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In-flight monitoring of particle deposition in the environmental control systems of commercial airliners in China

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Highlights

- Investigation of the particle deposition for different sizes in the environmental control systems of the commercial airliners.
- Particle mass concentration and particle size distribution were measured in 64 flights and compared to the outside particle level.
- The PM2.5 deposition rate in the ECSs of the older airplanes was higher than that in the newer ones.

ABSTRACT

Severe air pollution and low on-time performance of commercial flights in China could increase particle deposition in the environmental control systems (ECSs) of commercial airliners. The particles deposited in the ECSs could negatively affect the performance of the airplanes. In addition, particles that penetrate into the aircraft cabin could adversely impact the health of passengers and crew members. This investigation conducted simultaneous measurements of particle mass concentration and size distribution inside and outside the cabin during 64 commercial flights of Boeing 737 and Airbus 320 aircraft departing from or arriving at Tianjin Airport in China. The results showed that the PM2.5 mass concentration deposition in the ECSs of these airplanes ranged from 50% to 90%, which was much higher than that measured in an airplane with a ground air-conditioning unit. The average deposition rates of particles with diameters of 0.5–1 μm, 1–2 μm, 2–5 μm, 5–10 μm, and > 10 μm were 89±8%, 85±13%, 80±13%, 73±15%, and 80±14%, respectively. The in-flight measurement results indicated that the particle concentration in the breathing zone was higher than that in the air-supply zone, which implies a significant contribution by particles in the interior of the cabin. Such particles come from human emissions or particle resuspension from interior surfaces.

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

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1. Introduction

In commercial aircraft, a comfortable and healthy cabin environment for the passengers is created by the supplying of conditioned air through an environmental control system (ECS) (Pérez-Grande and Leo, 2002; Santos et al., 2014) The source of the conditioned air is compressed outside air that is drawn from the engine or auxiliary power unit (APU) when the aircraft is in the air or on the ground, respectively (Supplee and Murawski, 2008). As shown in Fig. 1, the outside air travels to the air cabin through three subsystems of the ECS, a bleed air system, an air-conditioning system, and an air distribution system (Nagda and Rector, 2003). In addition, a ground air-conditioning unit (GAU) can directly supply conditioned outside air to the cabin through the air distribution system when the aircraft is on ground (Kinsey et al., 2012), as shown in Fig. 1 (Cao et al., 2015). As the outside air is very clean (Spengler and Wilson, 2003) when the airplane is at cruising altitude, no filtration is needed for the bleed air (Rosenberger et al., 2015). However, when the airplane is on the ground, the particle concentration in the outside air can be high (Keuken et al., 2015; Winther et al., 2015; Yin et al., 2010). The particulate matter suspended in the outside air on the ground can be drawn into the ECS of the airplane and can deposit on various surfaces of the ECS components (Adhiwidjaja et al., 2000; Sippola and Nazaroff, 2004). This particle deposition can affect the thermal performance of the cooling systems (Qureshi and Zubair, 2014; Bell and Groll, 2011) and lead to component failures, expensive repairs, and shortened service life for the ECS (Mishra, 2015; Ma et al., 2015). ECS failures seriously affect the technical dispatch reliability of commercial airplanes (Wright et al., 2009).

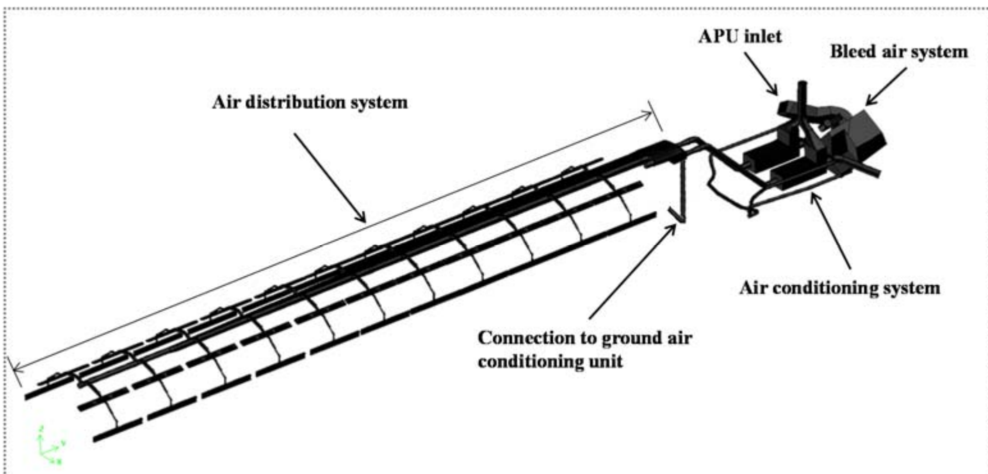


Fig. 1. Schematic of an environmental control system (Cao et al., 2015).

In China, particulate matter pollution at major airports is greater than that in major metropolitan cities in developed countries (Cao et al., 2015), and therefore the particle deposition could be more significant. In addition, the low on-time performance at major Chinese airports means that aircraft spend more time on the ground, where conditioned air is supplied through a GAU (http://www.flightstats.com/). Therefore, it is important to assess the particle deposition in the ECS and its impact on ECS performance.

Few prior studies have investigated particle deposition in ECSs. We previously measured particle deposition in the ECS of a retired MD-82 airplane parked at Tianjin Airport (Cao et al., 2015). The study used a GAU to supply conditioned air to the cabin. In China, APUs are used more frequently than GAUs (http://news.carnoc.com/list/152/152053.html). As the airflow path in an ECS is different when an APU is used than when a GAU is used, the particle deposition in the ECS would also be different. This paper reports our investigation of particle deposition in the ECS with an APU. The results can be used in the future to estimate the impact of particulate pollution on ECS performance.

2. Research methods

To study particle deposition in the ECS of a commercial airliner, this investigation conducted simultaneous measurements of particle mass and number concentration and particle size distribution inside and outside air cabins during 64 commercial flights from September 2015 to August 2016. To eliminate the impact of seasonal particle variations, 16 flights were studied in each season. For all these flights, APUs were used when the airplanes were on ground.

2.1. Flight routes

Air pollution has the greatest impact on commercial airplanes operating at the most polluted airports and making the most frequent stops at these airports, especially when there are long delays. It was essential to collect data on the flight routes of airplanes operating in China in order to better understand the impact of flight itineraries on ECS operation and identify the worst-case scenario. The data then served as a basis for the selection of flights for the experiment. An existing website (https://www.flightradar24.com/) provides flight information (including departure and arrival airports, scheduled departure and arrival times, actual departure and arrival times, flight numbers, and flight dates) for every aircraft worldwide within the previous week, but the information is not provided in the form of a database. This investigation collected historical data on the flight routes of airplanes operating in China for a period of three weeks during each season. This effort allowed us to determine the actual length of time the airplanes spent at each airport.

Since the air at cruising altitude is clean, the negative impact of air pollution on ECS performance and on passenger and crew health must occur when airplanes are on the ground. According to the website, the stopover time of each flight can be obtained from the actual departure and arrival times. This investigation selected Beijing Airport as an example because it is the largest and one of the most polluted in China (Cao et al., 2015). In 2015, there were about 2,471 commercial airplanes registered in China, and B737s and A320s accounted for 38% and 40%, respectively. Because the percentages were so high, this investigation focused on these two airplane models. As shown in Table 1, the stopover times for the airplanes were primarily in the range of one to two hours. Only a very small portion of the airplanes were on the ground for less than one hour. About 35% of the flights had stopover times in the range of two to eight hours, which may have been required by traffic control. Stopover times of more than eight hours were experienced by about 10% of the airplanes and may indicate that the airplanes remained at the airport overnight.

