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Source apportionment of volatile organic compounds (VOCs) in aircraft cabins

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A B S T R A C T

The presence of volatile organic compounds (VOCs) in the air of aircraft cabins was studied to identify possible emission sources and their contributions to aircraft cabin VOC concentrations. A total of 84 sampling events were included during 14 different flights. Based on the measured VOC concentrations, a receptor model using positive matrix factorization (PMF) coupled with information related to VOC sources was applied to identify the major VOC sources in aircraft cabins. Eight possible VOC sources were identified by the PMF method including service and humans, chemical reactions, fuels, materials, combustion, non-fuel oil, cosmetics and perfumes, and cleaning agents. Results of the source apportionment showed that 29% of the total VOC emissions in aircraft cabins can be attributed to service and humans, followed by chemical reactions (15%), fuels (13%), materials (12%), combustion (12%), non-fuel oil (9%), cosmetics and perfumes (6%) and cleaning agents (4%). The results of this study could be helpful in controlling the possible VOC sources for better cabin air quality.

1. Introduction

According to a survey in 2006, more than 750 million people use air travel each year and the total distance traveled is approximately 8.1×10^{11} miles [1]. Aircraft cabins represent a very different environment than building environments on the ground [2–4]. There could be many air pollutants in the aircraft cabin [2–7], among them volatile organic compounds (VOCs) are of particular interest for a number of reasons. In aircraft cabin air, VOCs can react with ozone, leading to an increase in the formation of airborne toxic chemicals and fine particles [8]. On the other hand, VOCs could directly affect cabin air quality. A number of studies have investigated VOC concentration levels in aircraft cabins [9–14]. Although the simple quantification of VOCs is meaningful, it is not sufficient to support the development of strategies to control VOCs in cabins. For the latter, source characterization and apportionment are needed. Identification of the possible emission sources of VOCs and their contribution to VOC levels is a critical issue for the development of effective VOC controls.

Studies have been carried out to understand the sources of VOCs in residences and atmospheric ambient air all over the world. These studies have indicated main VOC sources or activities such as smoking, cooking, cleaning products, consumer products, renovation products, building materials, and carpets [15–22]. In the atmospheric ambient air, coal burning, vehicle emission, gases, and vapor are the main VOC sources [23–28]. However, no similar studies have been carried out for the VOC source contribution in aircraft cabins.

In the aforementioned studies [15–28], the sources of VOCs inside homes or in atmospheric ambient air were investigated in a qualitative way by using receptor-oriented source apportionment models. These models have often been used to identify sources of air pollutants and to estimate source contributions to air pollutant concentrations. The most widely used models include the chemical mass balance (CMB) model [23–28] and the principal component analysis (PCA) model [22,29–31]. The CMB model requires detailed source profiles which have not been investigated sufficiently in aircraft cabins. The PCA model cannot properly handle missing and below-detection-limit (BDL) data, making it difficult to use in the present study. Positive matrix factorization (PMF) is a multivariable analysis method based on factorial analysis. It is an advanced algorithm that has been widely used in source apportionment of particulate matter and VOCs when local source profile measurements are lacking [32–37].

Generally, the basis for source identification is the use of different sources associated with different VOC types. These gases can be used as “tracers” to identify VOC sources. This is applicable if the characteristics of sources have been studied in detail. For

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example, for the VOC sources in atmospheric ambient air, isopentane is identified as a tracer of gasoline evaporation [38], and propene is the characteristic product of internal combustion engines and has been reported as a good indicator of vehicle exhaust in Shanghai [39]. However, very limited studies have been done for VOC sources in aircraft cabins, making this approach difficult to use. In the present study, we carried out source identifications using the limited results from the literature relevant to the emission sources or with similar characteristics to those in aircraft cabins.

2. Methods

2.1. Selection of tested flights

Tested flights were selected on the basis of: a) prevalence of aircraft type; b) flights with relatively high occupancy rate; and c) destinations covering different cities. Based on the guidelines mentioned above, a total of 14 flights were selected as detailed in Table 1.

2.2. Air sampling and chemical analysis

Air sampling on cabin was accomplished by drawing cabin air through the Tenax-TA tubes using a sampling pump (*Libra Plus*™ LP-1, A. P. BUCK INC., USA), calibrated to draw at 200 ml/min. The total sampling volume was 1000 ml. A package containing Tenax-TA tubes, field blank tubes and operating instruction were taken on each flight by the tester. The sampling was taken at a height of approximately 1.2 m above the cabin floor which was in the tester's breathing zone. Samples were collected during different flight phases (takeoff, climbing, cruise, descending and landing) for each of the 14 flights. At least five samples were collected during each flight, and the total number of samples in all the 14 flights was 84.

