling procedure

For accurate determination of individual compounds and concentrations, VOCs (C_6-C_{16}) were actively sampled by Tenax-TA adsorption tubes (0.20mg adsorbent, 60–80 mesh, Markes, UK) with a portable pump (BUCK-Libra Plus Model LP-1, A.P. BUCK Inc., USA) at a flow rate of 0.2L/min. Carbonyls were active sampled by DNPH adsorption tubes (SEEQ-144102 CNWBOND DNPH-Silica column, ANPEL Laboratory Technologies (Shanghai) Inc.) with the front end connected with the ozone removal tubes (SEEQ-144104 CNWBOND DNPH Ozone Scrubber, ANPEL Laboratory Technologies (Shanghai) Inc.). The sampling flow rate of carbonyls was 0.4 L/min. The total sampled air volume was controlled between 1L to 10L, and the sampling duration at any position should not be less than 5min to eliminate the interference of sudden pollutant sources. A total of 185 VOC samples and 165

carbonyls samples were conducted. All sampled tubes were sealed by aluminium foils, stored in a refrigerated bag on board, and then send to laboratory for analysis immediately after landing. To prevent transportation pollution, a blank tube was taken and analyzed for each test.

2.3 Analysis of VOCs and carbonyls

Tenax-TA tubes were analyzed using TD-GC/MS (TD-100, Markes, Inc. UK; Agilent 7890B/5975B, USA) according to the standard guide of measurement method for cabin air quality [38-40]. The thermal desorption system was a two-stage desorption unit The type of chromatographic column is HP-VOC (60.0 m × 0.20 mm × 1.1 μm film thickness). The column temperature program was as follows: ~40 °C for 3 min; ramp to 160 °C at 15 °C/min; held for 2 min and then ramp to 240 °C at 10 °C/min; held for 4 min at 240 °C (28 min in total). Helium was used as the carrier gas with a flow rate of 3 mL/min at 25°C. A mass spectrometer used the total ion scan mode so that the entire mass range (⩽30_m/z⩽300) can be scanned at a frequency of 2.5 Hz. Qualitative analysis will be conducted by using mass spectrometry database at NIST. The detection limit will be about 1 ng for each chemical compound (Signal-to-noise ratio S/N = 3/1). An external standard method was used for quality assurance/quality control for the concentration of VOCs. Mixed standard VOC solutions with five compounds (benzene, toluene, acetic acid, butyl ester, ethylbenzene, p/m-xylene, styrene, o-xylene and undecane) were quantified separately. A calibration curve including 0.02, 0.05, 0.08, 0.1, 0.2, 0.5, and 0.8 μg standards was obtained, and R^2 was higher than 0.98. Other VOCs' quantitative analysis is based on the response of toluene.

The DNPH silica cartridges were eluted by 5 mL acetonitrile and 20 μL of sample solution was injected and analyzed by HPLC (1260, Agilent, USA) to determine the concentrations of the carbonyl compounds [38-40]. A capillary column (Poroshell 120EC-C18, 4.6 × 100 mm, 2.7 μm) was used for separations. The binary phase consisted of water (eluent A) and acetonitrile (eluent B) was used in the mobile phase at 1.5 mL/min. The elution gradient was as follows: held at 65% A from 0 to 4.2 min; mobile phase A was decreased to 55% at 14.6 min; mobile phase A was decreased to 30% at 25 min; held at 30% A from 25 to 31 min; mobile phase A was increased to 65% at 31.1 min; held at 65% A from 31.1 to 34 min. The detection of the small molecules of aldehydes and ketones (360 nm) was used by UV spectra. The carbonyl concentrations will be quantified by external standard calibration. The calibration standards (Sigma-Aldrich Co. LLC) contain hydrazones of the following 13 carbonyl compounds: formaldehyde, acrolein & acetone, propionaldehyde, crotonaldehyde, methacrylaldehyde, 2-butanone, butyraldehyde, benzaldehyde, valeraldehyde, m&o-tolualdehyde, and hexanal.

3. Results

3.1 Detection rates and concentrations of carbonyls

The concentrations of individual carbonyl compound during cruising phase was shown in *Table 2*. Half of the detection limit value was used for statistical data analysis if the concentration is below the detection limit. Detection rate is defined as the ratio of samples with certain compound detected to the total number of samples. The data

showed that formaldehyde, acrolein & acetone, hexanal, 2-butanone, propionaldehyde, and butyraldehyde had detection rate higher than 50%, which were 98%, 96%, 89%, 76%, 62%, 60%, respectively. These six compounds are common carbonyls in cabin. While the detection rate of other target carbonyls was less than 50%.

Except for acetone, the mean concentration for single carbonyl compound was normally between 0.3–8.3μg/m^3. The concentration of carbonyls is generally in the similar level to those highly-detected VOCs in cabin, that the median concentrations for 97% of the 33 kinds of highly detected VOCs (detection rate higher than 50%) were in the range of 0-10μg/m^3. Acetone has relative higher concentration (avg.=20.7μg/m^3) in cabin. As acetone is a major VOC species from human breath [41], this is well expected in the cabin environment with high-occupant density. Formaldehyde, the substances with clear health hazards [20], its concentration during cruising phase of the aircraft were between 0-20μg/m^3 (med.=5.93μg/m^3). Compared with in the residential building environment, where average exposure concentrations to formaldehyde ranged from 20μg/m^3 to 60μg/m^3 as summarized in literature review [42-44], the formaldehyde concentration in flights were significantly lower. However, when compared with the chronic exposure limits (9μg/m^3, 8-hour inhalation REL) by US Office of Environmental Health Hazard Assessment [45], the over-limit rate of formaldehyde in the tested flights was still 18%. Besides, although the detection rate of some compounds, such as benzaldehyde and valeraldehyde, were not high, their maximum values were obviously higher than other compounds (51μg/m^3 and 40μg/m^3, respectively). This indicated certain explosive or specific emission in some of the tested flights.

Table 2. Descriptive statistics of carbonyl compounds concentrations (μg/m^3) during cruising phase.

