Cao, Q., Chen, C., Liu, S., Lin, C.-H., Wei, D., and Chen, Q. 2018. "Prediction of particle deposition around the cabin air supply nozzles of commercial airplanes using measured in-cabin particle emission rates," *Indoor Air*, 28: 852–865.

Prediction of particle deposition around the cabin air supply nozzles of commercial airplanes using measured in-cabin particle emission rates

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Abstract

Enhanced soiling on the surfaces around air supply nozzles due to particle deposition is frequently observed in commercial airliners. The problem is worsened by severe outdoor air pollution and flight delays in China. The particles in an aircraft cabin originate from both outdoor and in-cabin sources. This study conducted measurements on multiple commercial flights to obtain particle emission rates from in-cabin sources. Additional experiments on a retired MD-82 airplane provided justification of the in-flight measurements. The in-cabin sources emitted more particles during boarding/deplaning than during meal servicing and sitting. The average PM2.5 emission rates were 7.2, 2.6, 1.9, and 1.8 (μg/min per person), respectively, during the boarding/deplaning, sitting on the ground, sitting in the air and meal servicing. The corresponding PM10 emission rates were 15.4, 6.1, 5.3 and 5.4 (μg/min per person), respectively for these four periods. The average particle emission rate from in-cabin sources varied seasonally and was the highest in winter. With the measured data, this investigation used a CFD model to predict the accumulation of particles deposited around the nozzles of an airplane, taking into account flight routes and the outdoor particle concentrations at the airports where the airplanes were parked. For the most polluted airplane in China, the dirty spots/areas around the nozzles inside the airplane became visible after six months. The method proposed in this study can be used for any commercial airplane to predict the accumulation of particles deposited around the air supply nozzles.

KEYWORDS

Particle sources; Emission rate; Cabin environment; In-flight measurements; CFD simulations.

Practical Implications

This study presented the particle emission rates from in-cabin sources during different flight periods measured in multiple commercial flights and proposed a method to accurately predict the accumulation of particles deposited over time on the surfaces around airplane nozzles. The results can be used to improve the design of aircraft environments and to schedule cabin cleaning services.

1 INTRODUCTION

Particle deposition on the surfaces around air supply nozzles can lead to dirt streaking[1, 2] in commercial airliners. Around the nozzles, stronger turbulent diffusion toward the wall lead to a higher possibility of particle deposition at that location[3]. After a certain period of operation of the environmental control system, the deposited particles can cause dirty, smudged areas[4, 5] around the nozzles, which are unsightly and may cause the airplane to appear older. This deposition will increase maintenance costs because of the need for cleaning[6].

To address this problem, it is essential to accurately predict the accumulation of particles deposited on the surfaces around the nozzles in air cabins. CFD modeling with a Eulerian/Lagrangian method is a powerful and mature technique used to simulate particle deposition on indoor surfaces[7-10]. Few previous studies have focused on the mass accumulation caused by particle deposition around the air supply nozzles in the aircraft environment. Chen et al.[3] proposed a validated SST k-ω model with a modified Lagrangian method to simulate particle accumulation on the surface of a multi-slot diffuser in a room. They quantitatively validated the method of predicting the particle deposition rate in indoor environment using two cases with experimental data from the literature. However, the particle concentration inside the room, an important factor in total particle accumulation in the model, was set at a constant value. Particles inside an aircraft cabin were found to originate from unfiltered supply air[11] and in-cabin sources[12]. Furthermore, it was observed that particle concentration inside a cabin was not constant during different flight periods[13-15], because of variations in outdoor particle concentration and in-cabin particle sources. In order to use the proposed model to predict particle accumulation on the surfaces around the nozzles in an airplane, it is necessary to identify the dynamic particle concentration inside the aircraft cabin under different outdoor particle concentrations and in-cabin sources.

The particle concentration inside an aircraft cabin depends on both outdoor and in-cabin sources[16]. For outdoor sources, our previous study[17] has provided experimental data on the rates of particle deposition on the environmental control systems of airplanes due to different outdoor particle pollution levels. For in-cabin sources, passengers and their baggage could be the major contributors[18]. Several previous studies[19-22] experimentally measured the particle emission rates from clothed occupants and from various human activities in homes and classrooms, such as folding blankets, making a bed, vacuuming, walking around, and sitting[23-27]. They found that the factors affecting particle emission rates included the number of persons performing the activity[22], the type and intensity of the activity[24], the type of floor and seat cover[23], the clothing level[19], and the operational state of the mechanical ventilation system[27]. However, these factors would be very different in an airliner cabin environment from in an indoor environment in a building. As far as we could determine from the literature, no reliable experimental data on in-cabin sources have been previously published.

The present study conducted in-flight measurements to obtain particle emission rates from in-cabin sources, and proposed a method to accurately predict the accumulation of particles deposited over time on the surfaces around airplane nozzles. The approach may also be used to develop improved designs in the future.

2 METHODS

The following subsections describe the in-flight experiments; the process for obtaining particle emissions from in-cabin sources with the use of the measurement data; the estimation of particle concentration inside the cabin during different flights of an airplane, with the use of the particle emission rate data; and the CFD modeling that was conducted to predict particle accumulation around the nozzles in the cabin.

2.1 Particle emission rate from in-cabin sources

Measurements in commercial flights

This study conducted multiple in-flight particle measurements. Measurements were conducted on 66 domestic flights and 2 international flights, in economy and business class cabins. The domestic flights were round trips between Tianjin, China, and seven other cities in China, and the flight duration varied from 0.7 to 2 h. The average duration of the international flights, which were all round trips between Beijing and Chicago, was 13 h. The measurements were performed in all four seasons to take into account the effects of seasonal variations in clothing and outdoor particle concentrations on the particle emission rates. This study randomly divided the flights into the "training" flight group and the "testing" flight group as shown in Table 1. For each season, "training" group consisted of 12 domestic flights, which were used to obtain the statistical average particle emission rates from in-cabin sources. The measurement results on 2 international flights and other 18 domestic flights were used to validate the method of estimating particle concentration inside cabin using the statistical average particle emission rates from in-cabin sources.

TABLE 1 Basic information about the flights of "training" and "testing" groups

Flight group	Season	Airplane model	Round-trip flight routes	Flights	Seats	Duration	Measurement location
Training	Spring	B737/A320	TSN - SIA/ HRB/ DLC/ WUH/ CGQ/ SHA/ HGH	12	132-192	0.67-2 h	Economy class
	Summer			12			
	Fall			12			
	Winter			12			
Testing	Spring	B737/A320	TSN - SIA / HRB / DLC / HGH	4	132-192	0.75-2 h	Economy class
	Summer			6			
	Fall			4			
	Winter			4			
	Fall	B777	PEK - ORD	2	269	13 h	Economy class /Business class

Note: All the airports used abbreviations: Tianjin Airport (TSN), Xi'an Airport (SIA), Hangzhou Airport (HGH), Harbin Airport (HRB), Shanghai Hongqiao Airport (SHA), Shanghai Pudong Airport (PVG), Wuhan Airport (WUH), Dalian Airport (DLC), and Changchun Airport (CGQ).

After the particle concentrations were measured in the occupied zone and in the supply air, the particle emission rate could be obtained by means of a mass balance equation. The in-cabin particle concentration was monitored throughout the flight, from boarding to deplaning. Because of the restriction on lithium batteries, only one particle monitor could be carried onto the airplane. As a result, the particle concentration in the supply air and in the occupied zone was measured alternatively with the same particle monitor. We also recorded the times for closing of the cabin door, taxiing, taking off, cruising, descending, arriving, and the occurrence of passenger activities.

