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Experimental study of particle deposition in the environmental control systems of commercial airliners

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HIGHLIGHTS

- Study of the particle deposition for different sizes in the environmental control systems of the commercial airliners.
- Development of the correlation between the particle deposition rates and the air quality.
- Particle mass concentration and particle size distribution were measured on the real flights and compared to the outside particle level.

ABSTRACT

Serious air pollution and low on-time performance of commercial flights in China could result in more particles being deposited in the environmental control systems (ECS) of the commercial airliners and ground air-conditioning carts (GAC). The particle deposited in the ECS and GAC could cause performance issues of the airplanes and GAC. In addition, particles penetrated to the aircraft cabin could cause adverse health impact on the passengers and crew. This investigation measured the $PM_{2.5}$ particle concentrations and the quantities of particles of different sizes at the inlet and outlet of the GAC and ECS in an MD-82 airplane parked next to Tianjin Airport under different air quality levels. The results showed that the deposition rate of the $PM_{2.5}$ mass in the GAC and ECS was 40-50%, with most (30-40%) of the deposition occurring in the ECS. For particles with a diameter of 5 µm or larger, the deposition rate was greater than 90%. For particles with a diameter of 0.5 µm or less, the deposition rate was less than 25% so they entered into the aircraft cabin. In addition, particle mass and number concentration was measured on commercial flights. The results indicated that particle concentrations were high compared with that during the cruising when the airplanes were on the ground at the Chinese airports where ambient particle concentrations were also high.

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Keywords: Particulate matter, deposition, air-conditioning system, filtration, particle mass, particle number

1. Introduction

The environmental control system (ECS) in a commercial airliner is to maintain safety, thermal comfort, and air quality for passengers and crew by supplying conditioned air into the cabin. During a flight, the total air supply is a mixture of outside air and filtered re-circulated air. High efficiency particulate air (HEPA) filters are only used for recirculated air, not for outside air entering the aircraft.

However, the particle concentration of the outside air on the ground could be high. The mass concentration of particles with aerodynamic diameters less than 2.5 microns ($PM_{2.5}$) in major Chinese airports, as shown in Fig. 1, was 3 to 10 times higher than that in many major metropolitan cities in developed countries, such as 16 $\mu g/m^3$ in London, 10 $\mu g/m^3$ in Tokyo, and 14 $\mu g/m^3$ in New York [1]. As the air pollution in cities and that near the city airports was usually comparable [2], so we could assume the air pollution in London, Tokyo, and New York airports was low. For example, Ellermann et al. [3] investigated the air pollution on the apron of Copenhagen Airport and found the annual average concentration of $PM_{2.5}$ was only 17 $\mu g/m^3$. Thus, the particular matter pollution in major Chinese airports was very serious.

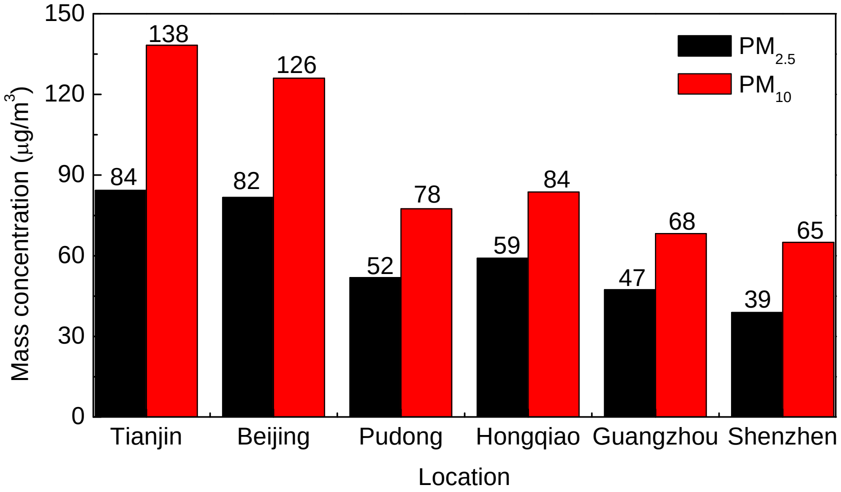


Fig.1. Annual average PM2.5 and PM10 mass concentration at six major airports in China measured from March 1, 2014 to February 28, 2015. [2]

In addition, the statistics from Flightstats [4] shows a very low on-time performance of about 30% for three major Chinese airports, which were the lowest in the world. For example, Shanghai CS Capital [5] estimated that passengers and crew spend extra 40 minutes on average in aircraft cabins between door closing and taking-off. Accordingly, GAC or APU has to be operated for a long time to supply air to an aircraft during the waiting period. Therefore, in China, a significant amount of particles could be brought into the commercial airliners before taking off.

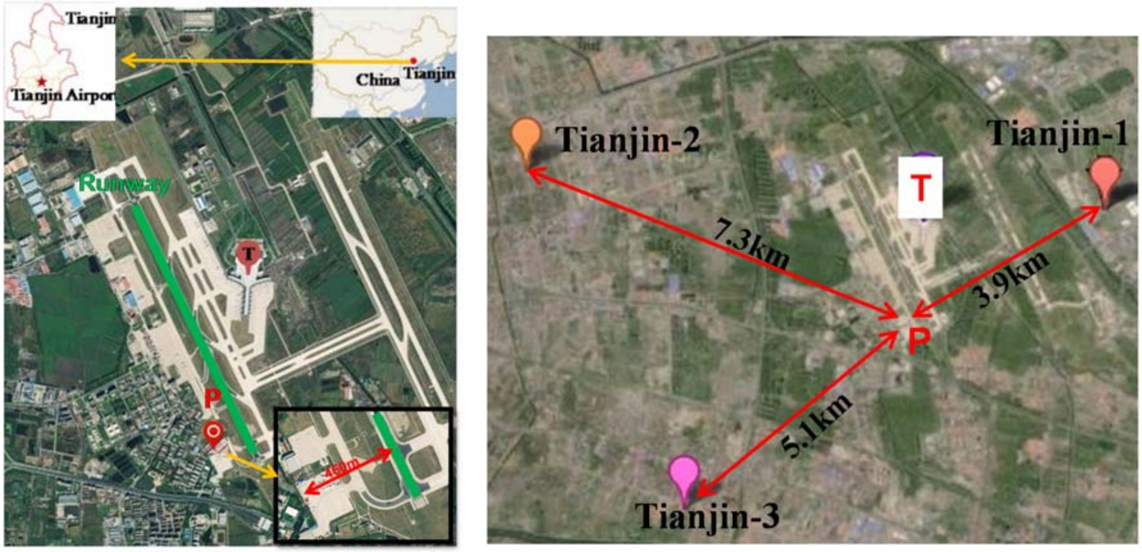
The outside air from a ground air-conditioning cart or APU will go through the ECS, which consists of heat exchangers, fans, turbines, and manifolds, before it is delivered into the cabin. The particles in the outside air are likely to deposit on the surface of the ECS components and ducts. The particle deposition on the ECS components would affect the performance and shorten the service life. For example, the increased particle concentration in the air will add mass loading to the HEPA filters when the air is circulated. Particle deposited on heat exchangers, turbines, and fans will decrease their efficiencies [6]. Meanwhile, such deposition can reduce the airflow rate through ducts, especially small diameter ducts, and thus can degrade the performance of the ventilation system [7]. Furthermore, the particle deposition on the duct systems would potentially increase the possibility of microbial contamination [8]. The accumulated dust and microorganisms in the supply air duct could turn into a pollution source [9], which will be brought into the aircraft cabin and be harmful to the health of the passengers and crew [10-12]. Therefore, it is important to investigate how much the particles were deposited in the ECS during ground operation. Our literature review shows that the past investigations on particle deposition in aircraft cabins focused on the particle transport inside the cabins during flights [13-16]. Few investigations were available on the particle deposition in the ECS.