Compounds	CAS NO.	DR[a]	Mean	SD	Min	5th	25th	Median	75th	95th	Max
Formaldehyde	50-00-0	98%	5.93	4.12	< LOD	0.39	3.02	5.60	7.87	14.48	20.03
Acrolein & Acetone	107-02-8 & 67-64-1	96%	20.68	11.87	< LOD	2.20	13.60	18.27	27.06	47.98	57.63
Propionaldehyde	123-38-6	62%	4.00	5.74	< LOD	< LOD	< LOD	1.58	6.43	15.28	29.52
Crotonaldehyde	123-73-9	22%	0.68	2.18	< LOD	< LOD	< LOD	< LOD	< LOD	8.76	10.24
Methacrylaldehyde	78-85-3	13%	0.32	0.98	< LOD	< LOD	< LOD	< LOD	< LOD	3.48	4.44
2-Butanone	78-93-3	76%	8.30	9.81	< LOD	< LOD	0.05	5.10	14.68	30.41	31.79
Butyraldehyde	123-72-8	60%	3.78	5.91	< LOD	< LOD	< LOD	1.86	5.82	16.13	33.54
Benzaldehyde	100-52-7	31%	2.37	7.63	< LOD	< LOD	< LOD	< LOD	1.19	17.72	51.28
Valeraldehyde	110-62-3	20%	1.48	5.61	< LOD	< LOD	< LOD	< LOD	< LOD	7.65	39.71
m&o-Tolualdehyde	620-23-5 & 529-20-4	36%	1.13	2.08	< LOD	< LOD	< LOD	< LOD	1.70	7.20	8.35
Hexaldehyde	66-25-1	89%	6.49	7.44	< LOD	< LOD	2.27	5.28	8.65	18.87	47.75

[a] *DR, detection rate*

Figure 1 compared the measured carbonyl compounds concentrations in aircraft with previous studies [6, 7, 15, 16, 17, 18, 19, 25, 26, 46]. The compounds on the horizontal axis are arranged in order of carbon number from small to large. Each point

represents the arithmetic mean/geometric mean/median value of the carbonyl compound. There are few existing measurements for carbonyls, only the researches by the team of Hannover Medical School (the blue marks in *Figure 1*) involved more carbonyls than other studies, and 9 compounds of their study were the same as in this study. Other studies involved only 1 to 3 carbonyls. Comparing carbonyls concentration in this study (black solid square) with Hannover Medical School's studies, the average concentration of each compound were very similar and low (mostly in the range of 0-5μg/m^3). The SD value of carbonyls in this study were larger (5-10μg/m^3) compared with Rosenberger's et al [17], which may due to the fact that only A380 and A321 were tested their study.

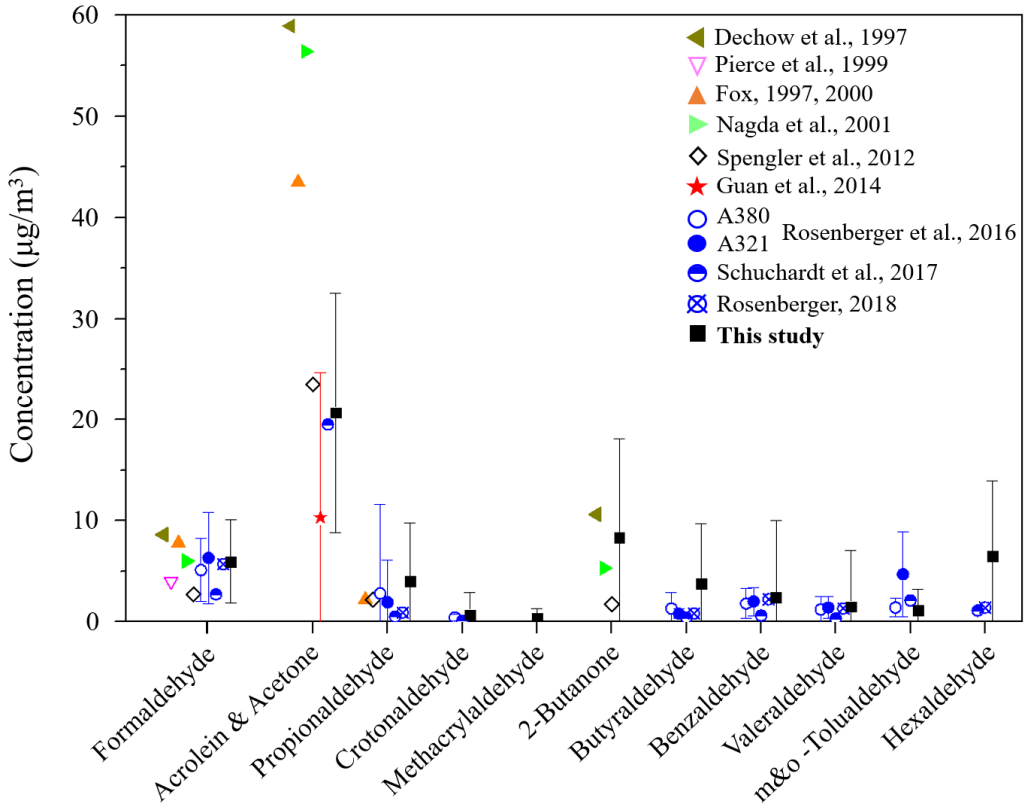


Figure 1. Comparison of carbonyls concentrations with previous studies.
Note: The GM/Median value were used if there was no AM value mentioned in the literature (GM for Dechow et al., 1997 [6]; Median for Spengler et al., 2012 [16] and Rosenberger, 2018 [19]); The bar represents the standard deviation (SD); sampling method of carbonyls were DNPH method except for Guan et al., 2014 [15] using Tenax as sampling materials.

Literature on aircraft cabin air quality in the 1990s (the triangle marks in *Figure 1*) only involved one or two aircraft types or only tested a small number (within 10 flights) of flights, mainly measured formaldehyde and acetone [6, 7, 25, 26, 46, 47, 48]. The mean concentrations of formaldehyde in the literature were generally at the similar level (all less than 10μg/m^3), although much higher concentrations of formaldehyde were

detected occasionally in 1990s. For example, maximum concentration of 82μg/m^3 was found by O'Donnell et al. [47]; and the maximum concentration in Dechow et al.'s study [6] was 32μg/m^3. This big difference of the maximum value should be related to a specific source of formaldehyde in different flights, rather than the common continuous-emission source such as inner materials of aircraft cabin. Cigarette smoking as an emission source of formaldehyde [49-50] may be related with high maximum concentration detected in some flights in the 1990s when smoking has not been banned (completely forbidden in 2000). Lindgren & Norback [48] considered that formaldehyde was not a problem in aircraft cabin when irrespectively of smoking. The formaldehyde concentration in the non-smoking flights measured in recent years (measurements in 296 flights, 11 aircraft models) also showed that the concentration distribution among different flights was more concentrated (mean concentration lower than 10μg/m^3) with smaller SD value (about 5μg/m^3) ([16-18] and this study). An exception is in Rosenberger's study [19] that a high concentration of formaldehyde (134μg/m^3) on the flight was measured during de-icing. Therefore, it is believed that the existing ECS could well control the formaldehyde pollution during normal cruising phase.