This investigation used a DustTrak 8533 aerosol monitor (TSI Corporation, USA) to measure particle concentration. The instrument was calibrated prior to the measurements. As the DustTrak monitor was based on a different measuring technique than that of the tapered element oscillating microbalance (TEOM), which is most accurate and used in government monitoring stations, the measured concentration data were calibrated by the TEOM data. We conducted side-by-side measurements of the DustTrak and TEOM at the government monitoring stations. Since a TEOM dehumidifies samples but the DustTrak does not, water vapor that has absorbed onto the particles would affect the particle results[28]. Our calibration used 234 hour data that was for different humidity conditions at various particle concentration levels. The DustTrak 8533 can simultaneously measure PM2.5 and PM10 mass concentration. The measurement results indicated strong correlation between the PM2.5 data measured by the DustTrak 8533 and TEOM when the relative humidity range was divided into seven groups, as shown in Table 2. The scaling factor for PM2.5 decreased from 0.423 to 0.279 with the increase in relative humidity. The measured PM10 data were less reliable than the PM2.5 data because of the difficulty of calibrating light scattering particle monitors, which has been reported in the literature[29] and was confirmed by our calibration measurements. The correlation factors, R^2, for PM10 were smaller than those for PM2.5. However, our measurement results showed that the relative humidity on the commercial flights ranged from 9% to 40%. The calibration factors for PM10 were acceptable in this range. Therefore, this study measured real-time PM2.5 and PM10 mass concentrations continuously at a one-minute interval. Different calibration factors in Table 2 were used to modify our measured PM2.5 and PM10 concentration.

TABLE 2. Correlation between PM2.5 and PM10 mass concentrations measured by a TEOM and by a DustTrak monitor under different relative humidity conditions

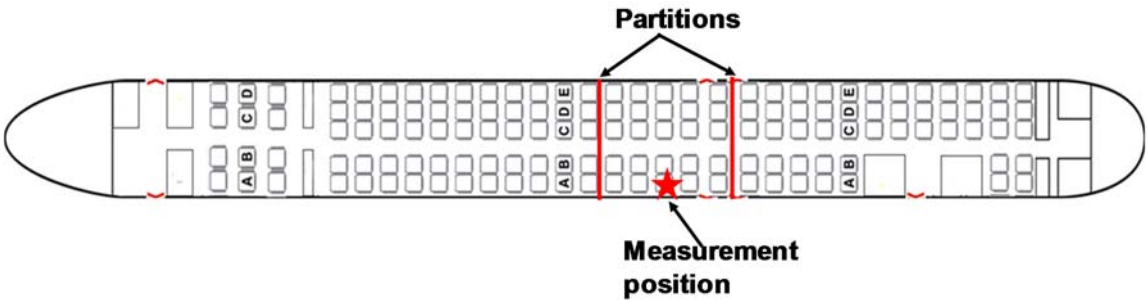
Relative humidity (%)	Correlation $Y_{TEOM}=A\cdot X_{DustTrak}$		R^2	
	$A_{PM2.5}$	A_{PM10}	PM2.5	PM10
RH<20%	0.423	0.798	0.85	0.81
20%≤RH<30%	0.409	0.717	0.93	0.76
30%≤RH<40%	0.328	0.477	0.90	0.57
40%≤RH<50%	0.307	0.412	0.93	0.33
50%≤RH<60%	0.308	0.355	0.94	0.73
60%≤RH<70%	0.289	0.330	0.98	0.73
70%≤RH	0.279	0.316	0.98	0.88

Measurements in a retired MD-82 plane

In-flight measurements can provide the most realistic results. However, there were some limitations on our commercial flights. For example, the particle concentrations in the supply air and in the occupied zone could not be measured simultaneously, and the cabin crew permitted measurement of the concentration in the supply air for only a few minutes. To confirm the in-flight results, this study also conducted measurements in a retired MD-82 airplane at Tianjin University, China. The air temperature inside the cabin was controlled by an air-conditioning cart. The cart was allowed to run prior to the experiment for at least one hour to ensure a steady-state condition. For MD-82, there is no recirculation. The supply air is 100% fresh air provided by the air-conditioning cart. To create a relatively low background particle concentration inside the cabin, an air filter was installed at the inlet of the air-conditioning cart. The filter removed

most of the particles in the supply air. To obtain the background concentration, we measured the particle concentration inside the empty cabin for 30 min.

As shown in Figure 1(a), this study conducted the measurements in a five-row section of the economy-class cabin of the MD-82 airplane, using partitions (as indicated by the red lines) to create the section. Twenty-five volunteers participated in the experiment to simulate passenger activities during a flight. The measurements in the MD-82 cabin simulated only sitting, meal servicing and deplaning/boarding, as shown in Figure 1(b), (c) and (d), respectively. Particle concentrations were measured continuously in the supply air and the occupied zone during the experiment. For measuring the particle concentration in the supply air, a hose was connected to the inlet of the particle monitor, and the other end was inserted into the air diffusers. Before the measurements, we compared the difference of particle concentration measured by DustTrak 8533 with and without a hose for the same air. A linear correlation ($y=1.37x$, $R^2=0.99$) was found from the comparison and the correlation was used to modify the data for considering the deposition at the hose. For measuring the concentration in the occupied zone, a particle monitor was placed on the tray table of the window seat in the middle row of the partitioned cabin section, as denoted by the star in Figure 1(a).



(a)

(b) (c) (d)

FIGURE 1 Schematic diagram of the MD-82 airplane and the measurement photos: (a) Measurement position in the five rows of the economy-class cabin in the MD-82 airplane, the red star denoted the measurement position, the red lines indicated the partitions used to create the section, and three measurement conditions: (b) sitting, (c) meal servicing, and (d) deplaning/boarding.

Particle emission rate from in-cabin sources

Some studies[31-33] showed that the cabin air was well mixed. With well-mixing assumption, the mass balance equation (Eq. (1)) states that the change rate of particle concentration inside a cabin of "training" flight No. i (i=1~12 in spring, i=13~24 in summer, i=25~36 in fall, and i=37~48 in winter) is equal to the change due to particles in the supply air, removal by the exhausts and deposition, and generated from in-cabin sources:

$$\frac{dC_{o,i}(t)}{dt} = \lambda_i C_{s,i}(t) - \lambda_i C_{o,i}(t) - K_i C_{o,i}(t) + \frac{S_{cabin,i}(t)}{V_i} N_i \quad (1)$$

where $C_{o,i}(t)$ (μg/m^3) is the particle mass concentration in the occupied zone; $C_{s,i}(t)$ (μg/m^3) the particle mass concentration in the supply air; λ_i (h^{-1}) the air exchange rate of the cabin; K_i (h^{-1}) the overall particle deposition rate in a cabin, which can be estimated according to the results from You and Zhao[34]. V_i (m^3) is the cabin volume; N_i (person) the number of passengers and crew members; and $S_{cabin,i}(t)$ (μg/h per person) the particle emission rate per person from in-cabin sources.

In general, a whole flight can be divided into several periods, such as boarding, taxiing out, climbing, cruising, meal services, descending, taxiing in and deplaning. During different periods, passengers have different activities, which lead to different particle emission rates. For each flight period, integrating the mass balance equation (1) from t=0 to t=T_i, the left-hand side yields:

$$\int_0^{T_i} \frac{dC_{o,i}(t)}{dt} dt = C_{o,i}(T_i) - C_{o,i}(0) \quad (2)$$

where $C_{o,i}(0)$ (μg/m^3) and $C_{o,i}(T_i)$ (μg/m^3) are the initial concentration (t=0) and final concentration (t=T_i) of each flight period in the occupied zone. The right-hand side yields:

$$\int_0^{T_i} \left[\lambda_i C_{s,i}(t) - \lambda_i C_{o,i}(t) - K_i C_{o,i}(t) + \frac{S_{cabin,i}(t)}{V_i} N_i \right] dt = T_i \left(\lambda_i \overline{C_{s,i}} - \lambda_i \overline{C_{o,i}} - K_i \overline{C_{o,i}} + \frac{\overline{S_{cabin,i}}}{V_i} N_i \right) \quad (3)$$

where $\overline{C_{s,i}} = \frac{1}{T_i}\int_0^{T_i} C_{s,i}(t)\,dt$ (μg/m^3) and $\overline{C_{o,i}} = \frac{1}{T_i}\int_0^{T_i} C_{o,i}(t)\,dt$ (μg/m^3) are the time-averaged particle concentration in the supply air and in the occupied zone, respectively; and $\overline{S_{cabin,i}} = \frac{1}{T_i}\int_0^{T_i} S_{cabin,i}(t)\,dt$ (μg/h per person) is the time-averaged particle emission rate from in-cabin sources; T_i is the time for each flight period.