This study conducted simultaneous measurements of $PM_{2.5}$ mass concentration, particle number and size distribution at the inlet and outlet of the ECS of an MD-82 airplane for simulating ground operations. In addition, the particle concentration was also measured on commercial flights to confirm the findings. The measured data were further analysed to understand the particle deposition in the ECS.

2. Experiments and methods

2.1. Site description

This investigation used a retired MD-82 airplane as the main experimental rig. The airplane was parked adjacent to the runway of Tianjin Binhai International Airport, as shown in Fig. 2(a). The airport had 10 million passengers in 2013 and was ranked 24th in China. The air quality in Tianjin was the tenth worst in China, and the $PM_{2.5}$ annual average concentration was 83 $\mu g/m^3$ in 2014 (China Environmental State Bulletin, 2014). Particular matter measurements were conducted at the MD-82 parking position where was only 460 m away from the runway. Three air quality monitoring stations around Tianjin airport as shown in Fig. 2(b) could provide the ambient air pollution data for the airport.



(a) (b)

Fig.2. (a) The MD-82 airplane parked at location P at Tianjin Binhai International Airport, where T is the terminal and the green line is the runway, and (b) Tianjin-1, Tianjin-2, and Tianjin-3 are the three air

quality monitoring stations near the airport.

2.2. Sampling and instrumentation

In order to obtain the particle deposition rate in the ECS, simultaneous measurements of particle concentration were conducted inside and outside the cabin under different air quality conditions. The measurements in the MD-82 airplane were mainly conducted in the afternoon from November 2014 to April 2015. Fig. 3(a) shows the MD-82 airplane was connected with a GAC that supplied conditioned air to the airplane. The GAC maintained the supply-air temperature at 20±1°C. The airflow rate was controlled at 9 L/s per passenger that is typical for commercial airliners. Simultaneous measurements of PM_{10} and $PM_{2.5}$ mass concentration were conducted at the inlet of the GAC, at the outlet of the GAC (or inlet of the ECS), and at the air supply diffusers (ECS outlets) in the first-class cabin, as showed in Fig. 3(b), (c), and (d), respectively. Both the particle mass concentration and particle size distribution were measured. Before each measurement, the ground air-conditioning cart had operated for two or three hours to obtain a steady working condition.

(a)

(b) (c) (d)

Fig.3. (a) The MD-82 aircraft with a GAC, and the measurement of particle concentration (b) at the GAC inlet (P1), (c) at the GAC outlet or ECS inlet (P2), and (d) at a gasper outlet in the first-class cabin (P3).

This study also investigated the particle level on commercial aircraft to further understand the particle deposition in ECS. The particle mass and number concentrations were measured inside the cabin during the flights. Due to the airport security concerns, the particle measurements outside the aircraft cabin were not permitted. The particle mass outside the cabin used the data from the nearest air quality monitoring station.

Fig. 4 shows a schematic figure of the ECS which consists of the key components such as an air-conditioning pack, a mix manifold, a main air distributor or manifold, air diffusers and the pipe that connects the ECS to the GAC. Many auxiliary components, such as anti-ice pipe lines and balance tubes, were neglected for the sake of simplicity. The outside air was brought into the aircraft cabin through the GAC connecting pipe or APU inlet.