The mean concentration of acetone in recent years (about 20μg/m^3) were much lower than that measured in the 1990s (40-60μg/m^3). For example, acetone concentrations were in the range of 7.4–579μg/m^3 and 22-130μg/m^3 in Dechow et al. [6] and Nagda et al. [26], respectively. It was also mentioned by Spengler et al. [16] that acetone levels (0-80μg/m^3) were lower than their previous study (52-150μg/m^3) [51]. Acetone, as an indicator of bioeffluents and chemicals from consumer products [11, 15, 52], were also correlated with ozone-related gaseous reaction[16]. The concentration decrease in nowadays may be related to the changes of consumer products and the decrease of the ozone concentration in aircraft cabin with the use of ozone catalytic convertor in bleeding-air. Although acetone could still be considered as a representative carbonyl compound in aircraft cabin due to its higher concentration proportion, the frequency of extreme values has been reduced during the past years. The literature review [11] mentioned that acetone levels were higher in aircraft (21.0-167.7μg/m^3) than in other transportation vehicles (30-92μg/m^3 [53]) and other indoor environments (averaged maximum=99μg/m^3 [54]) in the 1990s, while the acetone concentration in aircraft cabin in current study (avg.=20.7μg/m^3) were similar to that in other transportation vehicles (avg.=18.7μg/m^3/40μg/m^3/36μg/m^3/23.3μg/m^3 in subway/bus/taxi/private car, respectively) in nowadays [55-57].

3.2 Carbonyls and VOCs in different flight phases

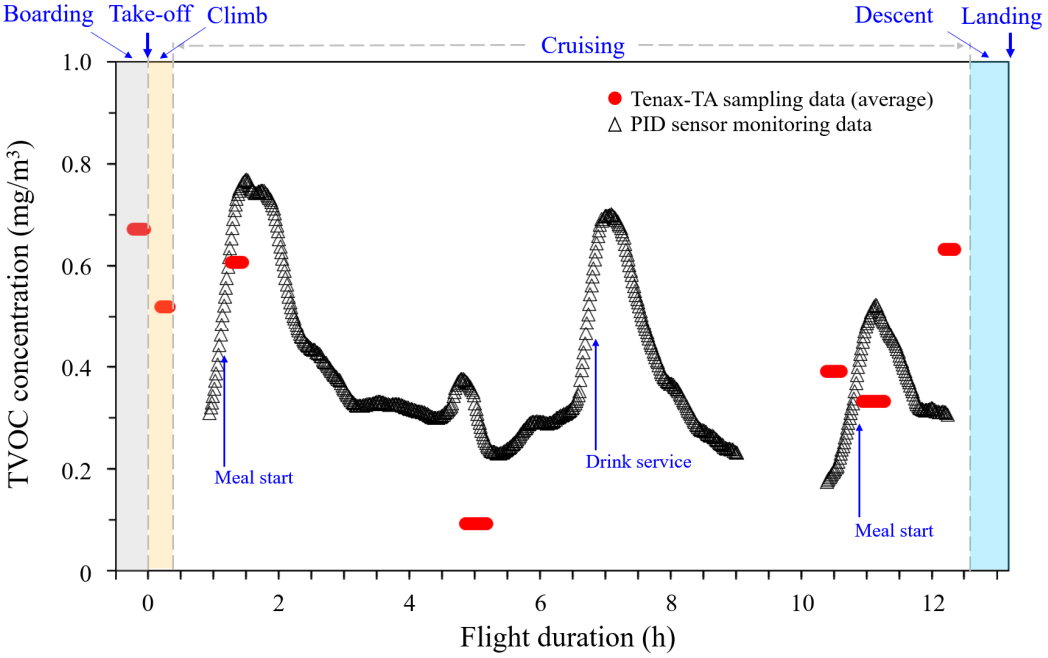
Different flight phases may affect the concentration of gaseous pollutants in cabin because of the possible variation of ventilation setting and the change of emission sources. *Figure 2* showed the TVOC concentration change in aircraft cabin of typical long-haul and short-haul flights during the whole flight phase continuously monitored by ppbRAE-3000, the VOC sampling data of the same flight were also marked in the figure.

- ***Boarding phase*** The pollutant concentration in cabin during boarding phase was

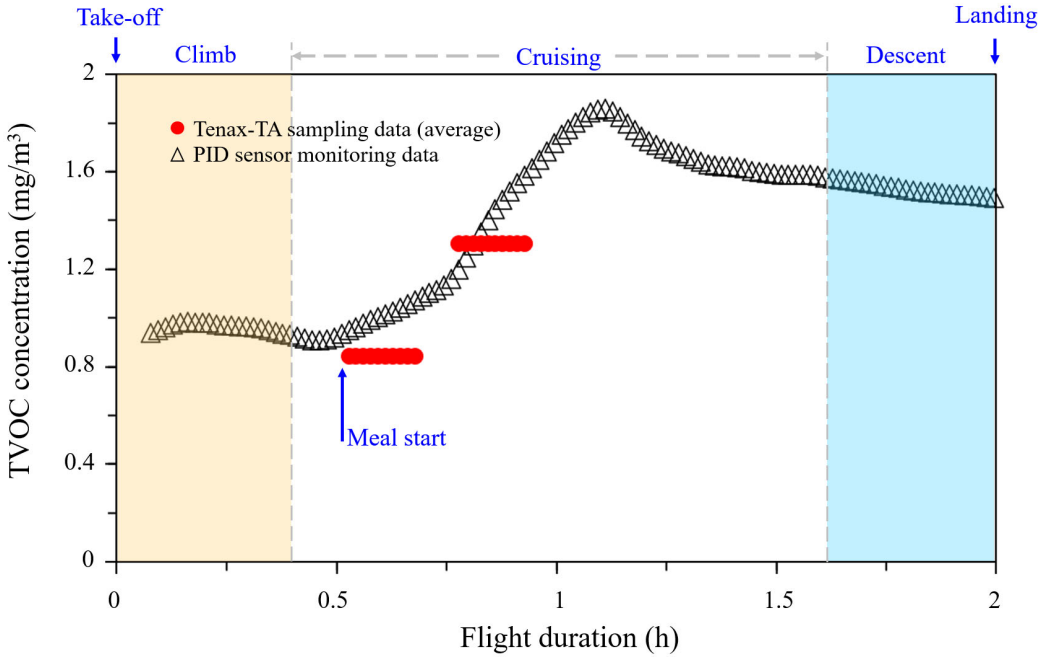
mainly affected by ambient air of the airport because the supply air to the cabin was provided by a ground air-conditioning system (GAC), or a bridge air-conditioning system, or the auxiliary power unit (APU) in the aircraft [58]. Considering the busy airport schedule in many big cities, the tail-gas from other airplanes or transport vehicles could be an important source of in-cabin VOCs during taxiing and boarding phase. Two of the ten flights with boarding phase samplings showed higher concentration (*Figure 2(a)*).

