Atmospheric Environment 89 (2014) 119–128

Contents lists available at ScienceDirect

Atmospheric Environment

journal homepage: www.elsevier.com/locate/atmosenv

Source apportionment of airborne particles in commercial aircraft cabin environment: Contributions from outside and inside of cabin

Zheng Li [a], Jun Guan [a], Xudong Yang [a,*], Chao-Hsin Lin [b]

[a] Department of Building Science, Tsinghua University, Beijing 100084, PR China
[b] Environmental Control Systems, Boeing Commercial Airplanes, Everett, WA 98203, USA

HIGHLIGHTS

- Particles larger than 0.3 um ($PM_{>0.3}$) were measured in 9 flights.
- $PM_{>0.3}$ counts first decreased, then increased in supply air and breathing zone.
- $PM_{0.3-2.0}$ in breathing zone mainly came from outside via bleed air.
- For $PM_{>2.0}$, contributions from outside and cabin interior were equally important.

ARTICLE INFO

Article history:
Received 30 September 2013
Received in revised form
17 January 2014
Accepted 20 January 2014
Available online 1 February 2014

Keywords:
Aircraft cabin
Particle concentration
Size distribution
Airflow rate
Source apportionment

ABSTRACT

Airborne particles are an important type of air pollutants in aircraft cabin. Finding sources of particles is conducive to taking appropriate measures to remove them. In this study, measurements of concentration and size distribution of particles larger than 0.3 μm ($PM_{>0.3}$) were made on nine short haul flights from September 2012 to March 2013. Particle counts in supply air and breathing zone air were both obtained. Results indicate that the number concentrations of particles ranged from 3.6×10^2 counts L^{-1} to 1.2×10^5 counts L^{-1} in supply air and breathing zone air, and they first decreased and then increased in general during the flight duration. Peaks of particle concentration were found at climbing, descending, and cruising phases in several flights. Percentages of particle concentration in breathing zone contributed by the bleed air (originated from outside) and cabin interior sources were calculated. The bleed air ratios, outside airflow rates and total airflow rates were calculated by using carbon dioxide as a ventilation tracer in five of the nine flights. The calculated results indicate that $PM_{>0.3}$ in breathing zone mainly came from unfiltered bleed air, especially for particle sizes from 0.3 to 2.0 μm. And for particles larger than 2.0 μm, contributions from the bleed air and cabin interior were both important. The results would be useful for developing better cabin air quality control strategies.

1. Introduction

The aircraft cabin air quality is important to the health and comfort of passengers and crew members (Mangili and Gendreau, 2005; Vogt et al., 2006). Exposure to pollutants such as airborne particles has been associated with increases in mortality and hospital admissions due to respiratory and cardiovascular disease (Dockery et al., 1993; Chen et al., 2012). Inhalable particles (PM_{10}) could be generated from human activities and chemical reactions in the cabin (You et al., 2013; Annette et al., 2003), as well as from the outside through the unfiltered bleed air. In current aircraft ventilation design, the re-circulated air is filtered by high efficiency particulate air (HEPA) filters, but not the compressed bleed air from the outside (Gladyszewska-Fiedoruk, 2012). Even flying at high altitude, the outside air contains particles of various sizes (Wang et al., 2008). Understanding the real-time particle concentrations in aircraft cabin and identifying their possible sources are important for cabin air quality assessment and control.

In-flight measurements of particle concentrations in aircraft cabin have been conducted in the past 20 years. PM_{10} in passenger cabins of DC9-12, DC9-41 and MD-81 aircraft were measured on 48 flights in which smoking was not forbidden (Malmfors et al., 1989). Average levels of PM_{10} in cabins for the three kinds of aircraft were 110 ± 14 μg m^{-3}, 130 ± 10 μg m^{-3}, and 150 ± 16 μg m^{-3} respectively. They heavily exceeded the World Health Organization Air Quality Guidelines (WHO AQGs, 50 μg m^{-3}, 24-h average

* Corresponding author. Tel.: +86 10 6278 8845; fax: +86 10 6277 3461.
E-mail address: xyang@tsinghua.edu.cn (Xudong Yang).

1352-2310/$ – see front matter © 2014 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.atmosenv.2014.01.042

concentration). O'donnell et al. (1991) carried out an investigation on 45 flights from seven aircrafts of the same model. PM_{10} were measured in non-smoking short haul flights. The average PM_{10} level (105 μg m^{-3}) exceeded the comfort criteria (75 μg m^{-3}). Another measurement of PM_{10} was performed on 26 intercontinental flights with and without tobacco smoking onboard in 2002 (Lindgren and Norbäck, 2002). Results indicated that tobacco smoking led to significant increase of PM_{10} level, particularly in the rear part of the cabin. The mean concentration of PM_{10} in the rear part of the aircraft was 49 μg m^{-3} during smoking, but for non-smoking condition, it was as low as 3 μg m^{-3} Lee et al. (1999) investigated the PM_{10} levels on 16 flights from June 1996 to August 1997. The average PM_{10} level on smoking flights (138 μg m^{-3}) exceeded the Hong Kong air quality standard (HKAQO, 55 μg m^{-3}, 1-year average concentration), and was much higher than that of non-smoking flights (7.6 μg m^{-3}).