A total of 19 VOCs were selected for chemical analysis in this study. These compounds were selected because they have been widely monitored in aircraft cabins [40,41]. To carry out the VOC analysis, the Tenax-TA tubes were put into a thermal-desorber (TD, Markes, Inc. UK), which injected the sample air into the gas chromatography (GC) (Model 6875, Agilent, USA), fitted with a mass spectrometer (MS, 5975B, Agilent, USA). An HP-VOC capillary (30.0 m × 200 μm × 1.12 μm film thickness) was used with helium as carrier gas at a flow rate of 3 ml/min. The initial temperature of the oven was 40 °C (4 min), and then increased up to 250 °C (hold for 5 min) at 10 °C/min. The instrument was checked daily in order to guarantee the retention times and responses of selected compounds using a standard calibration mixture injection.

Table 1
Flight information.

Flight	Date (yymmdd)	Aircraft	From	To	Duration (min)
1	20120917	B737-800	Tsingtao	Chengdu	170
2	20120917	B737-800	Chengdu	Tsingtao	150
3	20120918	B737-800	Tsingtao	Kunming	190
4	20120918	B737-800	Kunming	Tsingtao	170
5	20120919	B737-800	Tsingtao	Beijing	80
6	20120922	B737-800	Beijing	Tsingtao	80
7	20120923	B737-700	Tsingtao	Guangzhou	180
8	20120923	B737-700	Guangzhou	Tsingtao	165
9	20120924	B737-800	Tsingtao	Harbin	110
10	20120924	B737-800	Harbin	Tsingtao	120
11	20120925	B737-800	Tsingtao	Shanghai	80
12	20120925	B737-800	Shanghai	Tsingtao	85
13	20120926	B737-800	Tsingtao	Shenzhen	180
14	20120926	B737-800	Shenzhen	Tsingtao	165

2.3. Quality control and assurance

Quality control for the entire sampling process included laboratory and field blanks. Before each measurement, the sampling pump was calibrated using a soap-film flowmeter (GL-100, Zhongkezhonghuan, Inc., Beijing, China). All Tenax-TA tubes were cleaned at least three times with high purity nitrogen and analyzed in the laboratory before sampling to determine concentrations in the blank tube. During the in-flight measurements, a blank Tenax-TA tube was taken for field blank analysis.

Identification of VOCs on the Tenax-TA tubes was performed with external standard solutions based on retention times. Mixed standard VOC solutions (benzene, toluene, ethylbenzene, p-xylene, and o-xylene, hereafter “BTEX”) for identification and quantification of VOCs were obtained from the Institute for Reference Materials, Chinese Ministry of Environmental Protection. Each standard exceeded 96% purity and original solution was used at three concentrations of 10, 100 and 1000 μg/mL, then 2, 5, 8 μL from the first two original solutions, respectively, 2 and 5 μL from the third original solution, totally eight points were included in the calibration. The concentrations of other VOCs were calculated as toluene equivalent [42].

2.4. The PMF receptor model

The basic premise of PMF is to reduce the data dimensions similar to principle component analysis (PCA). However, the data used by PMF are directly from measured data and not the normalized data as in PCA. PMF can obtain a set of profile and score matrices by solving a constrained and weighted least-squares optimization equation:

$$x_{ik} = \sum_{j=1}^{p} g_{ij} f_{jk} + e_{ik} (i = 1, 2, \ldots, m;\ j = 1, 2, \ldots, n) \tag{1}$$

where x_{ik} represents the concentration of VOC compound i for the kth sampling; g_{ij} represents the profile matrices of compound i for jth source; f_{jk} represents the score matrices for the jth source and the kth sampling; and e_{ik} is the residual factor of compound i for the kth sampling.

Although PMF can overcome the limitation of PCA or other receptor models in which the result may be negative, the numbers used in the PMF may still present a problem. In this study, two guidelines were used: 1) the eigen-values of a matrix are greater than 1; and 2) the variances after deciding on the factors can explain most of the sum of VOCs. The PMF method gives a minimum object function Q, based upon the calculation of uncertainties (u):

$$Q = \sum_{i=1}^{m} \sum_{k=1}^{n} \left(\frac{e_{ik}}{u_{ik}} \right)^2 (i = 1, 2, \ldots, m;\ k = 1, 2, \ldots, n) \tag{2}$$

where u_{ik} represents uncertainty of compound i for the kth sampling. The uncertainty (U) is calculated using the following equation [43]:

$$U = \sqrt{(\mathrm{EF} \times \mathrm{conc})^2 + (\mathrm{MDL})^2} (\mathrm{conc} > \mathrm{MDL}) \tag{3}$$

where EF represents an error fraction (EF = the percent uncertainty × 100), which in the present study was set to 5%, and MDL represents the method detection limit (in the present study, MDL = 1/3 × min of measured concentration). If the concentration is less than or equal to the MDL, the equation is [32]:

$$U = \frac{5}{6} \times \mathrm{MDL} (\mathrm{conc} < \mathrm{MDL}) \tag{4}$$