Table 1
Average stopover times for A320 and B737 aircraft at Beijing Airport

Stopover time	< 1 h	**1–2 h**	2–3 h	3–4 h	4–6 h	6–8 h	8–10 h
B737	3%	**50%**	17%	5%	6%	9%	10%
A320	4%	**50%**	14%	6%	7%	8%	11%

The air-conditioning system may not operate throughout the entire stopover. During a stopover, similar procedures are conducted for each airplane (Zhao and Du, 2013; Tang and Liu, 2016), such as deplaning, catering and cleaning, and boarding, as detailed in (Zheng, 2011; Wei, 2006). The air conditioning is turned on after the crew members have boarded the plane, and turned off after all the passengers have deplaned. Fig. 2 illustrates the estimated air-conditioning time on the ground at Beijing Airport. Times for taxiing in and taxiing out are shown on the left and right sides of the figure, respectively, and ground services are shown in the middle. The average waiting time after the cabin door has been closed and the taxiing time at major airports were obtained from a report published by the Civil Aviation Administration of China (Report of Civil Aviation Administration of China, 2013, 2014). The estimated average air-conditioning time on the ground at Beijing Airport was about 100 min. This duration is in agreement with the stopover time at Beijing Airport, which was about 1 to 2 h.

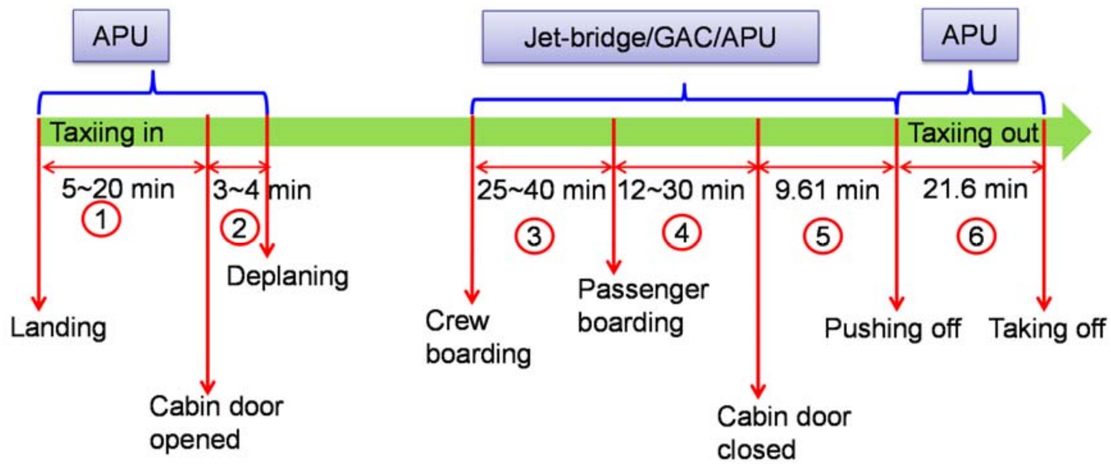


Fig.2. Estimated ground air-conditioning time at Beijing Airport

The impact of air pollution on commercial aircraft depends on the air pollution at airports and the time spent at these airports. To identify the worst-case scenario, this study calculated the weekly PM2.5 exposure for each airplane operating in China. The PM2.5 exposure is the sum of the PM2.5 concentrations at the airports where the airplane had stopovers, each multiplied by the air-conditioning time of the airplane at that airport (Moschandreas and Saksena, 2002). As PM2.5 concentration varied in seasons at different cities, it could be biased if we arbitrarily selected a season. Thus, this investigation used the annual PM2.5 concentration from different cities in China in 2015 (China Environmental State Bulletin, 2015) to calculate the PM2.5 exposure. Year 2015 looks like an average year in terms of pollution in recent years. The average air-conditioning time was estimated to be 100 min as discussed above. Table 2 lists the 20 most polluted airplanes in each of the three weeks that were tracked in China. Only airplane B6930 appears on the list for all three weeks. It may not have appeared as the most polluted airplane if we had tracked the airplanes for a longer period of time. Nevertheless, this investigation assumed that B6930 was the most polluted airplane and tracked its routes for three weeks as shown in Fig. 3. The figure shows that the flight routes were different every day. Clearly, the airplane experienced many short flights, or long operating hours on the ground, with over 40 departures each week.

Table 2
The 20 most polluted airplanes during the three weeks tracked in fall 2015.

Aug.18 – Aug. 24		Aug. 25 – Sep.1		Sep. 2 – Sep. 8	
Airplane tail number	PM2.5 exposure	Airplane tail number	PM2.5 exposure	Airplane tail number	PM2.5 exposure
B1731	2944.9	B6763	3136.5	B1635	3283.5
B6305	2857.9	B1635	3052.4	B5726	2996.5
B6611	2849.4	B1621	2984.5	B5660	2904.6
B6790	2832.7	B8110	2950.7	B8110	2851.4
B6763	2829.9	B1807	2902.8	B1988	2827.3
B1817	2807.2	B1988	2879	B6840	2816.9
B1506	2801.3	B1731	2861.4	B6832	2781.5
B5726	2794.5	B6865	2859.9	B6811	2736.2
B1858	2778.8	B5786	2782.2	B9969	2732.3
B6370	2777.4	B9969	2778.4	B6757	2690.4
B1739	2724.8	B6930	2757.3	B9981	2688.5
B5628	2717.7	B5650	2743	B9989	2665.1
B6373	2709.7	B1636	2743	B6930	2656.6
B1636	2707.3	B9927	2706.2	B6765	2655.6
B8162	2702.5	B1510	2693.6	B5628	2650.4
B6421	2688.1	B1897	2686.9	B1623	2647.3
B6811	2684.9	B5628	2677.7	B5163	2637
B6463	2677.5	B6830	2673.4	B6850	2636.3
B6865	2671.3	B6757	2665.6	B5723	2614.5
B6930	2670.2	B1800	2654.2	B5648	2607.3

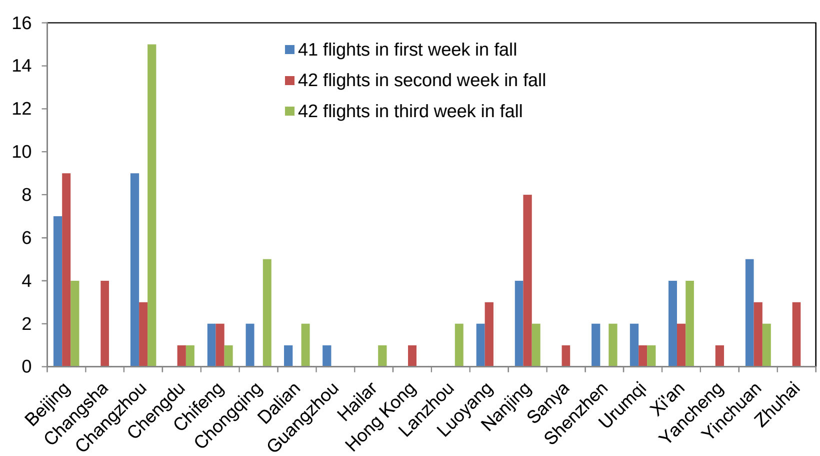


Fig. 3. Departure airports for airplane B6930 in each of the three weeks tracked in fall 2015

2.2. Flight information

According to our analysis of the flight routes of airplanes operating in China, short flights at severely polluted airports should be our focus. Note that we used Tianjin Airport both for our convenience and because it is the closest airport to Beijing. The capacity of Tianjin Airport was 20th in China in 2015, with 14.3 million passengers. The 64 flights chosen for monitoring were 32 round-trips from and to Tianjin (10 to Xi'an, 8 to Harbin, 7 to Dalian, 3 to Wuhan, 2 to Changchun, 1 to Shanghai, and 1 to Hangzhou). Fig. 4 shows the routes and the annual PM2.5

concentrations in the various regions in 2015 (China Environmental State Bulletin, 2015). The air pollution levels at these airports were higher than the WHO limit of 25 μg/m^3. The pollution at Tianjin Airport was the worst among all airports in China.