Thus, Eq. (4) can be obtained by combining Eq. (2) and Eq. (3),

$$\frac{C_{o,i}(T_i) - C_{o,i}(0)}{T_i} = \lambda_i \overline{C_{s,i}} - \lambda_i \overline{C_{o,i}} - K_i \overline{C_{o,i}} + \frac{\overline{S_{cabin,i}}}{V_i} N_i \quad (4)$$

Thus, the average particle emission rate from in-cabin sources for different flight periods, i.e. sitting, meal servicing and boarding/ deplaning, can be calculated by Eq. (5):

$$\overline{S_{cabin,i}} = \frac{V_i}{N_i} \left[\frac{C_{o,i}(T_i) - C_{o,i}(0)}{T_i} - \lambda_i \overline{C_{s,i}} + \lambda_i \overline{C_{o,i}} + K_i \overline{C_{o,i}} \right] \quad (5)$$

2.2 Estimation of particle concentration inside cabin during different flights of an airplane

A given airplane flies to and from many different cities in the course of a year, and the outdoor particle concentrations vary significantly from city to city. The particle emission rates from in-cabin sources varied during different flight periods because of various passenger activities, such as boarding, deplaning, sitting, and meal servicing. Therefore, for each flight period on each flight of a given airplane, j, the time-averaged particle concentration inside cabin should be calculated according to the corresponding particle emission rates, outdoor particle and flight information.

With the assumption of well-mixed air inside cabin, Eq. (6) can be obtained also based on the mass balance equation, similar derivation as Eq. (1) ~ Eq. (4).

$$\overline{C_{o,j}} = \frac{1}{\lambda_j + K_j}\left[\lambda_j \overline{C_{s,j}} + \frac{\overline{S_{cabin,j}}}{V_j} N_j - \left(\frac{C_{o,j}\left(T_j\right) - C_{o,j}\left(0\right)}{T_j}\right)\right] \tag{6}$$

To account for the variation in outdoor sources during different flights, the particle concentration in the supply air should be calculated for each flight with the use of information about flight routes and outdoor particle concentration in those cities, which can be estimated by,

$$\overline{C_{s,j}} = M\left(1 - P_{d,j}\right)\overline{C_{out,j}} \tag{7}$$

where $P_{d,j}$ is the particle deposition fraction in the environmental control system and $\overline{C_{out,j}}$ ($\mu g/m^3$) the averaged outdoor particle concentration. M is the fresh air fraction that is set to be 0.5 since the supply air consists of 50% returned air filtered by a HEPA filter and 50% outside air[35], and the filtration efficiency was assumed to be 100%.

The measurements on the "training" flights provided the statistical average data for the particle emission rates and the third term in the right-hand side of Eq. (6) for different flight periods in different seasons, since the measurements were conducted in four seasons to consider the seasonal variation.

For example, in spring,

$$\overline{S_{cabin,j}} = \frac{1}{12}\sum_{i=1}^{12}\overline{S_{cabin,i}} \tag{8}$$

$$\frac{C_{o,j}\left(T_j\right) - C_{o,j}\left(0\right)}{T_j} = \frac{1}{12}\sum_{i=1}^{12}\frac{C_{o,i}\left(T_i\right) - C_{o,i}\left(0\right)}{T_i} \tag{9}$$

Then the time-averaged particle concentration inside cabin for each flight period of a given airplane, j, can be calculated by Eq. (10),

$$\overline{C_{o,j}} = \frac{1}{\lambda_j + K_j}\left[\lambda_j M\left(1-P_{d,j}\right)\overline{C_{out,j}} + \frac{\frac{1}{12}\sum_{i=1}^{12}\overline{S_{cabin,i}}}{V_j}N_j - \frac{1}{12}\sum_{i=1}^{12}\left(\frac{C_{o,i}(T_i)-C_{o,i}(0)}{T_i}\right)\right] \quad (10)$$

Since this study accounted for accumulated particle deposition, by using the average data, it would show "averaged condition" that may sound more reasonable. The annual PM2.5 and PM10 concentrations were used as C_{out} to present the average outdoor particle level of different airports. The other two items in Eq. (10) used the averaged measurements results obtained from random flights throughout a year, which also presented the average level of in-cabin sources.

This study calculated the particle concentration inside cabin for different flight periods of each flight in the "testing" group using Eq. (10). The measurement results on "testing" flights were used to examine the validity of the derived estimation equation.

2.3 Modeling particles deposited around the air supply nozzles

Particle accumulation per square meter is widely used to evaluate the cleanliness of a surface[36-38]. Holopainen et al.[39] found that if the accumulation was greater than 1.0 g/m^2, the stains would be visible. For a given airplane, the accumulation of particles deposited on a surface around air supply nozzles over a certain period of time, m, can be calculated by:

$$m = \sum v_d \overline{C_{o,j}} T_j \quad (11)$$

where m (g/m^2) is the accumulated particle mass during a flight; v_d (m/s) the local particle deposition velocity, which can be calculated by a modified Lagrangian method proposed by Chen et al.[3] with the use of a CFD program; T_j is the time for each flight period. In the CFD calculation, the airflow field was first calculated by using the SST k-ω model. Then, the damping function was employed to correct the turbulence kinetic energy in the near wall regions[3]. Then, this investigation used the Lagrangian tracking method to calculate the particle movement trajectories and also the particle deposition velocities according to the proposed and validated model by Chen et al[3]. The review by Lai[40] showed that the indoor deposition rates of PM10 and monodisperse particles with a diameter of 5 μm, PM2.5 and monodisperse particles with a diameter of 1 μm, were in the same order of magnitude, respectively. Therefore, this study used the particle deposition velocity for monodisperse particles with a diameter of 1 μm and 5 μm to represent PM2.5 and PM10, respectively. The total accumulation on a given airplane was the cumulative number of particles deposited in different flight periods on all the flights of the airplane. This study used ANSYS Fluent 16.0, along with user-defined functions, to calculate the airflow field; recorded the particle trajectories; converted the trajectories to the particle concentration; and calculated the particle deposition velocity and the particle accumulations on the surfaces.

3 RESULTS

3.1 Particle emission rate from in-cabin sources

This study measured the particle concentration near the diffusers inside of the MD-82 cabin, and found that it was nearly the same as the particle concentration in the occupied zone. The supply air mixed quickly with the cabin air after it entered the cabin. This study measured particle concentration in occupied zone as shown in Figure 2(a). Figure 2(b) shows the position

where the particle concentration near diffusers was measured with a sampling hose. The supply air concentration was measured with a hose inserted into the diffusers as shown in Figure 2(c). Figure 2(d) shows the PM2.5 concentrations measured in occupied zone, near diffusers and in supply air. The particle concentration in supply air was constant at 3.8 μg/m^3, while the particle concentration near diffusers was close to that in occupied zone. Therefore, this study used the particle concentration in occupied zone in Eq. (11).