Due to both safety and health concerns, smoking has now been prohibited in commercial planes so it is no longer a source of particles in cabin. With the help of HEPA filters, the PM_{10} levels in cabins have been reduced sharply. Spicer et al. (2004) measured fine particle ($PM_{2.5}$) concentrations on a flight from Cincinnati to Salt Lake City in April 2004, and the mean concentration of $PM_{2.5}$ for the entire flight was 5.4 μg m^{-3}, much lower than the 24 h National Ambient Air Quality Standard 65 μg m^{-3}. Spengler et al. (2012) tested ultrafine particles ($PM_{0.1}$, UFP) on 55 flights, the maximum 15-min concentration across flights ranged from 1.00×10^3 counts L^{-1} to 3.12×10^8 counts L^{-1}, and the mean UFP for flights with lower latitude routes was 1.10×10^6 counts L^{-1} compared to a mean UFP of 5.50×10^4 counts L^{-1} for flights with higher latitude routes. No mass concentration was given and there is no convenient way to accurately convert from particle counts to mass concentration. In flights which had no food service onboard (an activity expected to raise UFP), UFP showed a positive trend with ozone.

Although these studies have been useful to reflect the particle level in actual aircraft cabin, potential particle sources and influencing factors (e.g. ventilation system, flight phase) were not investigated in depth. For this purpose, this study intends to: 1) obtain information of real-time particle concentration and size distribution in aircraft cabins for further analyzing cabin air quality; 2) calculate particle contributions of in-cabin and outside sources for offering suggestions to cabin environment control strategy. Real-time measurements of CO_2 and particle levels were conducted to estimate the cabin ventilation rate and the particle contributions from both in-cabin and outside sources.

2. Experiments and methods

The air distribution systems in aircraft cabin may vary with different aircraft types. In order to exclude the influence of aircraft types on particle concentrations, Boeing 737–800, which can carry a maximum of 180 passengers (without business class) or 168 passengers (with business class) and 10 crew members, is chosen as the measured airplane type. The seat map of the cabin measured is shown in Fig. 1. The cabin, hermetically closed, is centrally conditioned by the environment control system (ECS). Over each seat in the cabin, there is a personalized air supply outlet (personal gasper). Cabin air is returned through the grilles at the bottom sides of cabin.

Supply air, which is used to sustain temperature and pressure and preserve the overall quality of the inflowing air, is mixed by bleed air (originated from outside) and re-circulated air from the cabin (Hunt et al., 1995). Before blending with bleed air which is not filtered, re-circulated air flows through high efficiency particulate air filters (HEPA) located under the floor of the cabin, and these

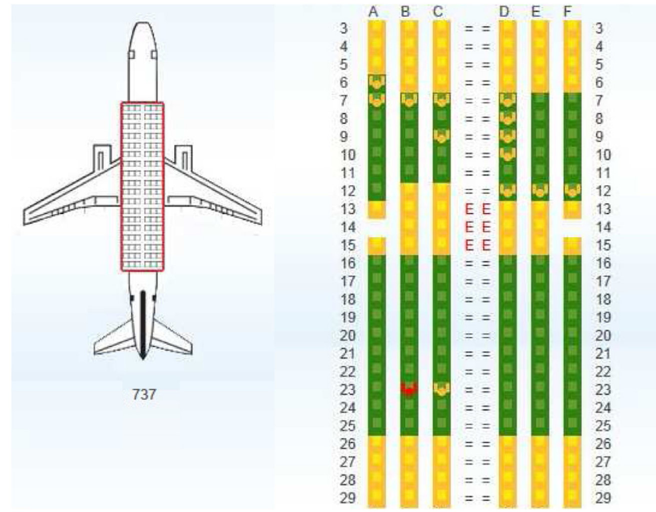

Fig. 1. Seat map of Boeing 737–800 (red "E" means emergency exit).

filters are highly effective in removing particles (Lufthansa, 2001). The air blend is delivered into the cabin by means of air vents placed high in the cabin. At the same time, one or more valves that also ensure the required air pressure level inside the cabin dump the used air (Gladyszewska-Fiedoruk, 2012). Fig. 2 shows the schematic of ventilation system in aircraft.

On-board measurements were conducted from 17 September 2012 to 10 March 2013 with a base in Qingdao Airport, China. The measurements included such cabin air parameters as concentrations of particle in supply air and breathing zone (the area above the folding table plate and below occupant's nose) air, CO_2 concentrations in supply air and re-circulated air, ozone and volatile organic compounds (VOCs). The schematic of tested regions and photos for measurements in aircraft cabin are shown in Figs. 2–3. Particle counts were measured by an Airborne Particle Counter (FLUKE Corporation, USA). The instrument simultaneously measures and records six channels of particle sizes (0.3–0.5 μm, 0.5–1.0 μm, 1.0–2.0 μm, 2.0–5.0 μm, 5.0–10.0 μm and ≥10.0 μm). The counter has a coincidence loss of 10% when the particle concentration is greater than 1.4×10^5 counts L^{-1} and a 100% counting efficiency when the measured particle diameter is larger than 0.45 μm. The instrument was calibrated and checked for zero point prior to each measurement using a zero counter filter. The setting flow rate of particle counter was 2.83 L per minute in measurements. According to the user manual, this instrument is not sensitive to pressure below the altitude of 1828 m (about 80 kPa), and it can adapt to the condition with humidity less than 95%. So it can be used in the aircraft cabin environment. The CO_2 concentrations in supply air and re-circulated air were measured and recorded continuously by the TELAIRE 7001 CO_2 monitor (General Electric Company, USA) which was insensitive to pressure either. Detection limit and threshold of the CO_2 monitor are 0 and 10,000 ppmv, respectively. The ozone and VOCs measurements are not within the scope of this paper and they were discussed by Guan et al. (2014).

Nine randomly selected short haul flights were tested (Table 1). Among these flight routes, the most northern city was Beijing, the most southern city was Shenzhen, the most western city was Kunming, the most eastern city was Qingdao, and the flight durations varied from 1 h 27 min to 3 h 50 min. Supply air and breathing zone air were both measured in the nine flights. In order to avoid the error caused by different instruments, they were measured staggered by one instrument throughout the flight. The CO_2