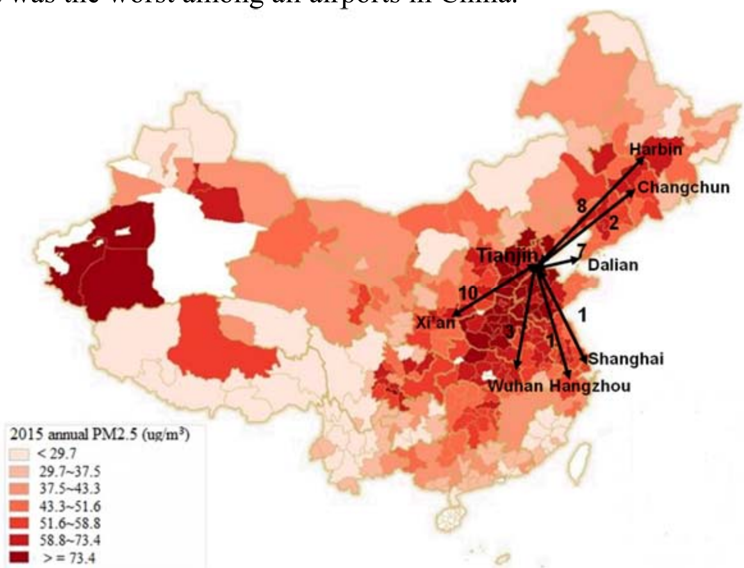


Fig. 4. Routes of the 64 flights and annual average PM2.5 concentrations in China.

Fig. 5 shows the aircraft age, flight schedule, and flight duration for the 64 flights. The website (https://www.flightradar24.com/) provides the flight information including the aircraft age. The flight times ranged from 40 min to 2 h and were slightly shorter than average. Because this investigation focused on ground operation, the flight duration was not very important for our monitoring. Among the 64 flights monitored, 39 of the aircraft were B737s and 25 were A320s, with an average age of five years. Airplanes with different ages can be used to determine the impact of surface roughness on particle deposition. Twenty-eight flights departed in the morning, 20 in the afternoon, and 16 in the evening, reflecting actual operations in China. The time of operation may not be important, but we used flights at different times in order to eliminate any possible effects of temperature and humidity on particle deposition. Table A-1 in the appendix shows the detailed flight information.

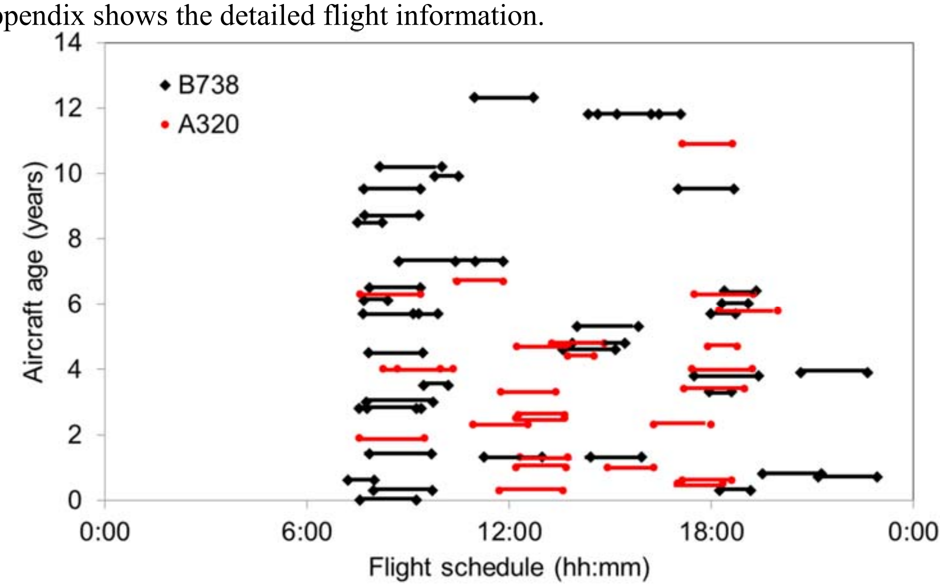


Fig. 5. Aircraft age, flight schedule, and flight duration for the 64 flights that were monitored [*(https://www.flightradar24.com/)*]

2.3. Measuring positions and instruments

As discussed in the analysis above, airplane pollution is related to airport pollution level and number of flights per week. Particle concentration measurements outside the cabin at the airport were conducted simultaneously with the in-flight measurements. The outside measurements were conducted at position P, which was 340 m away from the runway at Tianjin Airport as shown in Fig. 6(a). This position was closer than the distance from the runway to the terminal, T.

Figs. 6(b) and 6(c) show the measurement positions in the breathing zone and air-supply zone, respectively, inside the economy-class cabins. To obtain the particle deposition in the ECS of an airplane, the particle concentration in the supply air should be measured. However, such a measurement for a long time was not allowed by the airliners after the cabin door was closed. The particle concentration inside the cabin was mainly measured in the breathing zone. Occasionally, we could measure the particle concentration from the supply air before taxiing out for above five minutes. These short measurements can help us to determine the difference between the particle concentration in the breathing zone and that in the supply air, which was averaged about 23.1%. Unfortunately, the data from the supply air was too few to be used for calculating the particle deposition. Thus, the particle concentration in the breathing zone was used to calculate the particle deposition.

Fig.6. Measurement positions for particle concentration (a) outside the cabin at location P near Tianjin Airport, where T is the terminal and the green line is the runway, (b) in the breathing zone, and (c) in the air-supply zone.

To eliminate the effect of measurement position on the data, the seat selected was a window seat at the same location in all the flights. The window seat was chosen to minimize the impact of frequent activities in the aisle on the measurements of particle concentration. As the particle concentration inside and outside the aircraft cabin of commercial flights should be measured simultaneously, this study used two same instruments for the measurements. To comply the inflight safety requirements, the instruments should be portable and battery powered. This investigation selected two DustTrak monitors (TSI Corporation, USA) to measure the particle mass concentrations inside and outside the air cabins, and two Fluke 983 monitors (Fluke Corporation, USA) to measure the particle number concentrations. The instruments were calibrated before the measurements. As the DustTrak aerosol monitors selected for measuring particle mass concentration are based on a different measuring principle from that of the Tapered Element Oscillating Microbalance (TEOM) which is used in government monitoring stations, the measured mass concentration data were calibrated by TEOM data (Cao et al., 2015). The data correlation between the two Dusttrak 8533 was 0.99. The two Fluke counters had similar correlation for particle size smaller than 10 μm. The counters had a coincidence loss of 10% when the particle number concentration was greater than 1.4×10^5/L, and a 100% counting efficiency when the measured particle diameter was larger than 0.45 μm. The two Fluke counters were compact, lightweight, self-contained tools that allow for one-handed operation. The sampling time interval was selectable. We measured continuously real-time PM2.5 and PM10 mass concentrations and particle number concentrations for five particle sizes (diameters of 0.5–1 μm, 1–2 μm, 2–5 μm, 5–10 μm, and > 10 μm) at a one-minute interval.