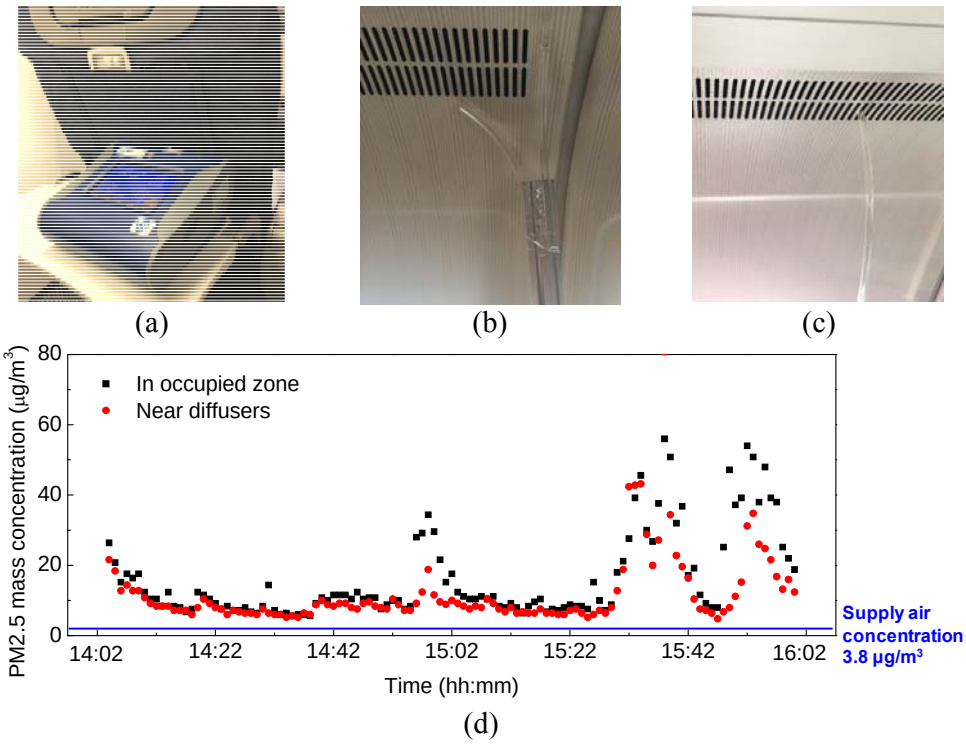


FIGURE 2 Comparison measurement of particle concentration at different positions inside MD-82 cabin, (a) in occupied zone, (b) near diffusers, (c) in supply air, and (d) measured PM2.5 data

Figures 3 shows the monitored particle concentrations in the occupied zone and the supply air during a commercial flight. The flight was from Tianjin to Xi'an with 180 passengers and 5 crew members. The airplane model was Boeing 737-800. According to the passenger activities during different flight periods, we grouped the flight into four periods: sitting when the airplane was on the ground, sitting when the airplane was in the air, meal servicing and boarding/deplaning as shown in Figure 3. When an airplane is in the air, the outside air is very clean. Furthermore, almost all airplanes use HEPA filters to clean the return air. Therefore, we assumed that the particle concentration in the supply air was zero when the airplane was in the air, including climbing, cruising and descending. Since the HEPA filters are only used for returned air, and half of the supply air is from outdoor which is not filtered at all, particles in outdoor air were brought into the airplanes when the airplanes are waiting on the ground. As shown in Figure 3, the particle concentration in supply air was higher when the airplane was on the ground than in the air. During boarding and taxiing, the PM2.5 and PM10 in supply air was about 4.1 and 5.5 μg/m^3, respectively, while they were close to 0 during cruising. The outdoor PM2.5 and PM10 were about 35 and 60 μg/m^3. The particle concentration in supply air was positively correlated to the outdoor particle concentration. When the outdoor air quality becomes worse, the particle concentration in supply air will be higher on other flights. However, our earlier studies[17,41,42] found that about 77% fine particles (dp≤2.5 μm) and 90% coarse

particles (2.5 μm<dp≤10 μm) deposited in the ECS before entering the cabin. The outdoor particle concentration had limited impact on the cabin PM2.5 concentration. The particle in occupied zone mainly come from the in-cabin sources. During sitting and meal servicing, the upper-body movements of the passengers may have generated some particles. Since the supply air brought some particles when the airplane was on the ground, the particle concentration in occupied zone during sitting on the ground periods were a little higher than during the sitting period in the air. During boarding and deplaning the particle concentration in occupied zone was the highest mainly because the movements of passengers and crew members were strong during this period.

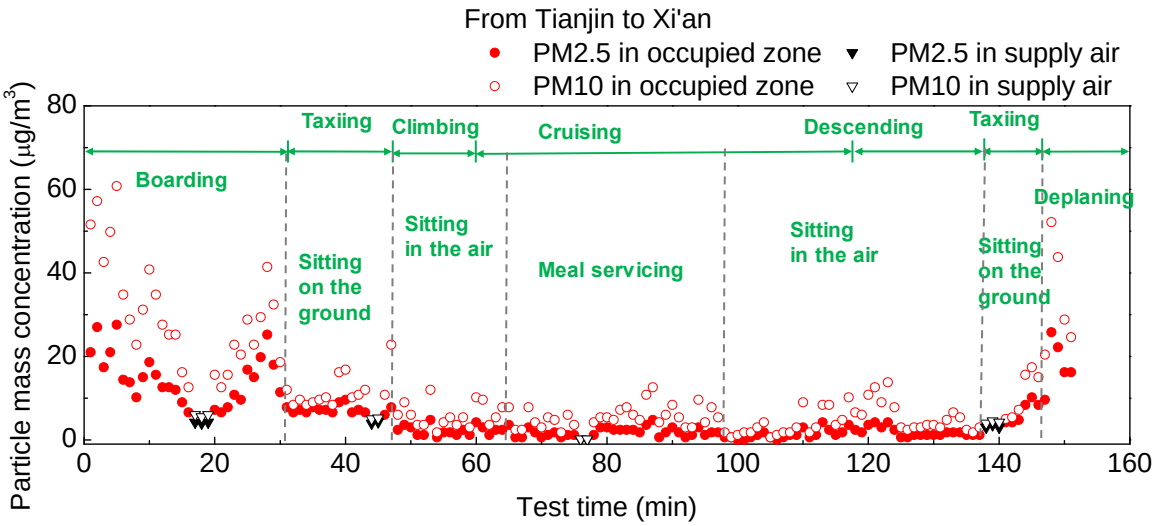


FIGURE 3 PM2.5 and PM10 mass concentration measured in the occupied zone and the supply air on a flight from Tianjin to Xi'an

This investigation conducted four measurements of the particle emission rate from in-cabin sources in the five-row section of the economy-class cabin of the MD-82 airplane. We chose four days with different outside particle concentration levels for the experiment. For each measurement, Table 3 shows the date, time, outside PM2.5 and PM10 concentration from the nearest air quality monitoring station, our measured outdoor PM2.5 and PM10 concentration, and background PM2.5 and PM10 concentration in the empty cabin. The monitoring station from local government used tapered element oscillating microbalance (TEOM) method to measure the PM2.5 and PM10 mass concentration, which is considered to be most accurate. Our Dusttrak 8533 used light scattering method to determine the mass concentration that is less accurate. Thus, we used the government monitoring station data to calibrate our data. When measuring outdoor particle concentration with a Dusttrak 8533, the unit was placed at the height of 3 m around the MD-82 airplane at Tianjin Airport. The outdoor particle concentrations measured by us were nearly the same as those from the air quality monitoring station at the airport, which validated our particle measurements. Note that the data from the monitoring station were updated every hour, while our measurement interval was every minute. The background particle concentration inside the cabin, which was monitored for at least 30 min before the volunteers entered the cabin, varied little and remained at a very low level. Meanwhile, the outside PM2.5 varied significantly, from 16.4 μg/m^3 to 82.6 μg/m^3. This implies that most of the particles were deposited on the filter of the air-conditioning cart and in the air supply system before the air entered the cabin.