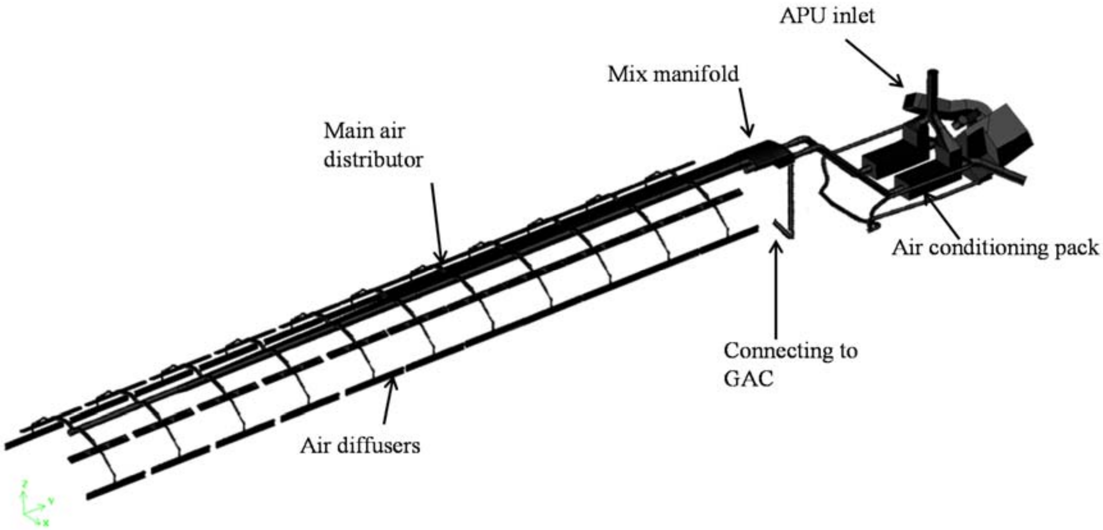


Fig.4. Schematic figure of the ECS

The particle mass concentrations were measured by DustTrak DRX aerosol monitors (Model 8533, TSI Corporation, USA) and DustTrak II aerosol monitors (Model 8530, TSI Corporation, USA). DustTrak DRX is a continuous, real-time, 90° light-scattering laser photometer that provides simultaneously size-segregated mass-fraction concentrations for PM_1, $PM_{2.5}$, PM_{10} and total PM size fractions. The instrument combines both particle cloud (total area of scattered light) and single particle detection to achieve mass fraction measurements. DustTrak II reports only one particle size at one time. The measurement precision was 1 $\mu g/m^3$. DustTrak DRX amd DustTrak II have the same accuracy as they were based on the same measuring technique and design parameters. The particle size distributions were measured by Fluke 983, an airborne particle counter (FLUKE Corporation, USA). It can simultaneously measure and record six channels of particle sizes (0.3 to 0.5 μm, 0.5 to 1.0μm, 1.0 to 2.0 μm, 2.0 to 5.0 μm, 5.0 to 10.0 μm and >10.0 μm). The experimental measurements obtained data with one-minute intervals. The measurements were made at ambient conditions without drying or heating the PM samples to remove adsorbed water. Since the primary purpose of the project was to evaluate PM loss through the ECS system, this probably does not affect the loss fraction significantly but the absolute concentrations will differ from those obtained with standard $PM_{2.5}$ and PM_{10} which are heated to measure dry samples in the three air quality monitoring stations around the airport.

2.3. Data analysis

In this investigation, the GAC supplied the MD-82 airplane with 100% outside air. The overall deposition rate on the air-conditioning cart and the ECS can be calculated by:

$$P_{deposition}=1-\frac{C_{inside}}{C_{outside}} \qquad (1)$$

where $P_{deposition}$ is the PM mass or number deposition rate in the GAC and the ECS, C_{inside} is the PM mass or number concentration measured inside the first-class cabin and $C_{outside}$ is the PM mass or number concentration measured outside of the airplane (at the GAC inlet). The data was averaged over an hour to reduce the fluctuations.

As pointed out by Wang et al. [17], particles could resuspension in ventilation duct and the suspension rate depends on air velocity and other factors. However, this investigation was unable to separate the deposition and resuspension, Eq. (1) represents the net deposition.

3. Results

3.1. Particle deposition in the ECS and GAC

Particle mass concentration outside the MD-82 cabin (at the GAC inlet) and inside the cabin (at a gasper outlet in the first-class section) was measured under different air quality levels at Tianjin Airport. Table 1 lists the $PM_{2.5}$ values from the three government monitoring stations designated as Tianjin-1, Tianjin-2, and Tianjin-3 as shown in Fig. 2(b) near the airport during our measurements to represent the air quality level. The table also shows the $PM_{2.5}$ mass concentrations measured inside and outside the cabin. The $PM_{2.5}$ deposition rate in the ECS and GAC ranged from 15.0% to 56.4%. When the outdoor $PM_{2.5}$ level was higher than 200 μg/m³, the particle deposition rate was greater than 40%. It seems that particle deposition rate increased as the air quality worsened.

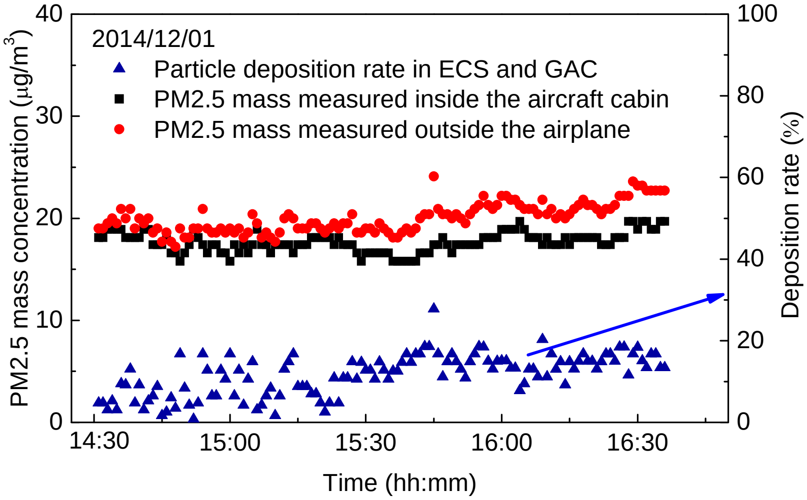
Table 1

$PM_{2.5}$ mass concentration deposition rates in the ECS of the MD-82 and in the GAC under different air quality levels.