2.4. Particle deposition rate

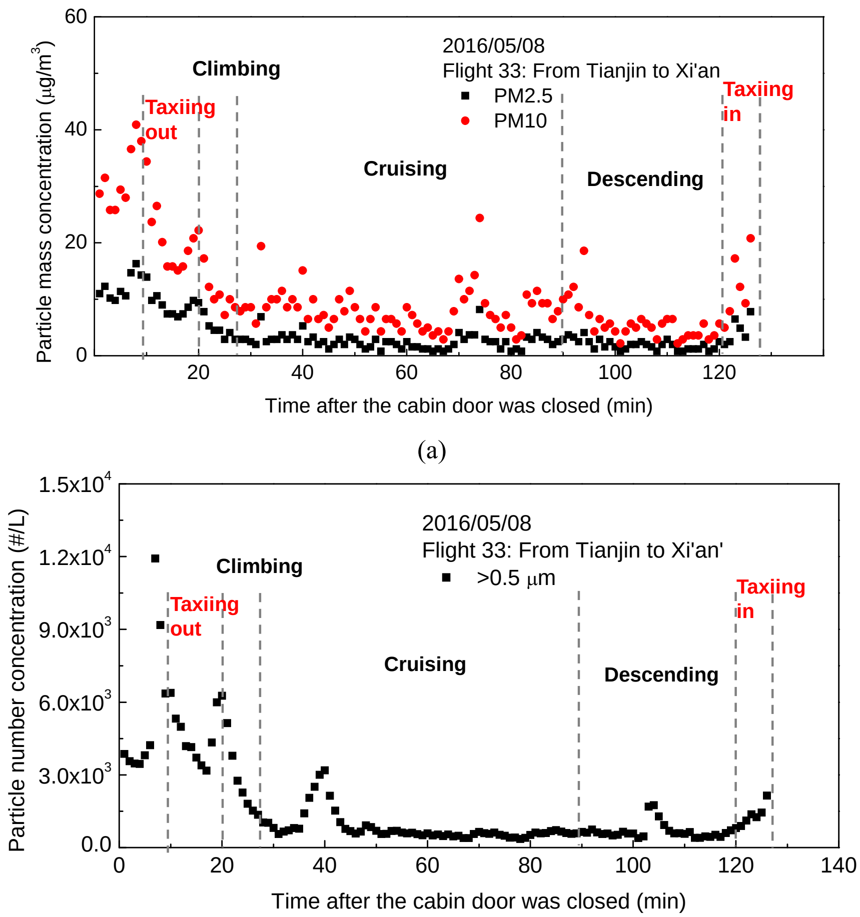
The objective of this investigation was to evaluate the particle deposition rate in the ECS when the airplanes were on the ground. When an APU was used to supply air to a cabin, approximately 50% of the returned air was recycled after passing through a high-efficiency particulate air (HEPA) filter (Bull, 2008). Thus, the particle deposition rate in the ECS when the airplanes were on the ground can be calculated by:

$$P_{deposition} = 1 - \frac{2C_{inside}}{C_{outside}} \quad (1)$$

where $P_{deposition}$ is the particle deposition rate in the ECS, C_{inside} the particle concentration measured inside the air cabin when the airplanes were on the ground, and $C_{outside}$ the particle concentration measured outside the cabin. The particle deposition rates were calculated at each time step and averaged over time for the results reported in this paper. Another method for calculating the averaged deposition rate was to use time-averaged particle concentration inside and outside the cabin as C_{inside} and $C_{outside}$ in Eq. (1). The difference between two methods was less than 0.1%.

3. Results

Fig. 7 (a) shows the particle mass concentration measured inside an air cabin during a flight from Tianjin to Xi'an, and Fig. 7(b) shows the particle number concentration. The PM2.5 and PM10 concentrations at Tianjin airport were 82 μg/m^3 and 135 μg/m^3, respectively. At Xi'an Airport the concentrations were 58 μg/m^3 and 91 μg/m^3, respectively. These results indicate that the particle concentration in the cabin was generally higher when the airplane was on the ground than when it was in the air. This difference occurred because the particle concentration at the two airports was much higher than that in the air. When the aircraft was in the air, the particles originated primarily the cabin interior. Human activities such as in-flight services and walking along the aisle could increase particle concentration inside the cabin. Serfozo et al. (2014) found that the activity of walking can cause an 84% increase in PM10 mass concentration in a microenvironment. At the same time, particles in the ventilation systems can be re-suspended and re-entrained into the airstream, as reported by Zhu et al. (2012). Thus, the particle concentration can suddenly increase when the aircraft encounters turbulence.



(b)

Fig. 7. Particle mass and number concentrations measured on a flight from Tianjin to Xi'an

Fig. 8 illustrates the correlation between the PM2.5 deposition rate in the ECS and the PM2.5 mass concentration measured at Tianjin Airport. The particle deposition increased as the outside air quality worsened. This trend was similar to that observed in the MD-82 airplane with a GAU in our previous study (Cao et al., 2015). In the commercial airplanes in the present study, the PM2.5 deposition in the ECS was 50% to 90%, which was much higher than that measured in the MD-82 airplane. This difference occurred because the airflow path in an ECS is longer and more complex when an APU is used than when a GAU is used although the air distribution system was the same as that shown in Fig. 1. The complexity of the components in the ECS caused a higher particle deposition rate. However, no obvious difference in the particle deposition rate was found between the B737s and A320s.

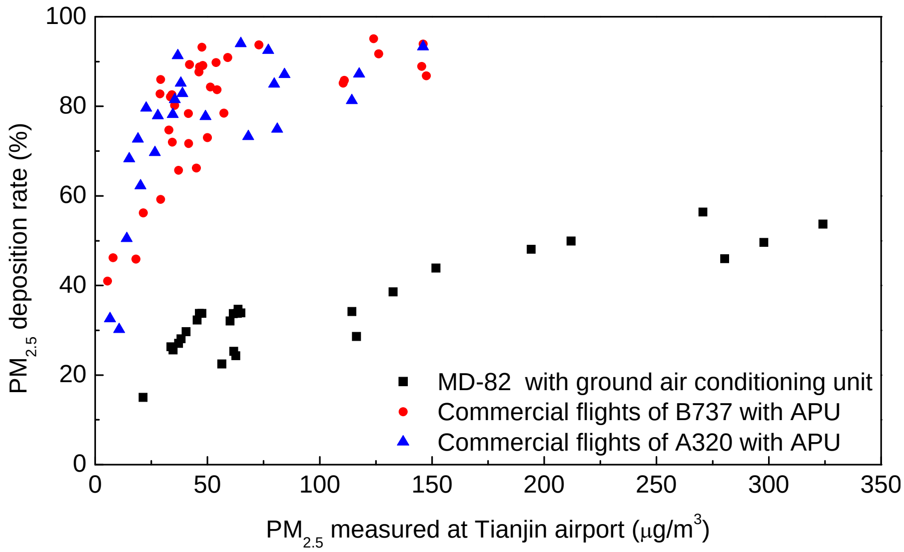


Fig.8. Correlation between PM2.5 deposition rate and PM2.5 mass concentration measured at Tianjin Airport

We suspected that the age of the aircraft would affect surface roughness within the ECS, which would in turn impact particle deposition. To investigate this possibility, we grouped flights with the same airplane model according to similar outside PM2.5 concentration because the outside particle level was the main factor affecting the deposition rate as discussed above. As the outside air was not filtered for commercial airplanes, the filter age was not an issue. Table 3 clearly shows that the PM2.5 deposition rate was higher in the ECSs of the older airplanes than that in the newer ones. The particles deposited on the surfaces of the ECS over time could increase the roughness and lead to a higher deposition rate (Othmane et al., 2010).