TABLE 3 PM2.5 and PM10 concentration inside the MD-82 cabin under different outdoor air quality levels

Date	Time	PM2.5 (PM10) (μg/m^3)		
		Outdoor		In cabin
		Monitoring station	Measured	
June 20, 2017	12:00-13:00	15 (33)	16.4±0.6 (30.5±1.3)	3.8±0.5 (4.9±0.6)
July 8, 2017	7:00-8:00	46 (177)	44.5±0.9 (73.2±1.5)	4.6±0.4 (5.6±0.5)
July 9, 2017	7:00-8:00	37 (65)	33.1±3.1 (51.0±5.9)	4.6±0.4 (5.5±0.5)
July 16, 2017	7:00-8:00	84 (99)	82.6±7.7 (95.7±8.2)	4.7±0.2 (5.6±0.3)

As shown in Figure 4, the PM2.5 and PM10 concentration in the supply air varied little and was nearly the same as the background concentration measured in the empty cabin. The particle concentration in the cabin was higher than that in the supply air during the experiment, which indicates that the passengers did indeed generate particles in the cabin. During the boarding and deplaning process, the particle concentration increased rapidly because of the movements of the passengers. Meal servicing could also have caused a slightly higher particle concentration. The particle concentration pattern measured in the MD-82 plane looks similar to that on the commercial flights.

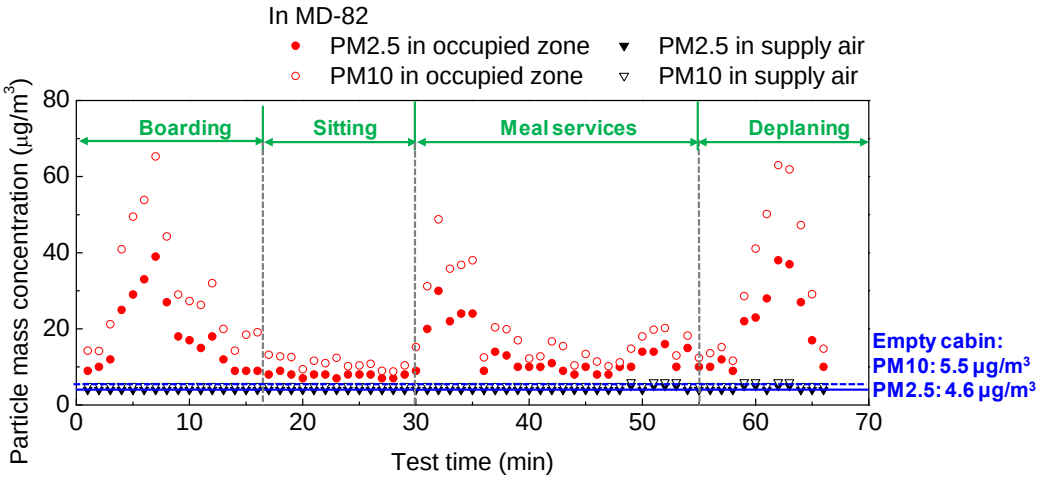


FIGURE 4 PM2.5 and PM10 mass concentration measured in the cabin and in the supply air of the five-row economy-class cabin of the MD-82 airplane.

With the measurement data for PM2.5 and PM10 concentration in the cabin and in the supply air as shown in Figures 3 and 4, this study calculated the PM2.5 and PM10 emission rates from in-cabin sources by means of Eq. (10). Typically, the particle emission rate is expressed in terms of the particle mass per second[43]. However, to account for the number of passengers, this study expressed the particle emission rate as particle mass per minute per person. Table 4 lists the average and standard deviation data of particle emission rates obtained from the MD-82 airplane calculated for each flight. The data show again that emission rates from in-cabin sources were highest during boarding and deplaning. The emission rates during sitting and meal servicing were similar. The average PM2.5 emission rates were 7.2, 2.6, 1.9, and 1.8 (μg/min per person), respectively, during the boarding/deplaning, sitting on the ground, sitting in the air and meal servicing. The corresponding PM10 emission rates were 15.4, 6.1, 5.3 and 5.4 (μg/min per person), respectively for these four periods. Particle emission was highest in winter, possibly as a result of the high clothing level. For example, the coats worn in winter may not be washed frequently, and taking off and putting on coats could produce more particles. Low humidity in winter can also be another reason. Some previous studies [44,45] showed that low relative humidity

could increase the particle emission and resuspension from indoor surfaces. Since high relative humidity affects the water film on any surface, which consequently affects particle adhesion to the surface and may make particles more difficult to escape. The measured results in the MD-82 cabin were comparable to those on the commercial flights, which confirmed the validity of our commercial-flight experiment. Thus, the particle emission rates can be used to calculate the particle concentration inside a cabin for modeling the accumulation of particles deposited on different surfaces of the cabin.

TABLE 4 Summary of mean ± standard deviation particle emission rate from in-cabin sources measured in the MD-82 cabin and on commercial flights in different seasons

Airplane model	Season	In-cabin PM2.5 emission rate (μg/min per person) (In-cabin PM10 emission rate)			
		Sitting on the ground	Sitting in the air	Meal servicing	Boarding/deplaning
B737/A320	Fall	2.3±0.8 (4.5±1.5)	1.6±1.1 (4.8±2.4)	1.6±0.8 (5.5±2.3)	6.9±2.6 (13.9±7.0)
	Winter	3.9±1.9 (8.8±3.0)	2.3±1.7 (7.0±3.8)	2.2±1.1 (6.9±3.0)	11.1±6.3 (20.9±10.8)
	Spring	3.0±2.0 (7.4±4.1)	1.9±0.8 (4.7±1.8)	1.8±0.8 (4.9±1.4)	5.4±2.1 (14.0±5.8)
	Summer	2.5±1.3 (5.1±2.9)	1.9±0.8 (4.8±2.3)	1.7±0.8 (4.6±2.0)	4.4±1.8 (11.8±5.5)
MD-82	Summer	2.0±0.2 (5.0±0.3)		2.4±0.3 (6.5±0.7)	5.4±0.9 (11.0±1.5)
Average		2.6±1.6 (6.1±3.3)	1.9±1.2 (5.3±2.8)	1.8±0.9 (5.4±2.3)	7.2±4.6 (15.4±8.5)

To evaluate whether the proposed calculation method could produce the particle concentration inside cabin with reasonably good accuracy, we compared the measured and estimated PM2.5 and PM10 concentration in the aircraft cabin during different flight periods, as shown in Figure 5. Each point presents the comparison of the measured and estimated particle concentration inside cabin on each flight in the "testing" group. For each point, the measured C_o was the time-averaged particle concentration inside cabin during a certain flight period on a certain "testing" flight, and the estimated C_o was the corresponding time-averaged particle concentration calculated by Eq. (10). The particle concentration inside the cabin during sitting was divided into two periods, when the airplane was on the ground and when it was in the air, because of the different outdoor particle concentration levels. When the airplane was in the air, the PM2.5 and PM10 concentration inside the cabin was below 5 and 12 μg/m^3, respectively. The concentration was much higher on the ground, especially during the boarding and deplaning periods. The average relative error between the estimated and measured PM2.5 concentrations inside cabin was 14.0%, and the value was 15.2% for PM10. This comparison indicates that the calculation method can quantitatively predict the average particle concentration inside the aircraft cabin when the particle emission rates from in-cabin sources are known.