- ***Take-off phase*** The cabin air-conditioning system is always temporarily turned off or APU is used for cabin environmental control to reduce the power loss of engine and to keep the maximum thrust to take-off. Such operation results in the decrease of bleeding air (fresh air) during take-off [12], which can be proved by the increased cabin CO_2 concentration [59]. Thus, the concentration of VOCs emitted from in-cabin sources would increase correspondingly during take-off. On the other hand, it is widely assumed that certain specific flight maneuvers (e.g., thrust change during take-off or ascent) may cause increased oil leakage [17, 19], and this may result in engine oil related VOCs entering the cabin through ECS, and those VOC concentration may increase during take-off phase.
- ***Cruising phase*** The supply air was provided by engine to ECS during cruising phase, and the bleeding airflow rate reached the maximum, with the general proportion of 40-60% [17, 25]. There was no special VOCs emission source during this phase, and the VOCs concentrations was mainly in-flight emission and in-cabin airborne chemical reaction. As shown in *Figure 2*, the concentration of long-haul flights could reduce to a lower steady-state concentration with the effect of ventilation during cruising phase, while the concentration of short-haul flights seems keeps at elevated concentration.
- ***Meal phase*** The meal/drink service introduced extra VOCs in cabin. The VOCs emitted in galley operation may be negligible for the entire cabin, because the gas pollutants were difficult to affect the areas outside three rows of seats under ECS [60]; but the passengers' centralized dining caused obvious higher concentration of some VOCs.
- ***Descent phase*** The ventilation rate decreased during this phase as showed by the increased CO_2 concentration [59, 61], therefore the concentrations of pollutants with constant emission intensity may have a slight increase.

In short-haul flights, the TVOC concentration change was generally consistent with the literature [62], which first increased during climbing, and then kept elevated during cruising phase, and decreased during descent in general. The sustained and slow growth of the VOC concentrations before descent phase in short-haul flights indicated that VOC in cabin air mainly came from cabin interiors during the level flight phase [62]. Also the intensity of the internal sources was higher than that of the ventilation dilution strength for short-haul flights. In long-haul flights, obvious differences could be observed for different flight phases, and the influence of VOC sources and ventilation rate was significant. Therefore, the analysis of VOCs in different flight phase for long-haul flights was conducted in the following section.



(a) Long-haul flights



(b) Short-haul flights

Figure 2. Typical TVOC concentration during a whole flight duration

Figure 3 shows the mean concentrations of carbonyls in different flight phases of long-haul flights. The total concentration of carbonyls in different flight phases ranged from 50-100μg/m^3 in general. Carbonyls concentrations increased during take-off phase (average increment 23.7μg/m^3), and decreased to the lowest level during cruising phase (avg.=54.7μg/m^3). The carbonyls concentration during meal phase increased 18% compared with that in cruising phase, indicating possible catering emission sources.

Carbonyl concentration during the descent phase is 33% higher than that in cruising phase.

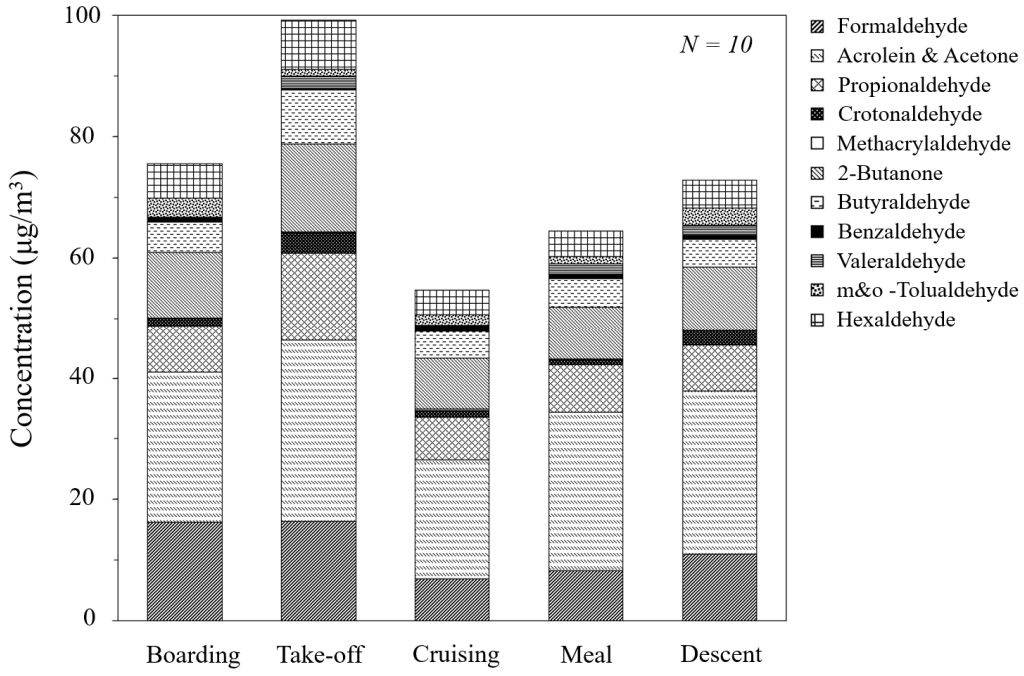


Figure 3. Carbonyl concentrations in long-haul flights during different flight phases

Figure 4 shows VOCs concentration in different flight phases. VOCs were divided into four categories of benzene series, aldehydes, alkanes and other VOCs. Similar to carbonyls, benzene series, aldehydes, and alkanes had an average increment of 1.7μg/m^3, 8.8μg/m^3, 3.1μg/m^3 (8.9%, 62.6%, 13.7% increments) in take-off phase compared to the boarding phase, and then the VOC concentrations decreased in the following flight phases. Different with carbonyls, VOCs showed little relationship with catering, and only some compounds (mainly D-limonene and ethyl acetate) classified in "other VOCs" showed an increase during meal phase. Besides, the large fluctuation (indicated by the SD value) of "other VOC" during boarding phase (mainly D-limonene and tetrachloroethylene) indicated the possible influence of airport ambient air pollution, bleeding air pollution or personal consumer products during boarding.

Except for the meal phase, the variation of VOC concentration in different flight phases of long-haul flights was the same as that of CO_2 (avg. concentration: boarding phase 1242 ppm, take-off phase 1440 ppm; cruising phase 1061 ppm, descent phase 1245 ppm), which indicates that the cabin ventilation played a leading role in the change of VOC concentration in aircraft cabin of long-haul flights. Only when the source intensity increased (e.g. meal phase), the concentration would increase, and it would take approximately an hour to reduce to the level of cruising phase after the meal (*Figure 2(a)*), similar results (20-30 min for the meal service, and no more than 40 min to restore to the normal level) were mentioned by Guan et al. [15].