Table 3
PM2.5 mass deposition rates in the ECS with different aircraft ages.

Flight number	Aircraft model	Aircraft age (years)	PM2.5 deposition rate (%)	Outside PM2.5 ($\mu g/m^3$)
Flight 10	A320	0.3	50.5	14.1
Flight 2	A320	10.9	68.3	15.2
Flight 62	B738	1.4	73.0	41.5
Flight 44	B738	3.8	84.3	46.5
Flight 35	B738	8.5	89.8	47.5
Flight 33	B738	2.8	78.4	50.0
Flight 27	B738	5.7	88.8	51.3
Flight 43	B738	12.3	93.2	53.8
Flight 18	A320	0.5	74.9	81.1
Flight 7	A320	4	85.0	79.7
Flight 12	B738	1.3	85.8	111.0
Flight 11	B738	7.3	91.7	126.3

The particle number concentration and size distribution were also measured inside and outside the cabins during the 64 flights with five different particle sizes (diameters of 0.5–1 μm, 1–2 μm, 2–5 μm, 5–10 μm, and > 10 μm). Fig. 9 depicts the average deposition rates, which were 89±8%, 85±13%, 80±13%, 73±15%, and 80±14%, respectively, for the five particle sizes. The results did not indicate a higher deposition rate for larger particles, which was a surprise to us. We suspect that human-generated particles in the cabins could have played an important role here. Li et al. (2014) found that as particle size increased, the contribution to the particle concentration in the breathing zone from the supply air decreased. For particles with a diameter larger than 2.0 μm, the contributions from the supply air and cabin interior activities were both important.

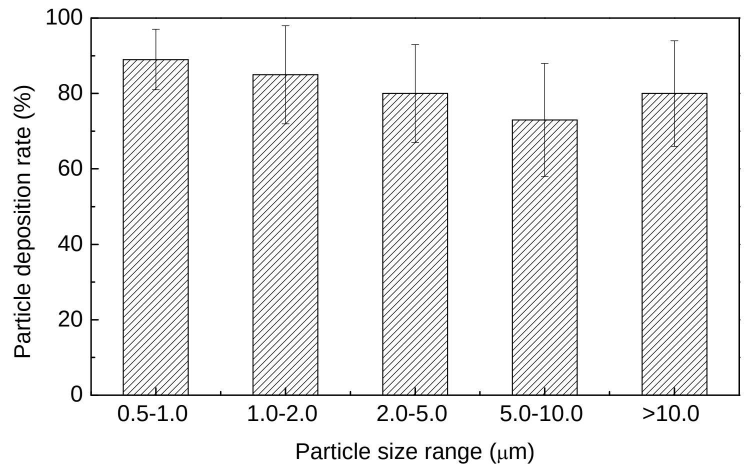


Fig.9. Average particle number deposition rate for five size ranges during 64 commercial flights

Fig. 10 was for different flights which indicated that the emissions of particles due to passenger and crew activities were different in different flights. This would cause some errors in the results. For example, Fig. 9 shows a lower particle deposition when the particle diameter was between 5 and 10 micron. It seems that many particles in this diameter range were generated by the passengers and crew. This would need a further study. However, the error would not alter the conclusions of most particles from the outdoor air were deposited in the ECS.

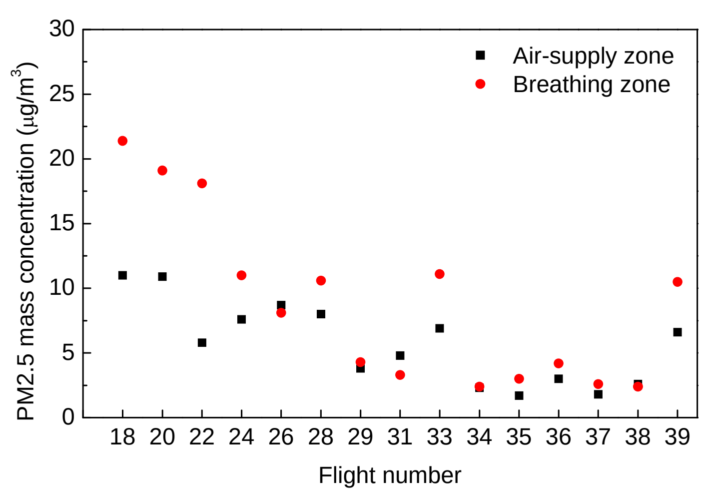


Fig.10. PM2.5 mass concentration measured in the breathing zone and air-supply zone during commercial flights.

4. Discussion

With the use of our measurement data inside and outside the cabin and the results from our previous investigation, we can estimate the impact of severe particulate pollution on the important ECS components of aircraft operating in China.

4.1. Effect of particle deposition on the heat exchanger

The heat exchanger is an important ECS component, and particle deposition on the surfaces of the heat exchanger will increase the pressure drop and thermal resistance, leading to higher maintenance costs and sometimes to component failures. Here we use PM10 deposition as an example. The deposition of PM10 on a heat exchanger, M_c, in the course of a day can be calculated by:

$$M_c = Q_V \Delta t n_{m,out}(1 - \eta_{ds1})\eta_c \quad (2)$$

where Q_V is the ventilation airflow, Δt is the air-conditioning time per day on the ground, $n_{m,out}$ is the PM10 concentration at the airport, η_{ds1} is the deposition fraction on the supply duct (Liu et al., 2016), and η_c is the deposition fraction on the heat exchanger (Liu et al., 2016).

This investigation used Beijing, Tianjin, New York, and London as reference airports. We assumed that each airplane made six flights in a day and that the air-conditioning time on the ground was 100 minutes per flight (130 minutes for the first flight). Thus, the total air-conditioning time on the ground per day was 630 minutes. Fig. 11 shows the relative pressure drop over time at different airports according to the method recommended in (Siegel, 2002). The flight time required to reach a pressure drop of 2.3 times the initial value is 5.7 times longer in the U.S. or Europe than in China. This implies that the heat exchangers for airplanes operating in China should be cleaned 5.7 times more frequently than those in the U.S. or Europe.

