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Measurements of volatile organic compounds in aircraft cabins. Part I: Methodology and detected VOC species in 107 commercial flights

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ABSTRACT

To better understand the overall VOC species and levels and their key influencing factors in aircraft cabin, we conducted in-flight measurements in 107 commercial flights from August 2010 to August 2012. These flights were randomly selected and a sampling method using syringe was developed to obtain overall information of VOCs in actual cabins. On average 59 VOCs in each flight were detected within a total of 346 VOCs in the 107 flights, with the percentage of 41% for alkanes and alkenes, 15% for esters and alcohols, 11% for ketones and aldehydes, 6% for halides, 20% for aromatics and 6% for other VOCs (e.g. nitrogen-containing compounds). Main VOCs with high detection rate were compared at three different flight phases and at meal services for further analysis, respectively. Influences of several potential factors including air route, aircraft model and seasonal variation on the detection rates of cabin VOC species were preliminarily analyzed by chi-square test and logistic regression methods. The statistical results indicate that certain level of correlation between o-xylene, tetrachloroethene, benzene, 1,4-dichloro-, formamide, N,N-dimethyl-, ethane, 1,2-dichloro- and nonane ($p < 0.05$) and these factors. Factor analysis by logistic regression method further quantified the detection risk of above 6 selected VOCs with those three factors. This study could serve important first step to better understanding of cabin air quality and its major influencing factors.

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1. Introduction

The aircraft cabin environment is different from other indoor environments such as buildings in many respects. In aircraft cabin, people encounter a combination of environmental factors that include low humidity, reduced air pressure, and potential exposure to air contaminants, such as ozone (O_3), particulate matters, various volatile organic compounds (VOCs), and biological agents [1–5]. Both the occupant density and air tightness in aircraft cabin are also much higher than in buildings. Furthermore, with the rapidly growing number of air passengers, more attention has been paid to the increasing sensitivity of the public to potential health implications of cabin air quality [6]. And thus, the understanding of current situation of various air contaminants in cabin environment is important to further develop effective contaminant source prediction methods, control strategies, standards and regulations.

VOCs represent a significant class of air contaminants in built environment. Adverse health effects potentially caused by VOCs may include (1) irritant effects, including perception of unpleasant odors, mucous membrane irritation, and exacerbation of asthma; (2) systemic effects, such as fatigue and difficulty concentrating; and (3) toxic, chronic effects, such as carcinogenicity [7–9]. Dechow et al. [10] evaluated differences between air distribution systems on two types of commercial aircraft in 1997. Health risks from exposures to environmental tobacco smoke (ETS) for nonsmoking airliner occupants, as well as risks from other pollutants of concern for all airliner occupants were an important issue as smoking area existed in aircraft cabins. Consolidated Safety Services (CSS) [11] and Pierce et al. [12] performed measurements of a total of eight Boeing 777 flights for the purpose of comparing cabin air quality measurements with potential exposure related symptoms reported by passengers and crew respectively in 1998 and 1999. Nagda et al. [13] carried out a study (ASHRAE RP959) involving a total of 10 flights on aircraft bleed and cabin air quality in 2001. Approximately 50 compounds which are related to hazardous air pollutants, air toxics and ozone precursors identified under the Clean Air Act, were listed in conformance with EPA Method TO-14. The data of in-flight

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measurements indicate that some of selected VOCs were not detected in bleed air and cabin air. Dumyahn et al. [15] and Spengler et al. [16] reported the results of a total of 27 flights on nine types of aircraft monitored, comparing cabin air quality with the air quality of various modes of public transportation, including travel by bus, train, and subway. Fox [17] published the results of a study performed on a single type of aircraft to evaluate air-cleaning capabilities of air filters integrated into the environmental control system in 2000. Ross et al. [18] reported measurements made on 22 flights of British Airways Health Services to provide cabin air quality data for physiologic evaluations in 2000. For a comprehensive assessment of chemical species in a cabin environment, a broader analytical window of species including unsaturated VOCs and their reactions with oxidants (e.g. ozone) is necessary [19]. Chester et al. [1] and MacGregor et al. [14] reported measurement data of four flights for cabin air quality including VOCs and other air contaminants in cabins respectively in 2004 and 2008. Analysis on a list of 54 VOCs selected indicates that ethanol and acetone were the dominant VOCs observed on all flights.