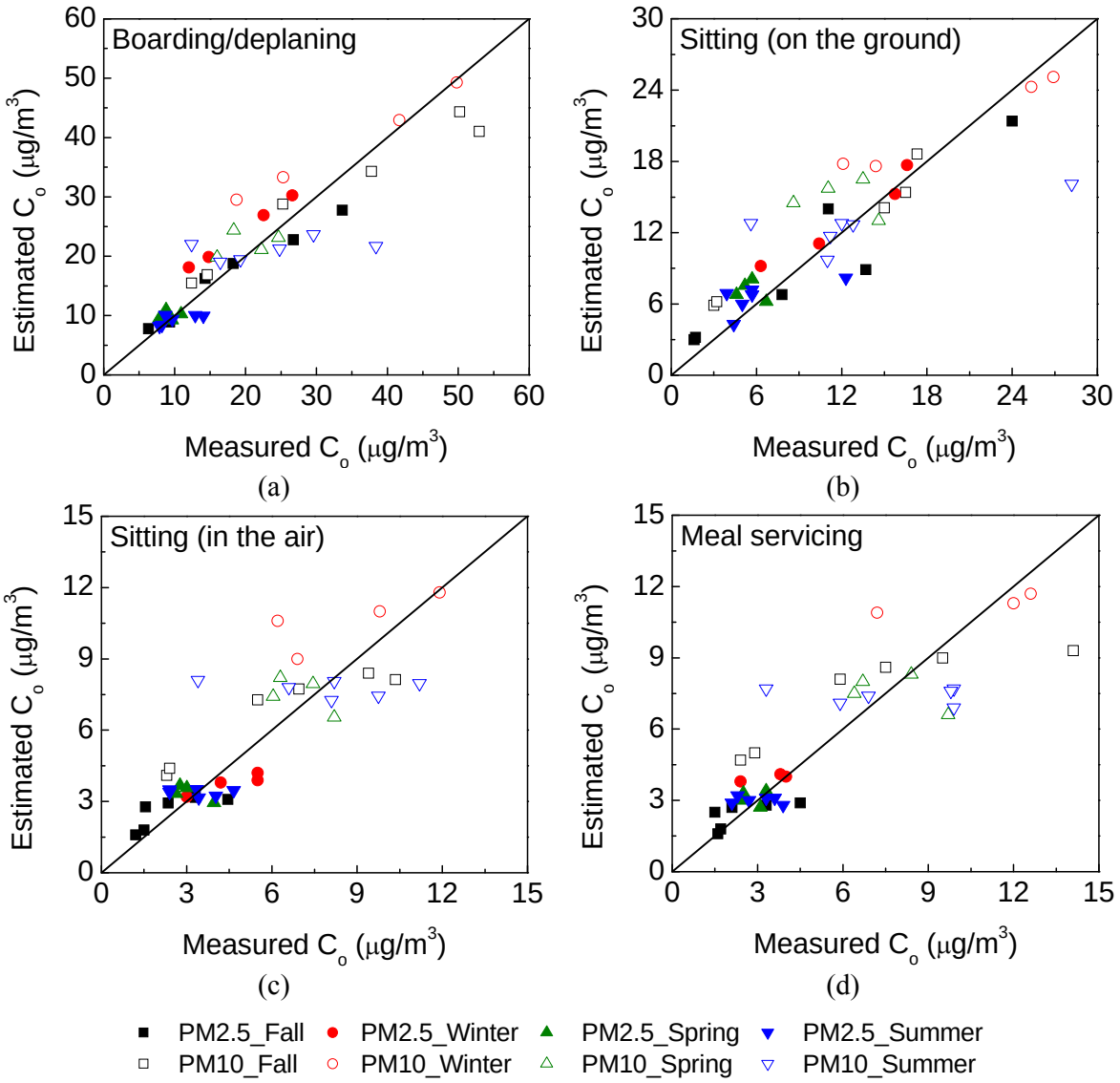


FIGURE 5 Comparison of measured and estimated PM2.5 concentration in aircraft cabins (for the testing group) in different seasons during different flight periods (a)boarding/deplaning, (b) sitting (on the ground), (c) sitting (in the air), and (d) meal servicing

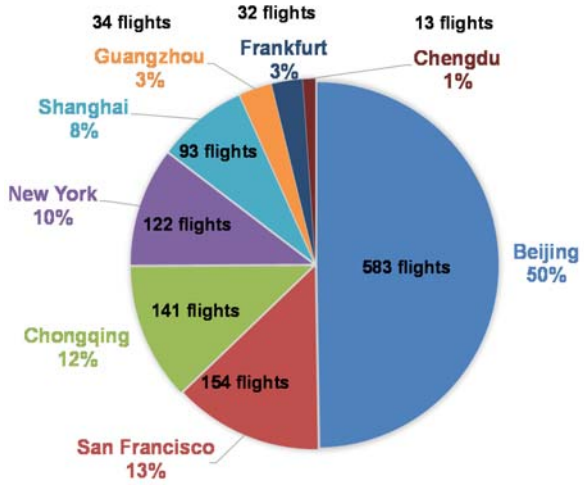
In general, the differences should be acceptable, but there are some patterns. For example, the estimated concentration in winter was consistently higher than the measured data during the boarding and deplaning periods. The clothing level could be a major factor between the "training" and "testing" groups. The estimated concentration during sitting and meal serving periods in the summer and fall varied much more than the measured data. This implies that the number of flights used in the training group is not sufficient to be more inclusive.

3.2 Accumulation of particles deposited around air supply nozzles in cabins

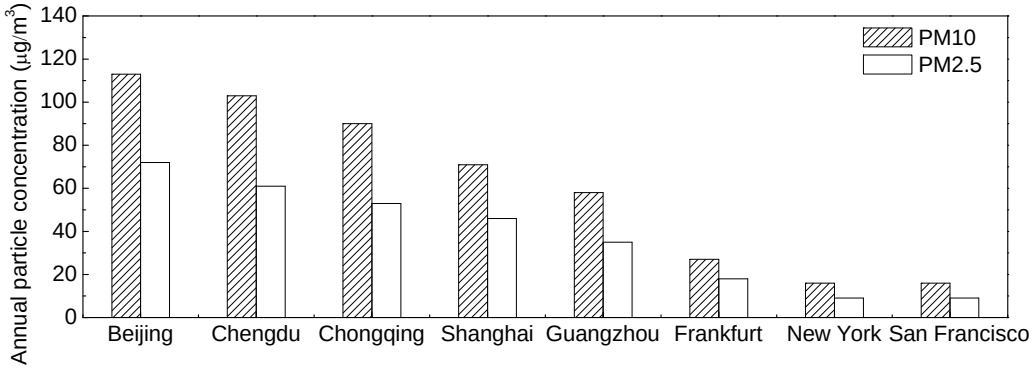
To predict the accumulation of particles deposited around the air supply nozzles in airliner cabin, one must consider the outdoor concentration because it is a significant source[17]. This requires information about the flight routes of a typical airplane and the outdoor PM2.5 and PM10 concentration in the ground air. It is difficult to identify a "typical" polluted airplane, as the pollution level is related to many factors, such as particle concentration, time on the ground

during servicing, and flight routes. It is easier to find the most polluted airplane, one which has been parked primarily at airports with high levels of air pollution and has had long on-ground servicing times. Identifying such an airplane would facilitate the evaluation of worst-case accumulation of deposited particles. To identify the most polluted airplane, this study calculated the annual particle exposure for each airplane operating in China. The most polluted airplane had the highest annual particle exposure. The particle exposure is the sum of the particle concentrations at the airports where the airplane had stopovers, each multiplied by the air-conditioning time of the airplane at that airport.

The aircraft model is a very important factor because it determines air diffuser design, ground time, flight routes, etc. This investigation chose the Boeing 747 as an example. We studied the flight routes of the most polluted B-747 airplane in China. This airplane made 1173 flights in two years, as shown in Figure 6(a). All the flights departed from or arrived at Beijing airport, which has severe particle pollution. Outdoor PM2.5 and PM10 varies hourly and the variation may range from less than 10 $\mu g/m^3$ to more than 500 $\mu g/m^3$, such as in Beijing. In a year, airplanes will fly to different cities for many times at different time. Since this study accounted for accumulated particle deposition, the annual PM2.5 and PM10 concentrations were used to present the average outdoor particle level of different airports. For each individual airplane, the PM2.5 and PM10 concentration may depart significantly from the average. Figure 6(b) depicts the annual PM2.5 and PM10 concentrations of 2016 in the cities of the airports at which the aircraft was parked. Note that, the data of annual PM2.5 and PM10 concentration in Frankfurt, New York and San Francisco in 2016 were not found in the literatures and websites. This study used the data for other years provided by WHO report of Ambient Air Pollution Database. When the outdoor particle concentrations in those cities are known, the particle concentration originating from the outdoor environment can be determined.