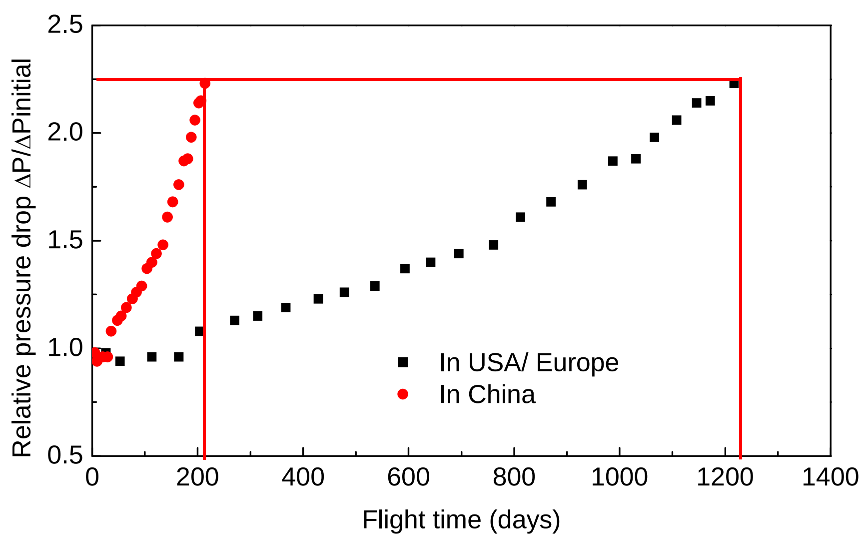


Fig.11. Comparison of the relative pressure drop in the heat exchanger in the ECS for airplanes operating in China, the U.S., and Europe.

4.2. Effect of particle deposition on filters

HEPA filters are installed in the airplane's ECS to reduce the passengers' exposure to particulate pollutants. When an airplane operates in a heavily polluted country like China, the filter service life is reduced. In order to evaluate the impact of air pollution on the filter, one can determine the PM10 mass that is loaded in the course of a day, M_f, by:

$$M_f = Q_V \eta_{f,eff}(\Delta t n_{m,in} + \Delta t' n'_{m,in}) \quad (3)$$

where Q_V is the airflow through the filter; $\eta_{f,eff}$ is the effective particle removal efficiency of the filter; Δt is the air-conditioning time per day on the ground; $n_{m,in}$ is the PM10 concentration at the airport; Δt' is the air-conditioning time per day in the air, which is the average flight time; and $n'_{m,in}$ is the average PM10 concentration inside the cabin when the aircraft is in the air. According to a statistical analysis of the flight history, the average daily flight times of the A320 and B737 airplanes were 8.25 h and 7.95 h, respectively.

Table 4 shows our in-flight particle measurements during 64 commercial aircraft departing from Tianjin, Xi'an, Hangzhou, Harbin, Wuhan, Dalian, Changchun, and Shanghai, China. The table provides the average PM10 concentration inside the aircraft cabins. We have also obtained the PM10 concentration inside cabins during various international flights from the literature, as shown in Table 4. Lindgren and Norback (2002) measured particle concentration on several flights departing from Stockholm, Tokyo, Copenhagen, New York, and Seattle and determined an average PM10 concentration for these flights. Although no ground PM10 data was provided as a reference (Lindgren and Norback, 2002), Spicer et al. (2004) showed that in the U.S., particle concentration varied little inside the cabin, whether the aircraft was on the ground or in flight. In China, however, the particle concentration inside the cabin on the ground was much higher than that during flight, as shown in Fig. 7. This difference arises from the difference in ambient air quality between the U.S. and China. We assumed that the PM10 concentration in Stockholm, Tokyo, Copenhagen, New York, and Seattle was the same as that in the cabins.

Table 4
PM10 concentration inside the cabins of airplanes flying in China and abroad

Average PM10 (μg/m^3)	On the ground	During flight
Tianjin, Xi'an, Harbin, Dalian, Changchun, Wuhan	30.2	8.3
Stockholm, Tokyo, Copenhagen, New York, Seattle	Not reported	3 (Lindgren and Norback, 2002)

This study used the method proposed by Xu et al. (2013) to calculate pressure drop and dust load on the filters used in aircraft. Fig. 12 shows the calculated pressure drop vs. flight time for airplanes operating at different airports. When the pressure drop through a filter reaches a level that is twice the initial resistance, the filter needs to be changed (GB50073-2013). The results in Fig. 12 indicate that the filters for airplanes operating in China should be changed six times more frequently than those in the U.S. or Europe. Since this study did not take particles with a diameter larger than 10 μm into account, the actual pressure drop in the filters in China would be much higher.

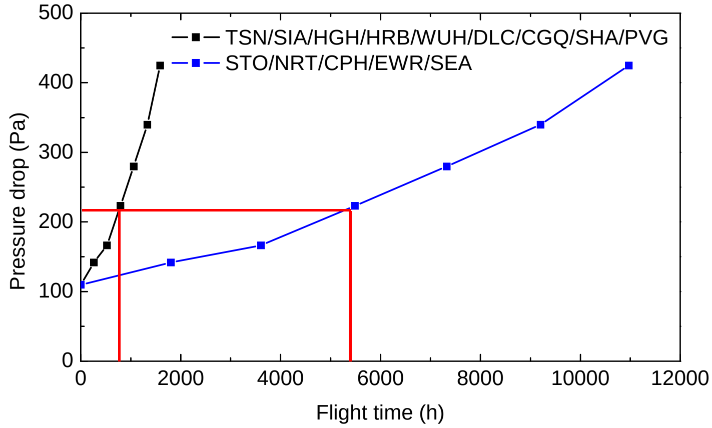


Fig.12. Comparison of the pressure drop in the filter for airplanes operating at different airports

5. Conclusions

This investigation collected data on more than 2000 flight routes over a period of three weeks in each season in China to identify the airplanes that were most strongly affected by air pollution. Most of the airplanes operating in China were A320s and B737s. The stopover times were mainly in the range of one to two hours. The average air-conditioning time when the airplanes were on the ground at Beijing Airport was about 100 minutes. The flight routes were irregular and differed from week to week. Shorter flight times were associated with longer operating times on the ground, which can increase exposure to air pollution, especially when an airplane has more than 40 departures in a week.

This study measured the particle deposition in the ECSs of 64 commercial flights for B737s and A320s departing from or arriving at Tianjin Airport in China. These airplanes used APUs for air-conditioning on the ground. The particle concentration inside the cabins when the airplanes were on the ground was much higher than the concentration during the flights. The particle deposition in the ECSs increased as the outside air quality worsened. The PM2.5 mass concentration deposition was in the range of 50% to 90%, which was higher than that with a ground air-conditioning cart.

The airplanes' age played a role in particle deposition. The PM2.5 deposition rate in the ECSs of the older airplanes was higher than that in the newer ones under the same outside air pollution level. The particles that accumulated on the surfaces of the ECS components increased the surface roughness. Particle deposition onto a rough surface was higher than that onto a smooth surface.

The average particle mass deposition rates measured on the 64 flights were 89±8%, 85±13%, 80±13%, 73±15%, and 80±14% for particles with diameters of 0.5–1 μm, 1–2 μm, 2–5 μm, 5–10 μm, and > 10 μm, respectively. In-flight measurements showed that the particle concentration in the breathing zone was higher than in the supply air, which confirmed the significant particle generation inside the cabins. The impact of this particle generation was not reflected in the deposition rate. The actual deposition rate for particles with a diameter larger than 2 μm must have been higher than the measured rate.

According to our comparison of airplanes operating in China with those in the United States and Europe, particle deposition on the heat exchangers of ECSs in China was 5.7 times higher than in the U.S and Europe. Furthermore, the HEPA filters for airplanes operating in China need to be changed 6.9 times more frequently than those in the U.S. and Europe.