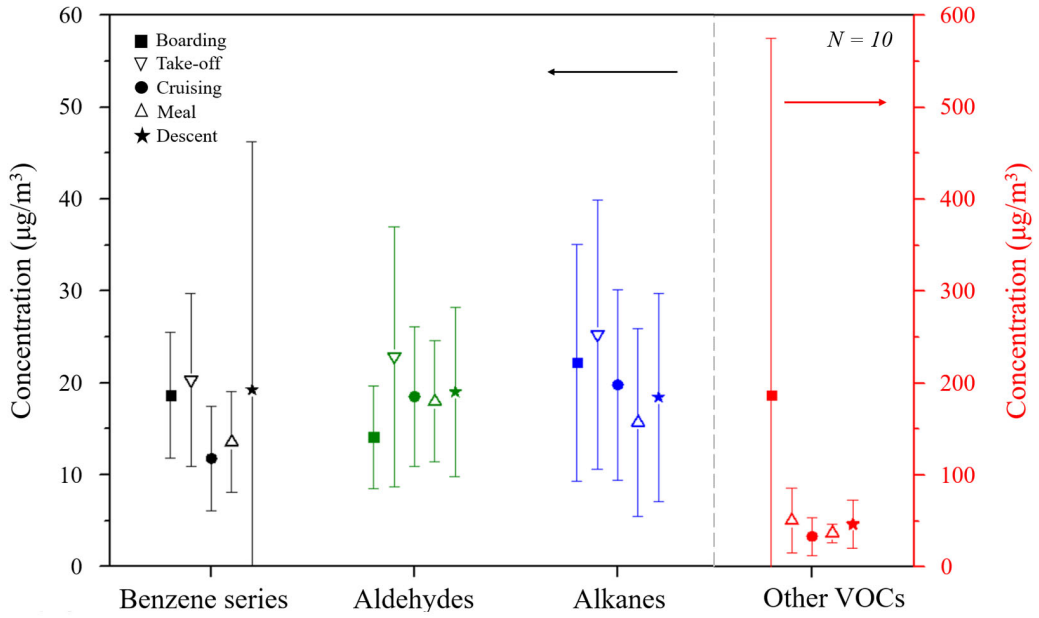


Figure 4. VOC concentrations in long-haul flights during different flight phases
Note: VOCs in Figure 4 contains only VOCs with detection rates above 50%.

3.3 Carbonyls and VOCs during meal service

Table 3 shows a comparison of carbonyls concentrations during cruising phase and meal/drink service phase by T-Test method. The statistical data including Mean and SD value of six short-haul flights and twelve long-haul flights were listed. For long-haul flights, formaldehyde, acrolein & acetone, propionaldehyde, 2-butanone, valeraldehyde, and sum of carbonyls all showed a significant correlation with meal service ($p<0.05$). The average concentration increments of single carbonyl compound were 1.6-6.3μg/m^3 during meal service phase, and total average concentration for carbonyls was about 15μg/m^3 higher than that in cruising phase, in which acrolein & acetone showed a major contribution. Different from long-haul flights, no carbonyls showed a significant correlation with meal service in short-haul flights. There is no uniform lower concentration of carbonyls during the cruising phase than the meal phase, which also confirms the discussions in Section 3.2 that the gaseous contaminants in cruising phase of short-haul flights is affected by sources occurs in other flight phase.

Table 3. Carbonyls concentrations during cruising phase and meal/drink service phase (N=18)

	Short-haul flights					Long-haul flights				
	Cruising		Meal		P-value	Cruising		Meal		P-value
	Mean (μg/m^3)	SD (μg/m^3)	Mean (μg/m^3)	SD (μg/m^3)		Mean (μg/m^3)	SD (μg/m^3)	Mean (μg/m^3)	SD (μg/m^3)	
Formaldehyde	10.88	5.15	9.13	3.36	0.28	5.95	3.96	7.60	6.21	**0.04**
Acrolein & Acetone	31.36	13.43	27.91	10.32	0.26	21.51	10.14	27.83	12.29	**0.00**
Propionaldehyde	2.70	3.83	2.32	3.38	0.15	5.53	8.05	7.76	9.89	**0.01**
Crotonaldehyde	1.48	3.30	1.43	3.20	0.18	0.93	2.81	1.30	3.01	0.18
Methacrylaldehyde	0.74	1.65	0.74	1.66	0.18	0.30	0.78	0.06	0.20	0.17

2-Butanone	12.20	13.65	10.90	11.85	0.21	6.64	6.94	8.60	9.90	**0.05**
Butyraldehyde	8.57	11.52	1.72	2.69	0.13	3.32	4.61	5.16	7.89	0.06
Benzaldehyde	1.14	2.54	1.04	2.32	0.18	0.91	1.05	0.72	0.87	0.16
Valeraldehyde	1.08	2.40	1.03	2.31	0.18	0.03	0.07	1.69	2.66	**0.03**
m&o-Tolualdehyde	1.39	3.11	1.38	3.09	0.18	1.42	1.78	0.90	2.00	0.14
Hexaldehyde	5.42	4.20	4.54	3.59	0.11	3.63	3.05	3.91	2.65	0.24
Sum of carbonyls	76.95	26.86	62.16	28.64	0.06	50.17	32.67	65.52	45.38	**0.00**

For VOCs, correlation test results showed that D-limonene and cyclohexanone were significantly higher ($p<0.05$) during meal phases than that during cruising phases for short-haul flights; D-limonene, ethyl acetate, and oxime-, methoxy-phenyl-_ were significantly related to meal service ($p<0.05$) for long-haul flights. Therefore D-limonene could be considered as a typical compound released from meal/drink in aircraft cabin, and its average concentration increments were significantly higher than other VOCs in both short-haul and long-haul flights (5.3μg/m^3 and 26.2μg/m^3, respectively).

Table 4. VOC concentrations during cruising phase and meal/drink service phase (N=18)