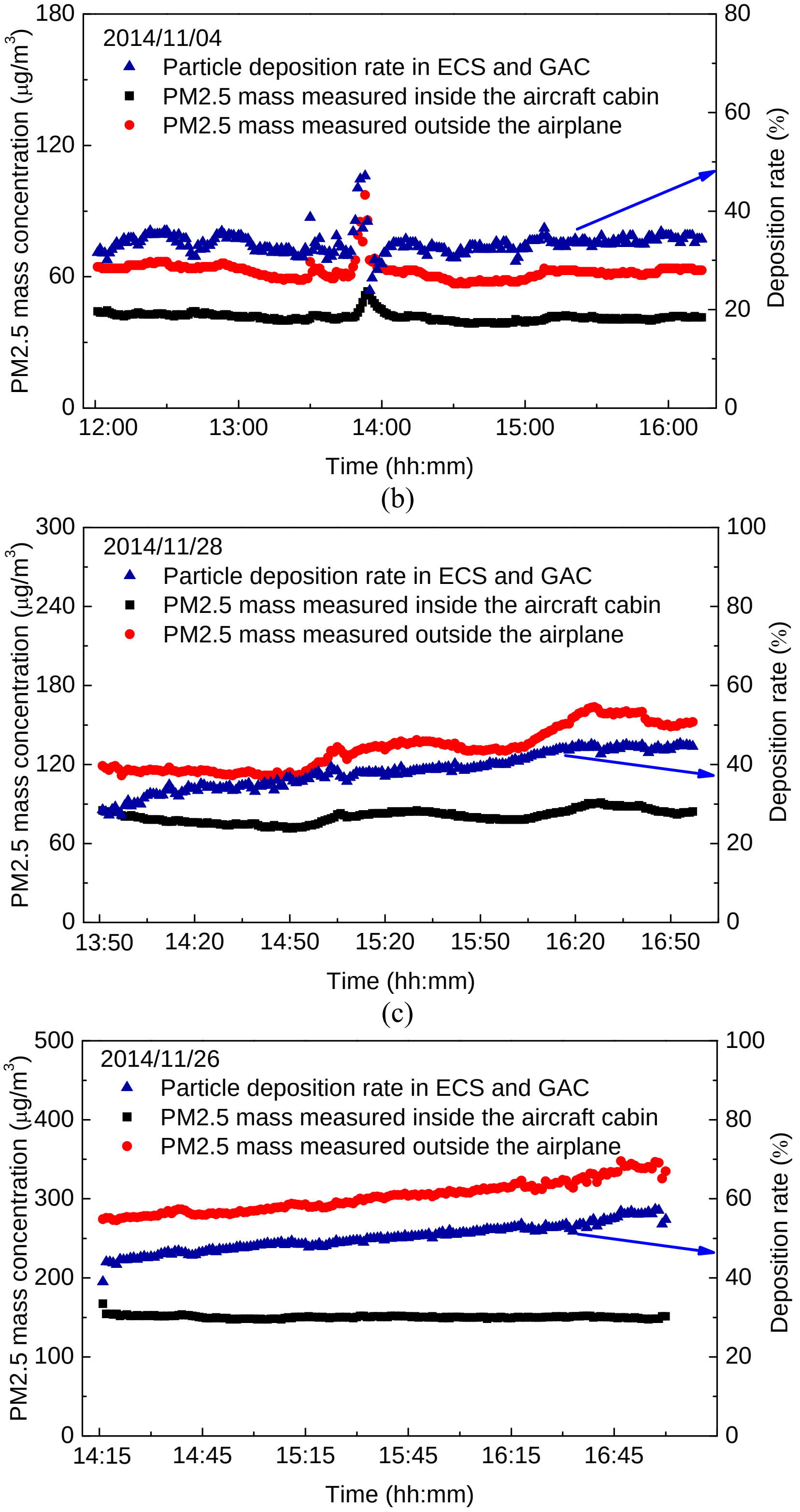
Date	**Time**	**$PM_{2.5}$ (μg/m³)**			**$PM_{2.5}$ (μg/m³)**		**Deposition rate (%)**
		Tianjin-1	**Tianjin-2**	**Tianjin-3**	**ECS outlet**	**GAC inlet**	
Nov. 4, 2014	12:00	N/A	N/A	N/A	42.9	64.9	33.9
	13:00	77	82	61	41.9	63.3	33.8
	14:00	67	71	53	40.8	60.1	32.1
	15:00	63	62	56	40.8	61.5	33.7
	16:00	N/A	N/A	N/A	41.5	63.6	34.7
Nov. 14, 2014	13:00	40	32	90	25.8	34.7	25.6
	14:00	35	37	76	28.5	40.5	29.7
	15:00	31	40	82	27.5	38.2	28.1
	16:00	35	44	68	24.9	33.8	26.3
	17:00	38	27	61	27.0	37.1	27.1
Nov. 25, 2014	12:00	91	63	79	30.8	45.4	32.3
	13:00	74	123	66	30.8	46.4	33.8

	14:00	58	165	56	31.4	47.5	33.8
Nov. 26, 2014	14:00	339	290	316	151.4	280.3	46.0
	15:00	335	313	318	150.1	297.8	49.6
	16:00	331	314	312	150.0	324.1	53.7
Nov. 28, 2014	13:00	123	122	74	83.0	116.4	28.6
	14:00	124	100	74	75.2	114.3	34.2
	15:00	128	101	74	81.5	132.7	38.6
	16:00	134	115	119	85.1	151.7	43.9
Dec. 1, 2014	16:00	17	16	7	18.1	21.3	15.0
Dec. 2, 2014	14:00	45	N/A	29	43.7	56.4	22.5
	15:00	N/A	N/A	48	47.4	62.6	24.3
	16:00	71	N/A	54	46.1	61.7	25.3
Jan. 26, 2015	11:00	226	211	204	118.0	270.7	56.4
	14:00	178	269	222	106.2	211.9	49.9
	15:00	189	220	128	100.8	194.2	48.1

Fig. 5 further shows the $PM_{2.5}$ concentrations inside and outside the MD82 cabin on a good day, moderate day, unhealthy day, and hazardous day, respectively. AQI ranges of 0-50, 51-100, 101-150, 151-200, 201-300, and 300+ indicate that the air quality is good, moderate, unhealthy for sensitive groups, unhealthy, very unhealthy, and hazardous, respectively, according to the China's Ministry of Environmental Protection. The concentration inside the cabin correlated positively with that in the outside air. As the air quality worsened, the deposition rate increased.



(a)



(b)

(c)

(d)

Fig. 5. $PM_{2.5}$ mass concentrations measured inside and outside the MD82 cabin on days under different air quality levels: (a) good, (b) moderate, (c) unhealthy, and (d) hazardous.

By statistically analysing the measured $PM_{2.5}$ concentration data versus the data from the monitoring stations, Fig. 6 confirms that the heavier the outdoor air pollution was, the higher was the deposition rate of particles in the GAC and ECS. The reason is that when the air quality was bad, there were a greater percentage of large particles, which can be easily deposited.