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References

Adhiwidjaja, I., Matsusaka, S., Tanaka, H., Masuda, H., 2000. Simultaneous phenomenon of particle deposition and reentrainment: effects of surface roughness on deposition layer of striped pattern. Aerosol Sci. Technol. 33 (4), 323-333.

Bell, I. H., Groll, E. A., 2011. Air-side particulate fouling of microchannel heat exchangers: Experimental comparison of air-side pressure drop and heat transfer with plate-fin heat exchanger. Appl. Therm. Eng. 31 (5), 742-749.

Bull, K. 2008. Cabin air filtration: Helping to protect occupants from infectious diseases. Travel Med. Infect. Dis. 6 (3), 142-4.

Cao, Q., Liu, Y., Liu, W., Lin, C. H., Wei, D., Baughcum, S., et al., 2015. Experimental study of particle deposition in the environmental control systems of commercial airliners. Build. Environ. 96, 62-71.

Code for Design of Clean Room, GB50073-2013.

Keuken, M. P., Moerman, M., Zandveld, P., Henzing, J. S., Hoek, G., 2015. Total and size-resolved particle number and black carbon concentrations in urban areas near Schiphol airport (The Netherlands). Atmos. Environ. 104, 132-142.

Kinsey, J.S., Timko, M.T., Herndon, S.C., Wood, E.C., Yu, Z., Miake-Lye, R.,C., Lobo, P., Whitefield, P., Hagen, D., Wey, C., Anderson, B., Beyersdorf, A., Hudgins, C.H., Thornhill, K.L., Winstead, E., Howard, R., Bulzan, D.I., Tacina, K.B., Knighton, W.B., 2012. Determination of the emissions from an aircraft auxiliary power unit (APU) during the alternative aviation fuel experiment (AAFEX). J. Air Waste Manage. 62 (4), 420-430.

Li, Z., Guan, J., Yang, X., Lin, C.H., 2014. Source apportionment of airborne particles in commercial aircraft cabin environment: Contributions from outside and inside of cabin. Atmos. Environ. 89, 119-128.

Lindgren, T., Norbäck, D., 2002. Cabin air quality: Indoor pollutants and climate during intercontinental flights with and without tobacco smoking. Indoor Air, 12 (4), 263-272.

Liu, Y., Cao, Q., Liu, W., Lin, C.-H., Wei, D., Baughcum, S., Norris, S., Long, Z., Shen, X., Chen, Q. Numerical modeling of particle deposition in the environmental control systems of commercial airliners on ground, In Building Simulation (pp. 1-11). Tsinghua University Press.

Ma, J., Lu, C., Liu, H., 2015. Fault diagnosis for the heat exchanger of the aircraft environmental control system based on the strong tracking filter. PloS one, 10 (3), 294-299.

Mishra, R. K., 2015. Fouling and corrosion in an aero gas turbine compressor. J. Fail. Anal. Prev. 15(6), 837-845.

Moschandreas, D. J., Saksena, S., 2002. Modeling exposure to particulate matter. Chemosphere, 49(9), 1137-1150.

Nagda, N. L., Rector, H. E., 2003. A critical review of reported air concentrations of organic compounds in aircraft cabins. Indoor Air, 13 (3), 292–301.

Othmane, M. B., Havet, M., Gehin, E., Solliec., 2010. Mechanisms of particle deposition in ventilation ducts for a food factory. Aerosol Sci. Technol. 44 (9), 775-784.

Pérez-Grande, I., Leo, T. J., 2002. Optimization of a commercial aircraft environmental control system. Appl. Therm. Eng. 22 (17), 1885-1904.

Qureshi, B. A., Zubair, S. M., 2014. The impact of fouling on the condenser of a vapor compression refrigeration system: An experimental observation. Int. J. Refrigeration, 38, 260-266.

Report on operational efficiency of the national commercial flights in 2013. Civil Aviation Administration of China.

Report on operational efficiency of the national commercial flights in 2014. Civil Aviation Administration of China.

Rosenberger, W., Beckmann, B., Wrbitzky, R., 2015. Airborne aldehydes in cabin-air of commercial aircraft: measurement by HPLC with UV absorbance detection of 2,4-dinitrophenylhydrazones. J. Chromatogr. B, 1019, 117-127.

Santos, A. P. P., Andrade, C. R., Zaparoli, E. L., 2014. A thermodynamic study of air cycle machine for aeronautical applications. Int. J. Thermodyn. 17 (3), 117-126.

Serfozo, N., Chatoutsidou, S. E., Lazaridis, M., 2014. The effect of particle resuspension during walking activity to PM 10 mass and number concentrations in an indoor microenvironment. Build. Environ. 82, 180-189.
Siegel, J. A., 2002. Particulate fouling of HVAC heat exchangers. Doctoral dissertation, University of California, Berkeley.
Sippola, M.R., Nazaroff, W.W., 2004. Experiments measuring particle deposition from fully developed turbulent flow in ventilation ducts. Aerosol Sci. Technol. 38 (9), 914-925.
Spengler, J.D., Wilson, D.G., 2003. Air quality in aircraft. Proceedings of the Institution of Mechanical Engineers, Part E: J. Process Mech. Eng. 217 (4), 323-335.
Spicer, C.W., Murphy, M.J., Holdren, M.W., Myers, J.D., MacGregor, I.C., Holloman, C., Janes, R.R., Tucker, K., Zaborski, R., 2004. Relate air quality and other factors to comfort and health symptoms reported by passengers and crew on commercial transport aircraft (Part I), ASHRAE Project 1262-TRP. Battelle Science and Technology International, Columbus, OH. .
Supplee, D.S., Murawski, J.T., 2008. An attempt to characterize the frequency, health impact, and operational costs of oil in the cabin and flight deck supply air on US commercial aircraft. J.ASTM Int. 5(5), 1-15.
Tang, F., Liu, S., 2016. Research of aircraft ground service scheduling problems. In Control and Decision Conference (CCDC), 2016 Chinese (pp. 3405-3410). IEEE.
Wei L., 2006. Research on optimization of airport ground operation and aircraft departure process. Master's thesis, Civil Aviation University of China.
Winther, M., Kousgaard, U., Ellermann, T., Massling, A., Nøjgaard, J. K., Ketzel, M., 2015. Emissions of NOx, particle mass and particle numbers from aircraft main engines, APU's and handling equipment at Copenhagen Airport. Atmos. Environ.100, 218-229.
Wright, S., Andrews, G., Sabir, H., 2009. A review of heat exchanger fouling in the context of aircraft air-conditioning systems, and the potential for electrostatic filtering. Appl. Therm. Eng. 29 (13), 2596-2609.
Xu, B., Liu, J., Ren, S., Yin, W., Chen, Q., 2013. Investigation of the performance of airliner cabin air filters throughout lifetime usage. Aerosol Air Qual. Res. 13 (5), 1544-1551.
Yin, H., Tian, J., Ye, Z., Yang, Y., Tang, W., Xin, X., 2010. Study on characteristics of TSP and its bounded pollutants in the vicinity of Shuangliu International Airport, China. In Bioinformatics and Biomedical Engineering (iCBBE), 2010 4th International Conference (pp. 1-4). IEEE.
Zhao G., Du Y., 2013. Research on airport apron service based on particle swarm optimization. In Management Science and Engineering (ICMSE), 2013 International Conference (pp. 484-488). IEEE.
Zheng P., 2011. Research on optimization models and methods for civil airport gate assignment problem. Ph.D. thesis, Beijing Jiaotong University.
Zhu, Y., Zhao, B., Zhou, B.,Tan, Z., 2012. A particle resuspension model in ventilation ducts. Aerosol Sci. Technol. 46 (2), 222-235.