	Short-haul flights					Long-haul flights				
	Cruising		Meal			Cruising		Meal		
	Mean (μg/m^3)	SD (μg/m^3)	Mean (μg/m^3)	SD (μg/m^3)	P-value	Mean (μg/m^3)	SD (μg/m^3)	Mean (μg/m^3)	SD (μg/m^3)	P-value
Toluene	25.34	43.49	87.59	178.77	0.18	8.32	6.79	6.39	2.40	0.12
Benzene	1.73	1.98	8.23	15.93	0.21	2.54	1.94	2.71	1.02	0.34
Ethylbenzene	0.80	0.50	3.07	4.96	0.16	1.24	1.94	1.36	1.67	0.33
p-Xylene	2.14	1.96	8.84	15.39	0.16	3.17	5.15	3.92	4.99	0.22
Phenol	2.92	2.01	6.55	7.65	0.14	4.00	6.53	2.79	4.54	0.12
o-Xylene	0.67	0.74	3.97	7.17	0.19	0.74	1.67	0.41	1.22	0.28
Nonanal	12.27	3.91	30.29	38.75	0.15	9.12	7.07	8.45	5.43	0.33
Hexanal	3.73	2.22	8.32	11.50	0.16	2.77	2.10	2.28	0.89	0.14
Decanal	10.79	3.33	12.78	8.17	0.31	5.41	4.01	6.47	6.65	0.25
Octanal	3.18	0.93	5.47	5.07	0.15	1.75	1.64	1.05	1.31	0.09
Benzaldehyde	3.91	2.64	4.11	2.99	0.44	2.83	2.24	3.21	2.97	0.15
Pentanal	0.63	0.62	0.98	1.31	0.24	0.18	0.29	0.07	0.25	0.16
D-Limonene	10.77	8.71	16.07	10.42	**0.01**	17.00	21.35	43.21	60.91	**0.04**
Styrene	0.60	0.82	5.07	8.45	0.15	2.18	3.32	2.65	3.69	0.21
1R-.alpha.-Pinene	0.04	0.09	0.26	0.35	0.11	0.59	0.79	1.69	5.76	0.20
Eicosane	1.16	2.60	3.31	3.89	0.09	5.55	6.37	5.00	5.50	0.38
Tetradecane	4.89	4.01	8.69	12.31	0.19	5.50	4.71	6.49	6.25	0.28
Dodecane	2.33	0.82	5.40	8.92	0.22	0.90	1.03	0.70	1.04	0.23
Undecane	0.92	0.62	1.58	2.01	0.21	0.16	0.38	0.26	0.51	0.26
Tridecane	1.76	1.78	3.20	3.27	0.23	1.48	2.22	2.22	2.53	0.15
1-Hexanol, 2-ethyl-	2.55	2.00	7.18	8.00	0.07	3.51	4.64	2.40	2.44	0.08
Benzyl Alcohol	0.65	0.96	2.02	2.11	0.08	2.18	4.66	2.20	6.28	0.49
Ethyl Acetate	1.27	0.87	3.12	2.77	0.08	2.73	4.32	4.85	3.90	**0.03**
5-Hepten-2-one, 6-methyl-	3.11	1.91	4.53	2.19	0.12	1.85	1.85	1.87	2.41	0.49
Acetophenone	1.25	1.14	1.69	1.11	0.24	0.94	0.98	0.98	1.13	0.45
Cyclohexanone	1.23	2.00	2.24	2.06	**0.05**	1.54	3.05	1.33	2.46	0.31

Trichloromethane	2.63	4.51	3.18	6.38	0.30	0.20	0.30	0.28	0.40	0.18
Naphthalene	2.23	2.96	3.56	5.33	0.14	4.84	5.15	5.37	5.23	0.38
Oxime-, methoxy-phenyl-	0.63	1.15	0.00	0.00	0.14	0.54	0.68	0.97	0.86	**0.04**

410

411 **3.4 Influence of flight duration on carbonyls and VOCs concentrations during**
412 **cruising phase**

413 Different flight duration means different exposure time. Considering that flight
414 duration is always coupled with aircraft types, that most long-haul flights are twin-aisle
415 aircraft (96% of the tested flights) while short-haul flights are mostly single-aisle
416 aircraft (79% of the tested flights). The concentration levels of individual VOCs were
417 analysed and discussed separately for short-haul flights (<4h, domestic flights) and
418 long-haul flights (>4h, international flights).

419 *Figure 5* and *Figure 6* shows the comparison on carbonyls and VOCs
420 concentrations during cruising for long-haul and short-haul flights. The mean
421 concentrations of all the carbonyls in short-haul flights were about 0.1-7.5μg/m^3 higher
422 than that in long-haul flights. Similar results were found for VOCs, the mean
423 concentrations of 76% highly-detected VOCs in short-haul flights was about 0.1-
424 34.4μg/m^3 higher than in long-haul flights. Overall, the difference of mean
425 concentration between the long-haul and short-haul flights for benzene series,
426 aldehydes, alkanes, other VOCs (DR>50%), carbonyls were 44.2μg/m^3, 17.9μg/m^3,
427 18.6μg/m^3, 31.5μg/m^3, 20.4μg/m^3, respectively (as shown in *Figure 7*). This 18-
428 44μg/m^3 concentration difference between flights were higher than that between
429 different flight phases of single flight as discussed in Section 3.2. Similar situation was
430 also found by Spengler et al. [16] that the average concentration of propionaldehyde is
431 3.6μg/m^3 for short-haul flights and 1.7μg/m^3 for long-haul flights.

432 It is believed that ventilation is responsible for the obvious lower concentration in
433 long-haul flights. The mean concentrations of CO_2 during cruising phase of short-haul
434 and long-haul flights were 1290ppm and 1013ppm respectively, and the estimated
435 ventilation rate were 0.51 and 0.74 pounds/min/person respectively. The different
436 ventilation rate means that the average VOC concentrations in long-haul flights should
437 be about 70% of the concentrations in short-haul flights assuming that the emission
438 rates per person were the same in different flights. The measured data shows that the
439 average concentration of benzene series, aldehydes, alkanes, other VOCs (DR>50%),
440 carbonyls in long-haul flights were 34%, 59%, 53%, 59%, and 69% of the
441 concentrations in short-haul flights, respectively. Thus, in addition to the difference
442 caused by different ventilation rate between short-haul and long-haul flights, the
443 cruising period VOCs in short-haul flights should also be influenced by the emission
444 during take-off and meal-service as discussed in Section 3.2 because of the short flight
445 duration, especially for benzene series.

446 The pollutant concentration is also more consistent between various long-haul
447 flights that the fluctuation (shown by the standard deviation (SD) in *Figure 5* and *Figure*
448 *6)* of the concentration for most carbonyls (91%) and VOCs (76%) were lower in long-
449 haul flights. The concentration SD for carbonyls were 0.52-9.45μg/m^3 lower in long-
450 haul flights, and for VOCs were 0.07-78.36μg/m^3 lower. The smaller difference of
451 single contaminant between different flights indicates that the larger ventilation in long-

haul flights plays obvious dilution effect, therefore no extreme high concentration occurs even with sporadic strong emission source in some flights. For example, the relative standard deviation of toluene in short-haul flights (RSD=195%) was much higher than that in long-haul flights (RSD=83%), and similar results were founded for D-limonene (RSD=201% and 106%, respectively).