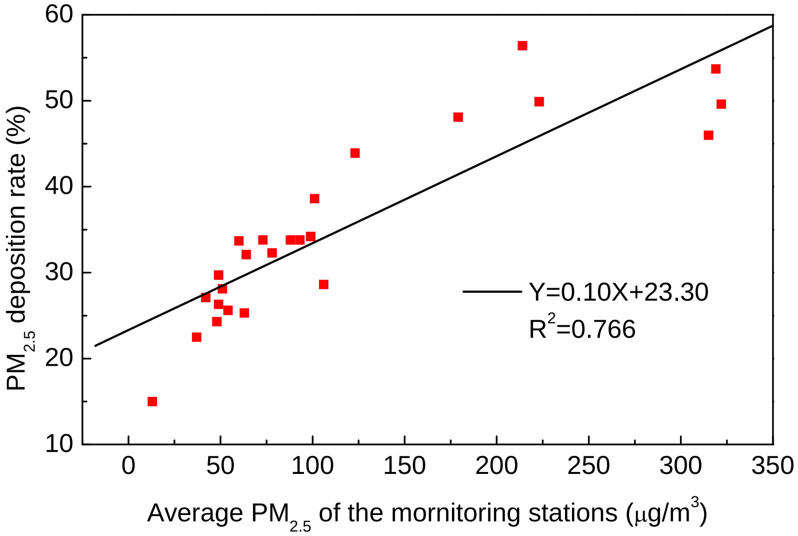


Fig. 6. Correlation between $PM_{2.5}$ deposition rate and average $PM_{2.5}$ of the monitoring stations.

The particle number and size distributions were also measured with a Fluke 983 counter at the airport outside the airplane on days with different AQI values. As shown in Fig. 7, when the AQI value was high, the air contained more large particles by percentage. When the AQI value was low, most of the particles in the air (80%) were very small in size (0.3 to 0.5 μm). Since particles with small diameters do not have much mass, their contributions to the $PM_{2.5}$ were small.

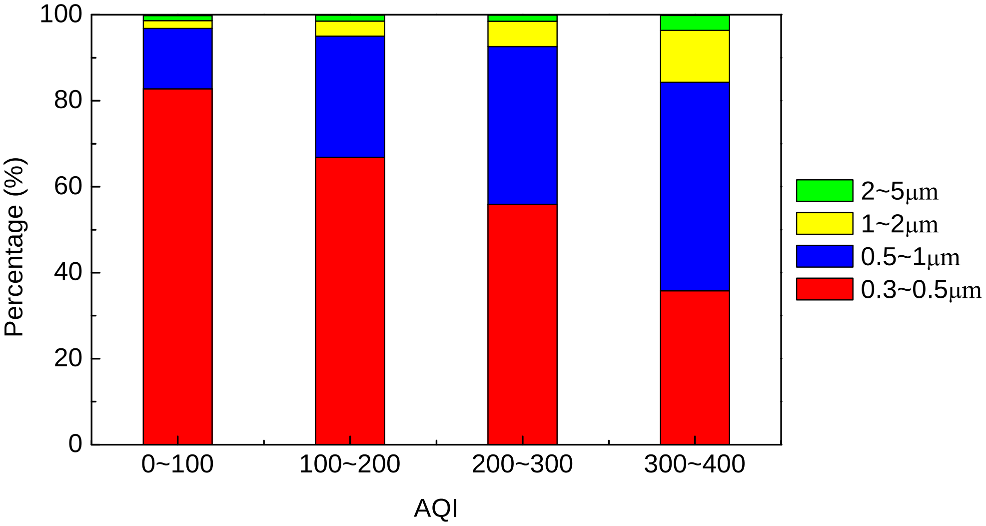


Fig. 7. Correlations between AQI value and percentage of particles in different size ranges.

To distinguish the particle deposition in the GAC from that in the ECS, simultaneous measurements of the $PM_{2.5}$ mass concentration at the inlet and outlet of the GAC and at the inlet and outlet of the ECS were conducted. Note that the outlet of the GAC was the inlet of the ECS. Since we had only two DustTrak meters, the measurements were conducted separately for the GAC and ECS. Table 2 shows the particle deposition rates in the GAC on spring days with different air quality levels. The primary pollutant in Tianjin in the spring was usually PM_{10} because of the dust in the air from the bare land around the airport [18]. In the spring, as shown in Table 2, the average $PM_{2.5}$ concentration of the three monitoring stations was generally low, while PM_{10} was relative high. The monitoring stations measured the $PM_{2.5}$ and PM_{10} by drying the samples while the DusTrak meter measured the sample with water vapor that has absorbed on the particles. The particle deposition rate in the GAC was about 10%, which was much lower than that in the ECS (30-40%). Most of the particles were deposited in the ECS because of its complex geometry, such as bends, heat exchangers, and turbines, before the air entered the main duct.

Table 2

$PM_{2.5}$ mass concentrations and deposition rates in the ground air-conditioning cart.

Date	Time	Average $PM_{2.5}$ (μg/m^3)	Average PM_{10} (μg/m^3)	Relative humidity (%)	GAC inlet $PM_{2.5}$ (μg/m^3)	GAC outlet $PM_{2.5}$ (μg/m^3)	Deposition rate (%)
Apr. 21, 2015	8:00	63	131	54	83.9	73.5	12.3
Apr. 22, 2015	8:00	80	145	52	62.0	54.7	11.7
Apr. 23, 2015	9:00	68	129	49	70.8	62.7	11.4

As the MD-82 cabin is very long, this study also investigated the particle deposition in the main duct along the fuselage. $PM_{2.5}$ mass concentrations were measured at gaspers in the rear of the economy-class cabin and in the middle of the first-class cabin, as shown in Fig. 8, on April 17, April 22, and April 23, 2015, respectively. The $PM_{2.5}$ mass deposition rate in the main duct of the aircraft was very low with a deposition rate of less than 5%. The results indicate that most of the particle mass deposition may have occurred at the complex components before the air entered the main duct.

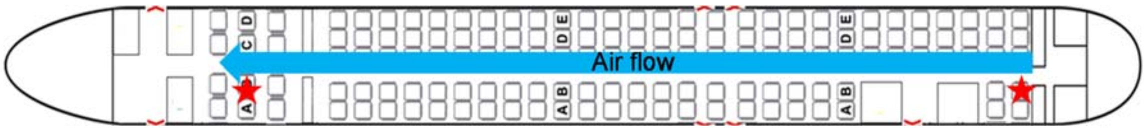


Fig. 8. Measuring positions (stars) for particle deposition in the main duct of the MD-82.

Table 3

$PM_{2.5}$ mass concentrations and deposition rates in the main duct of the MD-82.