(a)



(b)

FIGURE 6 (a) Airports at which the most polluted B-747 airplane was parked in 2016 and 2017, and (b) annual PM2.5 and PM10 concentration at those airports

Table 5 summarizes the additional parameters used in this study for modeling particle accumulation around the air supply nozzles of the most polluted airplane. Since this study focused on PM2.5 and PM10, the deposition fraction of PM2.5 and PM10 in the ECS should be known. Our previous studies measured[17,41] and calculated[42] the particle deposition fraction in the ECS, the results showed that about 77% of the fine particles ($d_p \leq 2.5$ μm) and 90% of the coarse particles (2.5 μm$<d_p \leq$10 μm) deposited in the ECS before entering the aircraft cabin. The air change rate was an important factor in the calculation of particle emission rate. However, it was difficult to measure the actual air change rate on a commercial flight. The air change rate for this airplane was estimated to be 30 h^{-1}, which was the average value obtained from the literature[12, 46-50]. To improve the results, efforts should be made to obtain more measurement data for the actual air change rate on commercial flights. This study assumed a fully occupied condition, and the same number of passengers and crew members on all the flights. The cabin volume was estimated from data on several airplane cabin mockups used in previous CFD simulations[46,51]. After the passengers deplaned, ground services such as catering and cleaning were conducted inside the aircraft cabin in preparation for the next flight. This study also considered the accumulation of deposited particles during this period. The PM2.5 and PM10 concentration was estimated to be 15 and 25 μg/m^3, respectively, according to our previous experiment on an MD-82 airplane and the particle emission rate during cleaning in residential buildings[23, 30].

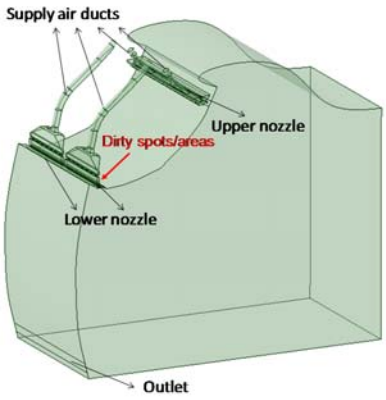
In this study, the times for different flight periods in Eq. (6) were an important factor in modeling the particle accumulation. Historical data on the time in the air for each flight of a given airplane are available online (https://www.flightradar24.com). For the B-747 airplane in this study, the data showed that the average time per flight was 424 min. However, there were no exact historical time data on boarding, waiting, taxiing, servicing, or deplaning. This study estimated the data according to the average times for these periods as recorded on the 66 domestic flights and the 2 international flights. Further statistical data are needed to improve the modeling.

TABLE 5 Parameters used for modeling particle accumulation on the most polluted B-747 airplane

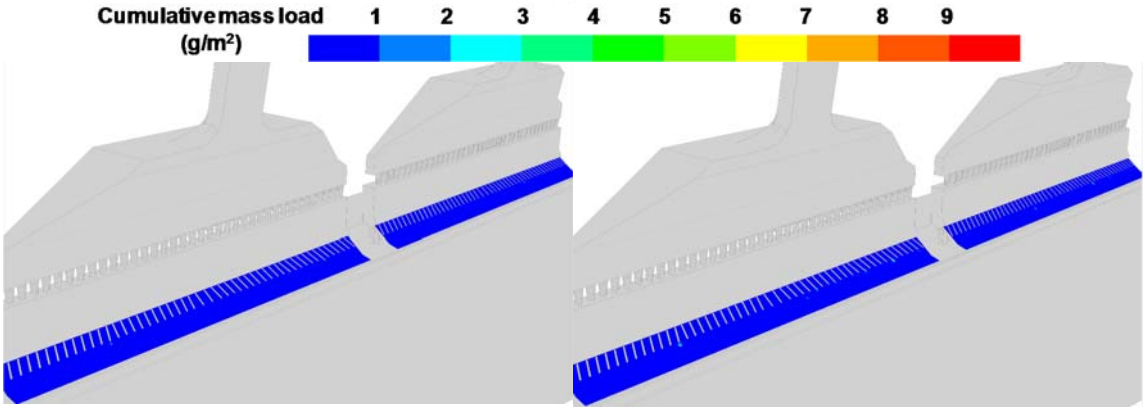
Parameter	Value
Total flights in 2016 and 2017	1173
Average time per flight	424 min
Air change rate[12, 46-50]	30 h^{-1}
Combined number of passengers and crew members	375

Cabin volume[46,51]		315.68 m^3
PM2.5 (PM10) concentration during ground services[23,30]		15 (25) $\mu g/m^3$
Total particle deposition fraction for particles	$d_p \leq 2.5$ μm	0.77
	2.5 μm$< d_p \leq$10 μm	0.90
Average time for	Boarding and deplaning	65 min
	Sitting on the ground	45 min
	Ground services	90 min
	Meal servicing	60 min
	Sitting in the air	364 min

With the above information, this study simulated the cumulative PM2.5 and PM10 deposition on the walls near the air supply nozzles of the airplane over one-month, three-month and six-month timeframes. We have built a geometry model of a half section, one-row Boeing 747 airplane cabin as shown in Figure 7 (a). The upper nozzles are installed above the luggage storage, while the lower nozzles are installed between the side wall and the overhead panel. The overhead panel is where the gaspers and buttons are installed. Since the dirty spots/areas are along the outflow regions of the lower horizontal nozzles, the geometry inside the duct and nozzles was not simplified in order to capture the detailed airflow feature in these sensitive areas. Figure 7 (b)-(g) show the deposition near the air supply nozzles. After one month of operation, the dirty spots/areas are still virtually invisible. However, after three months, the dirty spots/areas become visible (1.0 g/m^2). After six months, the dirty spots/areas are even more obvious. Therefore, the wall around the nozzles should be cleaned at least every six months for this most polluted airplane.



(a)



(b) (c)

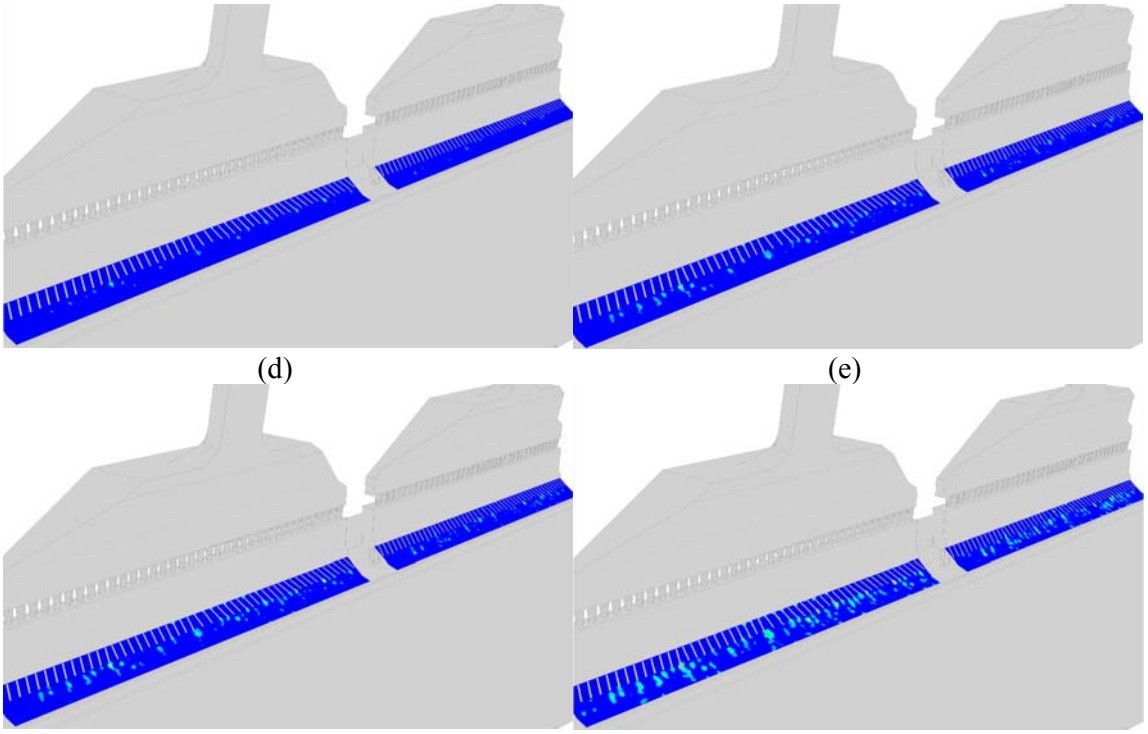


FIGURE 7 Accumulation of particle deposited on the wall near the air supply nozzles of the Boeing 747 airplane (a) geometry model of a half section, one-row Boeing 747 cabin, PM 2.5 accumulation over (b) one month, (d) three months and (f) six months and PM10 accumulation over (c) one month, (e) three months and (g) six months