Appendix

Table A provides detailed information on the 64 flights that were monitored. ATD is actual departure time, and ATA actual arrival time. The airport abbreviations are TSN for Tianjin Airport, SIA for Xi'an Airport, HGH for Hangzhou Airport, HRB for Harbin Airport, SHA for Shanghai Hongqiao Airport, PVG for Shanghai Pudong Airport, WUH for Wuhan Airport, DLC for Dalian Airport, and CGQ for Changchun Airport.

Table A.
Detailed information on the 64 flights that were monitored

Flight #	Monitoring date	Airplane model	Departure/ arrival airport	ATD	ATA	Airplane age (years)	Test position on seat/total rows of seats
1	Oct. 20, 2015	B737	TSN/SIA	7:59	9:44	0.3	20A/29
2	Oct. 20, 2015	A320	SIA/TSN	17:08	18:38	10.9	18A/26
3	Oct. 27, 2015	B737	TSN/HGH	8:10	10:00	10.2	17A/22

4	Oct. 27, 2015	B737	HGH/TSN	20:39	22:38	3.9	23A/28
5	Oct. 28, 2015	B737	TSN/HRB	14:22	16:13	11.8	25A/30
6	Oct. 29, 2015	B737	HRB/TSN	15:13	17:06	11.8	25F/30
7	Nov. 3, 2015	A320	TSN/HRB	17:26	19:13	4	23A/28
8	Nov. 4, 2015	A320	HRB/TSN	7:33	9:29	1.9	23A/28
9	Nov. 4, 2015	A320	TSN/SHA	11:46	13:23	3.3	25A/30
10	Nov. 6, 2015	A320	PVG /TSN	11:43	13:36	0.3	24A/29
11	Nov. 12, 2015	B737	TSN/ WUH	8:44	10:25	7.3	24A/29
12	Nov. 12, 2015	B737	WUH /TSN	14:26	15:56	1.3	25A/29
13	Nov. 12, 2015	B737	TSN/HRB	21:11	22:55	0.7	23A/28
14	Nov. 13, 2015	B737	HRB/TSN	14:39	16:27	11.8	24A/30
15	Nov. 15, 2015	B737	TSN/SIA	7:47	9:24	2.8	24F/29
16	Nov. 15, 2015	A320	SIA/TSN	13:16	14:49	4.8	24A/29
17	Jan. 14, 2016	B738	TSN/SIA	7:50	9:26	4.5	23A/28
18	Jan. 14, 2016	A320	SIA/TSN	17:00	18:21	0.5	24A/29
19	Jan. 15, 2016	B738	TSN/DLC	7:42	8:24	6.1	23A/28
20	Jan. 15, 2016	B738	DLC/TSN	17:57	18:37	3.3	25A/30
21	Jan. 16, 2016	A320	TSN/CGQ	10:27	11:50	6.7	18A/28
22	Jan. 16, 2016	A320	CGQ/TSN	16:18	18:00	2.3	23A/28
23	Jan. 17, 2016	A320	TSN/WUH	8:41	10:21	4	22A/27
24	Jan. 17, 2016	B738	WUH/TSN	13:53	15:27	4.8	23A/29
25	Jan. 18, 2016	A320	TSN/WUH	8:16	9:58	4	23F/27
26	Jan. 18, 2016	B738	WUH/TSN	14:02	15:50	5.3	12F/29
27	Jan. 19, 2016	B738	TSN/DLC	9:09	9:53	5.7	24A/28
28	Jan. 19, 2016	B738	DLC/TSN	17:59	18:44	5.7	23A/28
29	Feb. 24, 2016	A320	TSN/DLC	13:44	14:31	4.4	24F/29
30	Feb. 24, 2016	B738	DLC/TSN	18:15	19:10	0.3	25L/29
31	Feb. 25, 2016	B738	TSN/DLC	9:28	10:12	3.5	24A/29
32	Feb. 25, 2016	B738	DLC/TSN	18:23	19:21	6.4	24A/29
33	May 8, 2016	B738	TSN/SIA	7:33	9:15	2.8	23A/29
34	May 8, 2016	A320	SIA/TSN	12:16	13:39	2.6	25A/31
35	May 9, 2016	B738	TSN/DLC	7:30	8:15	8.5	23A/30
36	May 9, 2016	B738	DLC/TSN	18:20	19:06	6	24A/29
37	May 12, 2016	B738	TSN/SIA	7:46	9:45	3	24A/29
38	May 12, 2016	A320	SIA/TSN	14:55	16:17	1	22A/26
39	May 17, 2016	B738	TSN/SIA	7:35	9:15	N/A	28A/29
40	May 17, 2016	A320	SIA/TSN	12:19	13:45	1.3	24A/29
41	May 18, 2016	B738	TSN/SIA	7:41	9:23	9.5	24A/29
42	May 18, 2016	B738	SIA/TSN	17:01	18:41	9.5	24A/29
43	May 19, 2016	B738	TSN/HRB	10:59	12:43	12.3	28F/32
44	May 19, 2016	B738	HRB/TSN	17:30	19:25	3.8	25A/30
45	May 20, 2016	B738	TSN/SIA	7:40	9:19	5.7	23A/28
46	May 20, 2016	A320	SIA/TSN	12:13	13:39	2.5	25A/30
47	May 22, 2016	B738	TSN/HRB	13:36	15:09	4.6	23A/28
48	May 22, 2016	A320	HRB/TSN	18:13	19:58	5.8	23A/28
49	Jul. 5, 2016	A320	TSN/CGQ	10:56	12:33	2.3	22F/28

50	Jul. 5, 2016	A320	CGQ/TSN	17:08	18:36	0.6	24A/29
51	Jul. 6, 2016	B738	TSN/SIA	7:52	9:23	6.5	24A/29
52	Jul. 6, 2016	A320	SIA/TSN	12:14	13:45	4.7	24A/29
53	Jul. 27, 2016	B738	TSN/DLC	11:00	11:49	7.3	22A/27
54	Jul. 27, 2016	A320	DLC/TSN	17:54	18:47	4.7	24A/29
55	Jul. 28, 2016	B738	TSN/SIA	7:43	9:20	8.7	24A/29
56	Jul. 28, 2016	A320	SIA/TSN	12:12	13:41	1	24A/29
57	Aug. 1, 2016	B738	TSN/HRB	19:31	21:16	0.8	29A/31
58	Aug. 3, 2016	B738	HRB/TSN	11:15	12:59	1.3	23A/28
59	Aug. 3, 2016	A320	TSN/HRB	17:12	18:59	3.4	22A/26
60	Aug. 4, 2016	A320	HRB/TSN	7:34	9:22	6.3	23A/28
61	Aug. 4, 2016	A320	TSN/HRB	17:30	19:15	6.3	23A/28
62	Aug. 17, 2016	B738	HRB/TSN	7:51	9:42	1.4	23A/28
63	Aug. 21, 2016	B738	TSN/DLC	7:14	8:00	0.6	24A/30
64	Aug. 21, 2016	B738	DLC/TSN	9:48	10:30	9.9	23A/29