Date	Time	Average $PM_{2.5}$ (μg/m^3)	Average PM_{10} (μg/m^3)	Relative humidity (%)	Economy-class $PM_{2.5}$ (μg/m^3)	First-class $PM_{2.5}$ (μg/m^3)	Deposition rate in main duct (%)
Apr. 17, 2015	14:00	58	190	22	27.6	27.0	2.2%
Apr.22, 2015	9:00	73	126	40	30.5	29.5	3.2%
Apr.23, 2015	8:00	63	121	54	41.3	40.5	2.0%

$PM_{2.5}$ consists of particles with diameters smaller than 2.5 μm. Their deposition rate varied with size. To verify the deposition rate of particles with various sizes in the GAC and ECS, Table 4 shows the deposition rate at different air quality levels. The ambient $PM_{2.5}$ concentration in this table was the average of the data from the three government monitoring stations around Tianjin Airport. Large particles were deposited more easily than small ones, and almost all the large particles (5–10μm) were deposited in the GAC and ECS.

Surprisingly, when the air quality was bad, the number of fine particles (0.3–0.5μm) inside the cabin was found to be greater than that outside the airplane.

Table 4

The deposition rates for particle with various sizes on days under different air quality levels.

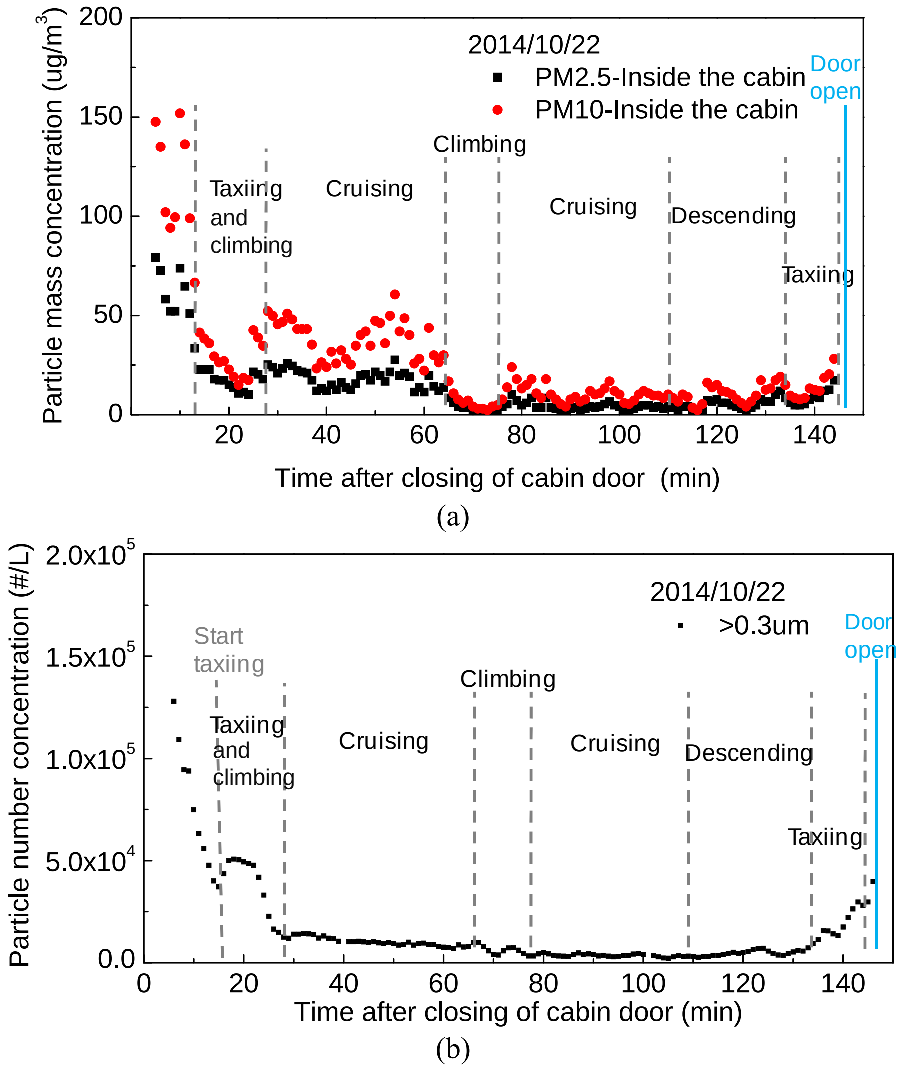
AQI value	Ambient $PM_{2.5}$ (μg/m^3)	Ambient O_3 (μg/m^3)	0.3–0.5μm	0.5–1.0μm	1.0–2.0μm	2.0–5.0μm	5.0–10.0μm	>10.0μm
<100	35	59	24.2%	38.3%	34.7%	61.9%	97.0%	99.0%
	40	33	25.4%	39.9%	40.3%	41.5%	79.6%	74.2%
	67	94	6.3%	18.1%	19.7%	78.3%	98.6%	98.0%
	73	58	23.7%	36.5%	24.0%	41.0%	91.4%	94.9%
100–200	112	73	1.8%	38.4%	29.0%	47.1%	92.7%	98.4%
	129	53	11.6%	54.2%	91.1%	99.3%	99.3%	96.4%
	131	44	-7.1%	30.6%	40.5%	69.6%	97.9%	97.5%
200–300	152	46	-35.2%	47.0%	79.1%	90.3%	96.5%	92.1%
	160	31	-10.2%	33.4%	47.4%	74.6%	98.4%	94.8%
	169	32	-21.0%	36.1%	58.7%	87.0%	93.5%	84.2%
	178	26	-7.7%	37.8%	89.7%	96.1%	99.4%	98.9%

We initially suspected that chemical reactions inside the cabin had produced additional fine particles. To determine which chemical reactions could generate fine particles, we conducted a literature review. Sarwar et al. [19] investigated secondary particles resulting from homogeneous reactions between O_3 and α-pinene. Their experimental results indicated that rapid fine particle growth occurred as a result of reactions between O_3 and α-pinene. Fan et al. [20] and Rai et al. [21] demonstrated that O_3 can initiate reactions in a complex mixture of commonly occurring indoor VOCs, which included terpenes, and that these reactions ultimately generated ultra-fine particles. Other studies have suggested that indoor air chemistry, particularly the reactions between terpenes and O_3, can generate fine particles [22-28]. Terpenes originate from many consumer products, such as cleaners and fragrances, and O_3 comes from the outdoor air. These studies concluded that ozone reactions with terpenes such as α-pinene and limonene can be important sources of sub-micron particles in indoor air. Such chemistry is not limited to terpenes, pinene, or limonene. Secondary aerosol formation can also occur with oxidation of a number of hydrocarbon species some of which may be present in the ambient air, especially when the O_3 level in the ambient air was high as shown on Table 4. Even water vapour on the aerosols could play a role and change the size distribution. To find the exact reason would need additional work in the future.