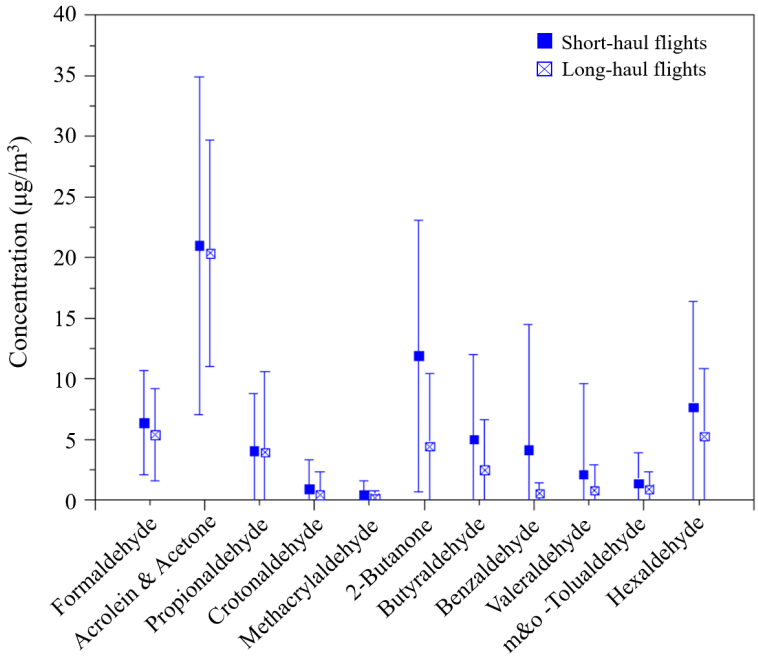


Figure 5. Carbonyls concentrations for long-haul and short-haul flights

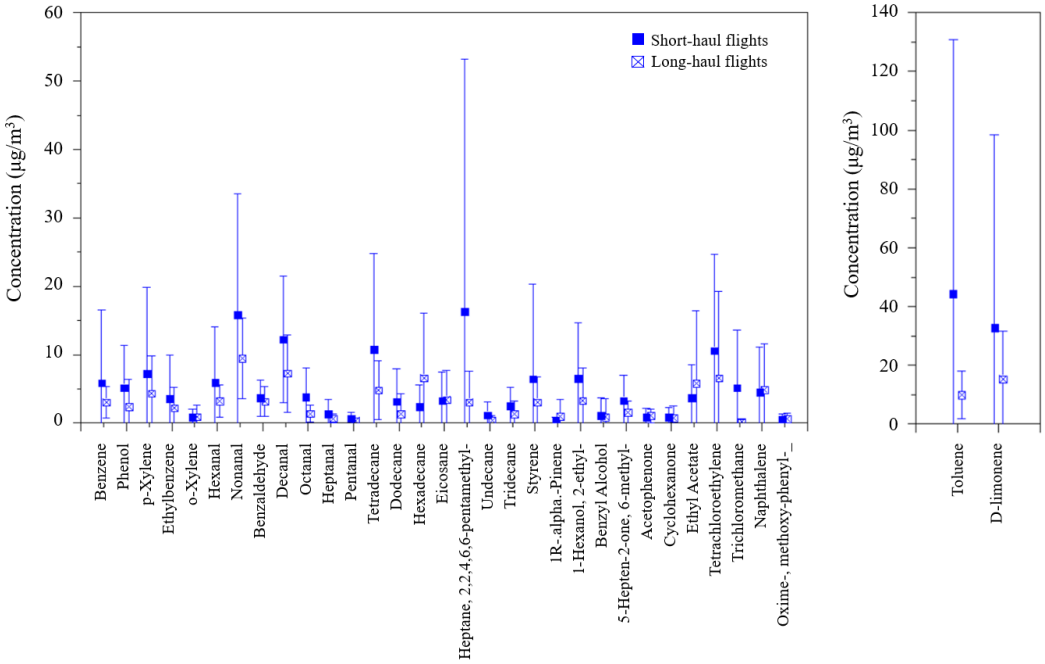


Figure 6. VOCs concentrations of long-haul and short haul flights

Note: only VOCs with detection rates above 50% is shown.

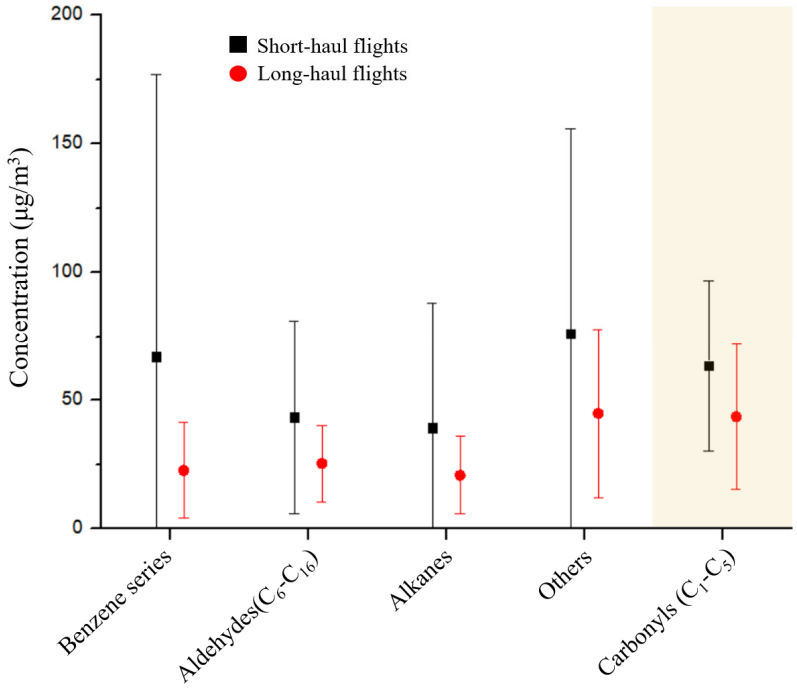


Figure 7. Comparison of VOCs concentrations of different aircraft types for short-haul flights

3.5 Influence of aircraft age on VOCs concentration

Other indoor environment, such as buildings and vehicles, usually face the problem of high VOCs emission from interior decorating materials, which is usually very significant in the first year and could last for more than 3 years [63-65]. For indoor environments, the TVOC concentration could reach 10^3-10^4μg/m^3, approximately 3-10 times higher than older homes, and decreased markedly after 1 year. [63, 65, 66]. For automobile cars, in-cabin TVOC could reach 10^4-10^5μg/m^3 at the delivery of a new car, and the concentration was approximately one-tenth of the initial concentration after one year [64, 67]. However, for subway cabins, the concentrations of aromatic VOCs in new metro carriage were 1-2 times lower than that in the old ones [68]. In order to explore whether the cabin interior materials (such as carpet, seats, interior wall and other construction materials) have significant contribution in new aircraft cabins, and whether there are possible special emission sources in aircraft cabin under the routine maintenance by airline companies, the influence of aircraft age on VOCs were analysed.