4 DISCUSSION

There were some limitations to this study. The first was the calibration of the Dusttrak 8533 monitor. Previous studies[27, 52] have reported that a light-scattering particle monitor must be calibrated because it estimates particle weight rather than measuring it directly[28]. As particles have different scattering properties, calibration factors vary when the monitor is used in different environments. With the calibration factors mentioned in the method, the Dusttrak monitor provided reasonably accurate particle mass concentrations in outdoor environments. However, particle characteristics (size distribution, particle density, refractive index, etc.) may have varied between the atmospheric particles and the emission aerosols from passenger activities inside the aircraft cabin. Therefore, further efforts are needed to confirm the variation of calibration factors in the aircraft cabin environment.

In this study, when estimating the particle concentration in the supply air, we regarded the particle level reported by a monitoring station as the particle concentration around the airplanes, since there were no direct data on particle concentrations at the various airports. Taking our previously measured results[17] as an example, the difference between the PM2.5 concentration measured at Tianjin airport and that reported by the nearest monitoring station was not constant. Sometimes the PM2.5 was higher at the airport, and at other times it was lower. Although the particle emission from the airplane engines was a significant source, the wind speed and direction could have influenced the measured difference. The average difference between the PM2.5 concentration around the airplanes and the reported PM2.5 concentration was about 8.7 $\mu g/m^3$. The impact of this concentration difference on the results was further decreased by the

significant particle deposition rate in the ECS. However, for some cities, the nearest particle monitoring station was at a considerable distance from the airport. In those cases, the difference in outdoor particle concentration was much higher. For a better understanding of particle-related pollution at airports in the future, we recommend that each airport acquire its own particle monitoring station to provide exact data on particle concentrations around airplanes.

Since it was impossible to measure particle concentration in the supply air during the climbing and descending periods, this study assumed that the particle concentration originating from outdoors was zero in these two periods. This assumption may have resulted in under-prediction of particle accumulation. However, a previous study showed a 97% decrease in the outdoor particle concentration at an altitude of 3 km[53]. It took about 5 min for the airplanes in our study to climb to this altitude. Therefore, the under-prediction may not be significant. We considered the method to linearize the variation of outdoor particle concentrations with the altitude, which only resulted in an increase of 0.6% particle accumulation. It was a rough estimate because of the limit information from the literature. To have the accurate correlation between the outdoor particle concentrations with the flying height of the airplane needs more information about the rate of climb for the airplanes and the outdoor particle concentration at different altitudes. Few literatures are found to create the database. To simplify the calculation, we would like to ignore it.

We measured particle concentration in the middle and rear of the MD-82 cabin and also at an aisle seat and a window seat in the same row to identify the spatial differences. Our results show that the differences among these locations were less than 2%. Of course, when the flight attendants heat food, the concentration near the galley area would be much higher. However, special activities, such as heating food, lasted only for a few minutes and may not occur in every flight. Thus, this study did not consider the impact of special activities on the particle concentration.

As shown in Table 3, this study measured the particle concentration inside empty MD-82 cabin. The PM2.5 concentrations in the occupied zone in the empty cabin were 3.8±0.5, 4.6±0.4, 4.6±0.4, and 4.7±0.2, respectively, for the four measurements. The particle concentration inside the cabin varied very little when the cabin was empty. When the cabin was occupied with passengers as shown in Figure 4, the particle concentration inside cabin increased and varied significantly when the passengers had different activities. It indicates that the passengers were the main factor influencing the particle concentration. This study conducted measurements on the MD-82 airplane with a fully occupied section, B737/A320 airplanes with 137~195 passengers and crew members and B777 airplanes with 219 passengers and crew members. The occupation densities were close to or exactly 100 %. The occupation densities were nearly the same while the passenger and crew number varied a lot due to different airplane models. To make a consistent comparison, this study used the particle generation rate averaged by the number of passengers and crew members.

This study focused on particle deposition around air supply nozzles. According to a previous study[34], the particle deposition velocity on other inner surfaces of an airplane, such as the ceiling, floor and cabin walls, is about three orders of magnitude smaller than that around the air supply nozzles. The reason for the difference is that, around the nozzles, stronger turbulent diffusion toward the wall lead to a higher possibility of particle deposition at that location[3]. After a certain period of operation, the dirty, smudged areas around the nozzles caused by the deposited particles become more obvious; they are unsightly, and the airplane may appear older.

In this study, we used a Boeing 747 airplane as an example to predict the particle accumulation around the air supply nozzles. The B-747 is a large, wide-body airplane that serves mainly international flights and long-haul domestic flights. For this type of airplane, the time in the air is usually longer than on the ground. A mid-size airplane, such as a B-737 or A-320, serves short-haul domestic flights. Since the particle concentration inside the cabin is obviously higher when waiting on the ground than during cruising, the accumulation may be higher for a B-737 or A-320 than for a B-747 if the diffusers of the airplanes were the same. However, the diffuser design is also a very important factor influencing the particle deposition around the diffusers. As investigated by the Chen et al. [3], the angle between the supply air jet and the wall, the area ratio of openings to bars of a multi-slot diffuser and the airflow rate affected the particle deposition on the surrounding surfaces. More information of detailed diffusers design on different types of airplanes are needed to conclude which type of airplanes has most serious particle accumulation around the diffusers.

5 CONCLUSIONS

This investigation conducted multiple in-flight measurements to obtain the emission rate of particles from in-cabin sources. With the measurement data, this study used a CFD program to predict the particle accumulation around the air supply nozzles in the most polluted Boeing 747 airplane in China. The following conclusions can be drawn from this study:

The in-cabin sources emitted more particles during the boarding and deplaning periods than during the meal servicing and sitting periods. The emission rates during sitting and meal servicing were similar. The average PM2.5 emission rates were 7.2, 2.6, 1.9, and 1.8 (μg/min per person), respectively, during the boarding/deplaning, sitting on the ground, sitting in the air and meal servicing. The corresponding PM10 emission rates were 15.4, 6.1, 5.3 and 5.4 (μg/min per person), respectively for these four periods.

The average particle emission rate from in-cabin sources varied seasonally and was the highest in winter. The measured results on commercial flights were comparable to those in the cabin of a retired MD-82 airplane on the ground with an air-conditioning cart, which confirmed the validity of the in-flight experiment.

The proposed calculation method is able to quantitatively predict the average PM2.5 and PM10 concentration inside an aircraft cabin during different flight periods in different seasons when the particle emission rate from in-cabin sources is known. The average relative error between the estimated and measured PM2.5 concentrations inside cabin was 14.0%, and the value was 15.2% for PM10.

For the most polluted B-747 airplane in China, the dirty spots/areas around the air supply nozzles become visible after six months. Therefore, the area near the air supply should be cleaned every six months.

ACKNOWLEDGEMENTS

The research presented in this paper was partially supported by the National Key R&D Program of the Ministry of Science and Technology, China, on “Green Buildings and Building Industrialization” through Grant No. 2016YFC0700500.

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