3.2. Particle deposition in ECS during commercial flights

To confirm the deposition of particles in the ECS, particle mass and number concentrations were measured on a number of flights. These included a test flight of a new regional aircraft in Xi'an, China, two commercial flights (an A319 and a B737) between Tianjin and Xi'an, and three commercial flights (two A320s and one B737) between Tianjin and Chongqing, China. The measurements during the commercial flights started after boarding was completed and stopped when the aircraft door was opened. Since the results of the in-flight measurements were similar, this section uses the data from the new regional aircraft and the commercial flight from Chongqing to Tianjin on a Boeing 737 as examples.

Fig. 9(a) shows the particle mass concentrations and Fig. 9(b) the particle number concentration measured inside the regional jet during the test flight. The airplane cruised at two different heights: first at 10,000 ft and then 31,000 ft. On the test day, the ground $PM_{2.5}$ and PM_{10} concentrations measured at the nearest monitoring station were 144 μg/m^3 and 288 μg/m^3, respectively. The particle concentration measured in the aircraft before taxiing and the outside PM concentration was used in equation (1) to obtain the deposition rate. The mass deposition rate was about 48% for $PM_{2.5}$ and 55% for PM_{10}. The outdoor particle number concentration on the ground was 3.7×10^5 #/L on average. Fig. 9 shows that when the jet was on the ground (parked at the gate or taxiing), the particles that penetrated into the cabin were mostly from the outdoor air. The particle concentration decreased after the airplane start taxiing because the HEPA filter in the ECS removed some of the particles from the return air. When the jet was in the air, the outdoor particle concentration decreased as the altitude increased. Although we did not have detailed information on the particle concentration in the outside air, the particle concentration in the cabin at 10,000 ft looks higher than that at 31,000 ft, which seems reasonable. There were peaks during the two cruising periods, as shown in Fig. 9 (a), which may have been caused by in-flight activities.



(a)

(b)

Fig. 9. (a) $PM_{2.5}$ and PM_{10} mass concentrations and (b) particle (>0.3μm) number concentration measured inside a regional aircraft in Xi'an.

Fig. 10(a) shows the particle mass concentrations and Fig. 10(b) the particle number concentration measured on a commercial flight (Boeing 737) from Chongqing to Tianjin. The $PM_{2.5}$ and PM_{10} mass concentrations measured at the air quality monitoring station closest to the departure airport were 103 μg/m³ and 117 μg/m³, respectively. The particle mass deposition rates were about 55.0% for $PM_{2.5}$ and 87.5% for PM_{10}. Greater quantities of $PM_{2.5}$ and PM_{10} were deposited during this flight than during the flight on the regional jet. This difference may have been caused by the longer pipelines and more complexity of the ECS on the Boeing 737 than those on the regional jet. At t = 80 min, the measurements were interrupted by the crew so no data was available.

The sudden increase in the measured particle concentrations during the cruising period may have been caused by cabin meal service and/or turbulence. Li et al. [16] investigated particle number concentration on several commercial flights and reported similar findings.

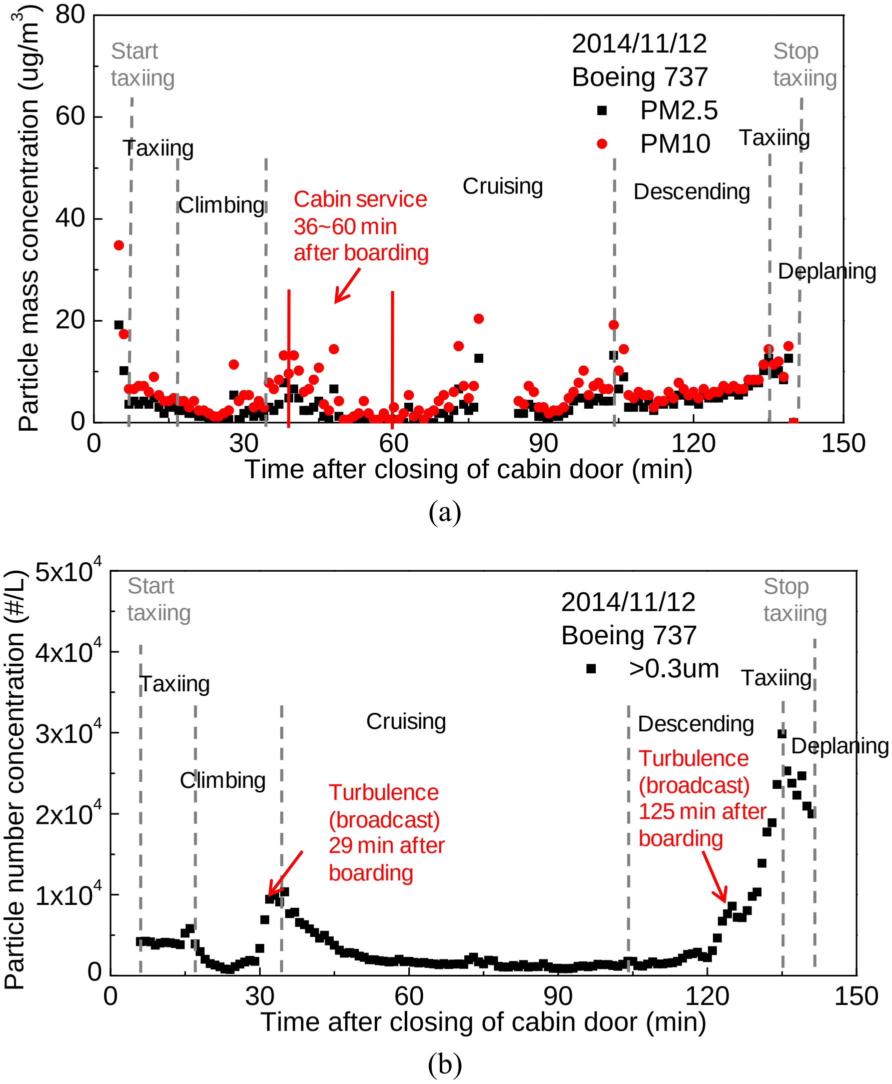


Fig. 10. (a) $PM_{2.5}$ and PM_{10} mass concentrations and (b) particle (>0.3μm) number concentration measured on a Boeing 737 flight from Chongqing to Tianjin.