Very few cabin VOC study has been reported in recent years, and yet, similar studies in other built environment remain to be very active. Spengler et al. [20] carried out environmental monitoring in the passenger cabin of 83 commercial flights in 2012. About one hundred VOCs were presented in this study, in which some passenger-related VOCs and aldehydes were higher for flights with decreased ventilation rates. However, no further explanations of detection risks and factor analysis of these VOC species or chemical group were mentioned in this report or other subsequent publications. In their study, they also compared the VOC data between cabin environment and other built environment [21–23], and indicated that the air quality and environmental conditions in the passenger cabin of commercial airplanes are comparable or better than conditions reported for offices, schools and residences, with a few exceptions. As for other related studies on different indoor environments, Ongwandee et al. [24] and Liang et al. [25] reported the VOC levels in office buildings and residential buildings, respectively. Müller et al. reviewed the exposure of some specific VOCs inside vehicles (e.g. car cabin), such as aromatic hydrocarbons and aliphatic hydrocarbons, and suggested that statistical data of field measurements were insufficient to reach a conclusion [26]. Apparently, the VOC species and concentrations vary significantly for different indoor environments, and such differences are attributed to specific indoor source conditions as well as key influencing factors such as pressure, relative humidity (RH), air change rate (ACH), chemical reaction and exposure time.

According to the review of existing publications, further studies on aircraft cabin VOCs are necessary in the following aspects: 1) A comprehensive and broad measurements of VOCs covering a wide variety of factors, including the aircraft model, flight route, flight phases, flight service (e.g., meal) to yield a general picture of cabin VOCs with both statistical and factorial values. 2) A list of possible VOCs with high detection rate and health risk should be emphasized to build the target VOC list although it happens to be lower concentration level for some selected VOCs reported in the literature (e.g. [10, 13, 14, 17 and 20]). 3) Statistical results should be given for the cabin VOC species, concentration ranges, and potential influence factors.

Due to its very special environment and safety restrictions, cabin air quality measurement faces more challenges than other built environment measurements. Regarding the air sampling method used, previous researchers took cabin air samples by pumping air through a sorbent tube or evacuated stainless steel canisters, and subsequently analyzed by gas chromatography/flame ionization detector (GC/FID) or by Gas Chromatograph/Mass Spectrometer (GC/MS) following ASTM Standards (e.g. D6196, D6399) or USEPA Compendium Methods (e.g. TO-15, TO-17). However, without special permission from the aviation authorities, using an electronic device such as an air sampling pump on-board is prohibited especially during the take-off and landing periods. For large-scale, "routine" in-flight tests, a simple and yet reliable air sampling method acceptable for aviation authorities, nearby passengers and crew members should be developed.

In this research program, two parts of work were conducted in an attempt to better understand the overall VOC species, levels and their key influencing factors in aircraft cabin. Firstly, an air sampling method that can meet the airline safety requirement was developed for the "routine" in-flight VOC measurements, and the validity of the method was confirmed. Using this sampling method, 107 flights were randomly selected and tested and statistical analysis of VOC species and their influencing factors are presented in this paper. Secondly, concentration levels of detected VOCs and their potential source analysis in cabins are conducted by quantitative analysis, which are presented in the companion paper.

2. The methodology of in-flight measurements

2.1. Information on studied flights

This study intends to have broader coverage of aircraft types, operating phases and other possible influencing factors on cabin VOCs. The measurements lasted nearly two years, from August 2010 to August 2012, and included a total of 107 flights. Fig. 1 lists the aircraft types and numbers of these tested flights. The measurements did cover a majority of the large commercial aircraft types currently being operated in China and worldwide. The domestic flights ($N = 76$) at less than 4 h durations and international or transoceanic flights ($N = 31$) at more than 4 h durations were in the proportion of all flights, in which single-aisle planes ($N = 66$), such as A320 series, A321 series and B737 series and double-aisle planes ($N = 41$), such as A330 series, B747 series and B777 series were all included. Notice that private aircraft and very short-haul flights (less than half an hour flight duration) were excluded in this study.

2.2. Testing equipment and procedure

For a whole in-flight test, at least three points including before take-off, cruise and landing in which each represents a typical

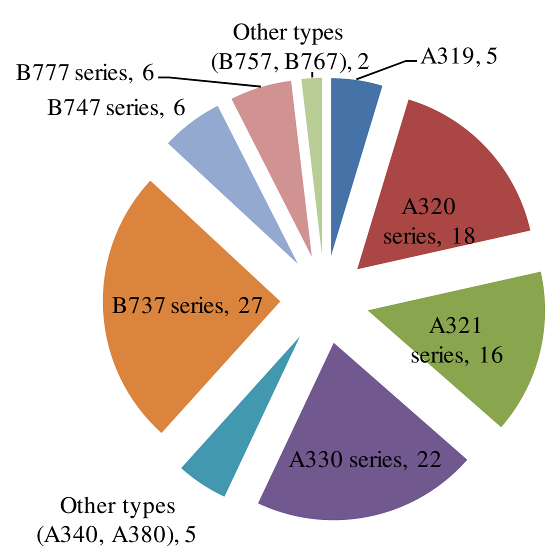

Fig. 1. Distribution of aircraft types of 107 measured flights.

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