Table 5 described the statistical data of carbonyls and VOCs concentrations distribution in flights of different aircraft age. The SD value of the mean concentration of carbonyls between different-age aircrafts were less than 4μg/m^3, indicated that no significant higher concentration of any kind of VOC categories were founded in newer aircrafts. Similar to carbonyls, the mean value of VOC categories was relatively stable in different-age aircrafts (fluctuated within 30μg/m^3), even slightly lower in the flights that aircraft age less than 1 year. Unlike the new decorated houses or the new produced

cars, the concentration difference between the "old" one and the "new" one could reach to the order of 10-10^2 [63, 64, 66]. It is considered that the quality of the inner surface materials of aircraft maybe better controlled and the ventilation rate is relative large in aircraft cabin in normal operation. In addition, the concentration distribution were wide but similar for flights in the all age groups. For example, the minimum-maximum concentration of carbonyls in all age group were distributed between 10-100μg/m^3. No special emission sources of VOCs were founded in certain-age aircrafts.

Table 5. Carbonyls and VOCs concentrations in flights of different aircraft age

		Aircraft age											
		<1 year			1-3 year			3-5 year			5-10 year		
	Compounds	Mean	SD	Min - Max	Mean	SD	Min-Max	Mean	SD	Min-Max	Mean	SD	Min
Carbonyls	Formaldehyde	5.03	2.74	1.72 - 7.90	5.14	4.55	< LOD - 15.09	5.78	3.84	0.58 - 14.07	6.52	4.45	0.25
	Acrolein & Acetone	19.03	9.72	3.38 - 29.78	18.32	8.84	5.54 - 33.13	24.71	12.93	14.05 - 57.63	19.36	14.33	< LO
	Propionaldehyde	0.93	1.06	< LOD - 2.58	7.82	8.56	< LOD - 29.52	4.62	5.77	< LOD - 16.03	3.47	4.60	< LO
	Crotonaldehyde	0.04	0.08	< LOD - 0.18	2.60	3.94	< LOD - 10.24	0.94	2.65	< LOD - 8.87	0.10	0.28	< LO
	Methacrylaldehyde	< LOD	/	< LOD	0.84	1.42	< LOD - 4.28	0.91	1.62	< LOD - 4.44	0.06	0.17	< LO
	2-Butanone	4.10	2.13	1.23 - 6.23	14.07	10.63	< LOD - 31.79	6.08	10.67	< LOD - 30.73	8.70	9.00	< LO
	Butyraldehyde	0.76	1.14	< LOD - 2.73	3.94	4.81	< LOD - 15.88	2.59	3.56	< LOD - 9.90	5.05	7.55	< LO
	Benzaldehyde	0.22	0.38	< LOD - 0.89	6.77	15.88	< LOD - 51.28	1.27	2.07	< LOD - 6.81	1.59	4.50	< LO
	Valeraldehyde	0.06	0.10	< LOD - 0.23	1.06	2.11	< LOD - 6.31	1.49	2.79	< LOD - 7.60	0.85	2.06	< LO
	m&o-Tolualdehyde	0.03	0.06	< LOD - 0.14	1.89	2.70	< LOD - 8.00	1.54	2.66	< LOD - 8.35	1.23	1.96	< LO
	Hexaldehyde	2.06	1.05	1.21 - 3.84	6.42	4.56	< LOD - 13.83	5.67	4.13	< LOD - 13.92	7.32	5.64	1.50
SUM of Carbonyls		32.28	11.12	13.27 - 41.47	66.84	42.57	18.55 - 139.35	51.18	32.71	13.92 - 113.37	53.87	27.86	15.4
Benzene series		39.50	27.69	8.55 – 72.62	55.08	52.48	4.90 – 176.60	28.54	19.28	2.50 – 66.39	53.28	126.73	2.65
Aldehydes		25.54	16.25	3.59 – 47.53	40.95	30.75	7.57 – 103.98	31.77	18.03	10.32 – 70.41	37.22	40.75	5.45
Alkanes		31.04	6.57	23.75 – 38.43	27.31	23.11	<LOD – 63..36	26.89	17.72	7.03 – 73.24	29.91	36.16	< LO
Other VOCs		68.70	34.08	26.02 – 115.71	55.65	37.29	13.82 – 119.50	78.31	94.75	16.85 – 358.67	56.57	65.93	2.55

4. Limitations of the study

On-board measurements of organic compounds of 56 flights were conducted to understand aircraft cabin air quality and the correlation between carbonyls and VOCs. The tested flights covered the newer aircraft models like B787 (eight flights) and A350 (three flights), which installed aircraft activated carbon filter for gaseous pollutants adsorption, while the effect of installing chemical filters on cabin VOCs concentrations are not analyzed in this study. Further analysis on the actual effectiveness of the existing aviation filters for various specifics VOCs still need larger sample size and more specific information of filters (e.g. latest replacement date). Due to the limitation of field conditions in the actual measurement, this study did not sampled contaminants at bleed air, supply air, return air separately. Multi-point measurements and calculation are needed for in-depth analysis on the influence of ECS and activated carbon filters.

5. Conclusions

This study quantitatively measured the carbonyl compounds and other VOCs in 56 commercial flights to obtain its concentration status in aircraft cabin. Effect of flight phases, flight duration, aircraft age were analyzed to explore the influence of ventilation and emission sources on cabin contaminant concentration. The following conclusions can be made:

1) Statistics data showed that except for acrolein & acetone (median=18.3μg/m^3), the mean concentration for one single carbonyl compound was normally between 0.3–8.3μg/m^3 in aircraft cabin, similar to the highly-detected VOC concentration. Formaldehyde concentrations in aircraft cabin (0-20μg/m^3 during cruising phase) were significantly lower than that in residential building indoor environment.The mean concentration of acetone in recent years (about 20μg/m^3) were much lower than that measured in the 1990s (40-60μg/m^3), and were similar to that in other transportation vehicles in nowadays.

2) Except for the meal phase, the variation of VOC concentration in different flight phases of long-haul flights was the same as that of CO_2, which indicates the importance of cabin ventilation in the change of VOC concentration in aircraft cabin of long-haul flights. While the sustained and slow growth of the VOC concentrations before descent phase in short-haul flights indicated that VOC in cabin air mainly came from cabin interiors during the cruising phase for short-haul flights. The large difference of boarding phase VOC concentrations between the tested flights may be related to ambient air pollution of airport or bleeding air pollution. Such bleeding air pollution may requires purification other than ventilation.

3) The effect of meal service on VOC concentration in cabin lasted for about 1 hour. Carbonyls and D-limonene could be considered as the typical compounds released from meal/drink. Overall, the mean concentration during cruising phase for benzene series, aldehydes, alkanes, other VOCs (DR>50%), carbonyls were 44.2μg/m^3, 17.9μg/m^3, 18.6μg/m^3, 31.5μg/m^3, 20.4μg/m^3 lower in long-haul than in short-haul flights respectively. Unlike the new decorated rooms or new vehicles, the inner-materials of the aircraft were not the strong emission sources in cabins.

Acknowledgments

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