4. Discussion

As far as we know, the government air quality monitoring stations, such as Tianjin-1, Tianjin-2, and Tianjin-3, probably used heated instruments with tapered element oscillating microbalances (TEOM) technology that dried the aerosols. However, we used DustTrak that was based on very different principles. A literature search revealed that a number of previous studies have addressed the differences between the TEOM and DustTrak methods. Kingham et al. [29] compared PM_{10} mass concentration data generated by a TEOM and a DustTrak monitor and found a good correlation, but the DustTrak results required a substantial correction factor to make the data comparable in real terms. The DustTrak monitor over-recorded the PM value relative to the TEOM by a factor of 2.73. According to Hill et al.[30], a DustTrak monitor appeared to over-predict $PM_{2.5}$ concentrations in a rural dust by a factor of approximately two, and by a factor of up to three under humid conditions. Chung et al. [31] found that the measurements from a DustTrak aerosol monitor overestimated PM_{10} concentration by a factor of approximately three compared to a TEOM in central California under a range of winter conditions.

Overall, the studies show that DustTrak data correlates well with TEOM data, but concentrations measured by a DustTrak monitor were two to three times higher than those measured by a TEOM. This difference occurs because the heating used by the TEOM may cause volatilization of semi-volatile aerosol components while the DustTrak includes absorbed water in the measurements. Standard usage of $PM_{2.5}$ and PM_{10} for health studies is to use dried or heated samples to exclude water which is not a pollutant. The challenge of using a wet sample is that the amount of water absorbed will depend on the humidity and also on the nature of the pollutant. If pollutants (e.g., nitrates or sulfates) form a hydroscopic coating on the dust particle or if the particle is sea salt, it will absorb more water. So the dependence with humidity will also depend on the nature of a given pollution event.

In order to identify the difference between the data from the government monitoring stations and that measured by DustTrak, this study compared the data measured by our DustTrak monitor and that at Tianjin-1 monitoring station. Fig. 11 shows the correlations between the two sets of data for $PM_{2.5}$ and PM_{10}. The DustTrak data has been multiplied by a factor of 0.46, as recommended by TSI China. However, the datasets for $PM_{2.5}$ and PM_{10} were still 35% and 56% higher, respectively, than those measured by the air quality monitoring station. The calibration factors should be 0.3 and 0.2, respectively, rather than 0.46. In other words, the DustTrak overestimated the data by a factor of 3.3 and 5.0 times for $PM_{2.5}$ and PM_{10}, respectively. The factors found in this investigation were slightly larger than previous studies.

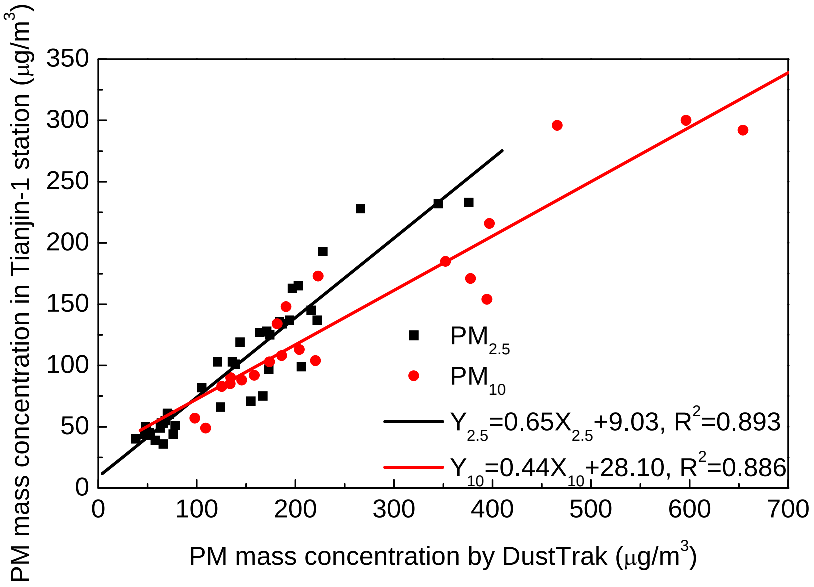


Fig. 11. Correlation between PM ($PM_{2.5}$ and PM_{10}) mass concentrations measured in the air quality monitoring station and by a DustTrak monitor.

Since standard PM air quality instruments dehumidify samples but the DustTrak not, water vapor that has absorbed onto the particles would affect the $PM_{2.5}$ and PM_{10} results reported here. The importance of humidity on these measurements may also be affected by the nature and amount of the pollution event (i.e., the relative importance of dust, soot, and volatile organic/inorganic compounds). More studies should be carried out in the future.

5. Conclusions

This investigation measured particle deposition in the environmental control systems of commercial airplanes and a ground air-conditioning cart. This investigation aimed to study the effect of heavy air pollution in Chinese airports on the aircraft ECS performance. The following conclusions can be obtained based on the measured results:

Simultaneous measurements of particle mass and number concentrations inside and outside the MD82 airplane with a GAC found that $PM_{2.5}$ deposition rate in the GAC and ECS accounted for 40-50% of the total particle mass. About 10% of the $PM_{2.5}$ mass was deposited in the GAC and 30-40% in the ECS. For particles with a diameter of 5 μm or larger, the deposition rate was more than 90%, while the deposition rate of very fine particles was minimal. PM_{10} deposition rate was expected to be very high because large particles contribute more than 90% of the total mass of PM_{10}. When the AQI value rose, both the number and percentage of large particles increased.

This investigation measured particle mass and number concentrations during a test flight of a regional jet and on several commercial flights. The results show that the particle concentrations in the cabin air were high when the airplanes were on the ground. At cruising altitude, the cabin air was very clean. However, cabin service and turbulence could have generated significant quantities of particles in the cabin air.

This study used DustTrak aerosol monitors for measuring particle mass concentration, and the Fluke 983 counter for particle number concentration at different sizes. The government air quality monitoring stations use instrument with drying capability to measure particle mass concentration. When the DustTrak mass concentrations for $PM_{2.5}$ were multiplied by a factor of 0.3, they were similar to those measured by a government air quality monitoring station.

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