Impacts of PM on Indoor Air Quality of Airport Terminal Buildings in a Core City of North China Plain

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ABSTRACT

With the economic growth and globalization, a great deal of airports are being or planned to be constructed or retrofitted in China. The air quality in airport terminal buildings has not been studied as in-depth as airport ambient air quality. Due to its unique architectural and operational characteristics, the airport terminal buildings have individual performance of indoor air quality. The contribution of outdoor particulate matter (PM) to indoor environment and passengers’ exposure to indoor PM is not well understood. The indoor (i.e., terminal buildings) and outdoor PM concentrations with particle sizes from 0.25 to 32 µm of Tianjin Binhai International Airport (IATA: TSN) were monitored continuously during two cases in winter and summer 2020. Higher indoor PM concentrations occurred in winter as well as in the arrival halls of TSN. During winter case, the indoor sources contributed more to the indoor environment than the outdoor sources, whereas the opposite was found during summer case. Sharp variation of indoor PM number concentrations existed in particles within the range of 0.25–0.40 µm in size, with a peak number concentration at particle size of about 0.30 µm. PM with smaller particle sizes were more likely to enter the indoor environment from outdoor. The comprehensive exposure in the TSN terminal buildings was higher than those in the transportation microenvironments, residences and other buildings. Significant diurnal variations of Respiratory deposition dose (RDD) were observed under various exposure durations. Our results highlight the need for further monitoring and improving the air quality in the terminal buildings.

Keywords: Airport, Terminal building, Particulate matter, I/O ratio, Respiratory deposition dose

1 INTRODUCTION

In 2019, 11.7 million flights carrying 1.4 billion passengers departed from or landed at airports in China (CAAC, 2020). As one of the major sources of particulate matter (PM) in urban areas (Johnson et al., 2008), aviation emissions have received increasing attention in recent decades as a result of the accelerating growth of air transport volumes and the expected expansion for the next decade (Amato et al., 2010; Kurniawan and Khardi, 2011; Masiol and Harrison, 2014). Substantial efforts have been made to illuminate the relationship between PM and human health (Englert, 2004; Valavanidis et al., 2008; Sangiorgi et al., 2013). Both the short-term effects (premature mortality, hospital admissions, etc.) and the long-term effects (morbidity, lung cancer, cardiovascular and cardiopulmonary diseases, etc.) of PM have been reported. Kim et al. (2007) attributed approximately 16,000 premature deaths annually to aviation emissions worldwide, with 87% attributable to PM with a diameter less than 2.5 µm (PM2.5).
The PM generated by airliners not only have a significant impact on the outdoor air quality but can also move to the indoor environment via multiple pathways. Considerable efforts have been made to figure out the amount and outdoor environmental effect of PM emissions from aviation emissions (e.g., Corporan et al., 2008; Whitefield et al., 2008; Herndon et al., 2005; Agrawal et al., 2008; Westerdahl et al., 2008), nevertheless, the conditions and extent under which aviation emissions infiltrate indoor (specifically, terminal buildings) and impact indoor air quality still remain unresolved (Tharwat et al., 2019; Ren et al., 2018; Hudda et al., 2020). Massey et al. (2012) found that the penetration of particle pollutants and the use of mechanical air conditioning systems in buildings or aircraft can adversely affect the indoor air quality. The PM in the airport outdoor area (e.g., stands, aprons, runways) are at a high concentration level (Zhu et al., 2005; Chen et al., 2006), which can easily enter the indoor environment because of frequently opened doors and HVAC (heating, ventilation, and air conditioning) system (Ren et al., 2018). Tharwat et al. (2019) dedicated to the volatile organic compounds (VOCs) pollutants in the maintenance room and found correlation between aircraft number and the concentration of light aldehydes/ketones.

The terminal buildings usually operate on a 24-h basis throughout the year and interact with a majority of the airport personnel and the passengers. In China, due to the low on-time performance of airlines (http://www.flightstats.com/), passengers usually spend one or more hours in terminal buildings. Therefore, the high level of PM pollution in the indoor microenvironment of the terminal buildings will seriously affect the health of the airport personnel and the passengers (Takegawa et al., 2021).

For the research related to indoor air pollution (Jenkins et al., 1992; Robinson and Nelson, 1995; U.S. EPA, 1996), some studies described the characteristics and impact factors of indoor pollutants in residences and schools, such as PM (Klepeis et al., 2001; Han et al., 2015; Qi et al., 2017), VOCs (Ielpo et al., 2021; Sangiorgi et al., 2013), NOx (Derbez et al., 2018; Ruggieri et al., 2019) and metals (Li et al., 2021). Derbez et al. (2018) found concentration and solubility of PM$_{2.5}$ elements could be used to identify the sources of indoor particles. Indoor air. An investigation carried out by Ielpo et al. (2021) in a school suggests the presence of indoor VOCs sources, both in the classrooms and the bathrooms. Others examined the relationship between indoor and outdoor PM (Abt et al., 2000; Adgate et al., 2002; Cao et al., 2005; Clayton et al., 1993). For example, Chen and Zhao (2011) reviewed the widely used parameters for the relationship between indoor and outdoor particle concentration, such as Indoor/Outdoor (I/O) ratio, penetration factor, and infiltration factor ($F_{in}$). The indoor-outdoor relationship of PM can be affected by ventilation, indoor pollution levels, building structures, and particle sizes. In a naturally ventilated indoor environment, pollutants are more likely to enter the room with the ventilation airflow due to the active indoor and outdoor air circulation and higher air exchange rate. Nevertheless, ventilation mainly relies on indoor air circulation in a mechanically ventilated environment, resulting in a relatively lower air exchange rate as well as infiltration factor (Goyal and Kumar, 2013). In general, fine PM has a higher penetration factor than coarse PM, and coarse PM deposits faster than fine PM in the indoor environment (Jones et al., 2000; Chen and Zhao, 2011). Studies on relationship between indoor and outdoor particles and found that I/O very extensively, from 0.02 to 31 (Chen and Zhao, 2011). However, most studies have shown findings that the indoor air quality is strongly related to ambient air. Ambient particles have been found to penetrate indoors very efficiently, Hänninen et al. (2004) found the infiltration efficiency of residential PM$_{2.5}$ particles ranged from 0.59 to 0.70 in four European cities. There could be more than 50% of urban PM$_{2.5}$ particles entering the indoor office environments in Milan, Italy (Sangiorgi et al., 2013). However, these researches mainly focused on residences and offices, few on airport terminal buildings. Since airports are equipped with HVAC systems like most office buildings and shopping malls, there is a certain possibility that similar situations will arise. As key features which distinguish airport terminals from other commercial buildings exist (Upham, 2001; Kotopoules and Nikolopoulou, 2014; Balaras et al., 2003), such as larger area and different human activity, it is necessary to analyze the impact of those factors on airport terminal buildings’ indoor air quality.

Existing studies provide different perspectives to understand the variations in PM pollution in the traffic microenvironments, one of which is the exposure of passengers in those microenvironments. Pramod and Gupta (2016) investigated the passenger exposure to inhalable, thoracic and alveolar particles in three transportation modes (bus, car, and auto rickshaw) in Delhi, India. Goel and Kumar (2016) examined pedestrian exposure to PM$_{10}$, PM$_{2.5}$, and PM$_{1}$ (particulate matter with...
aerodynamic diameters smaller than 10, 2.5, and 1 µm, respectively) on a roadside by estimating the total respiratory deposition dose (RDD) from data collection at traffic intersections. However, the key issue of passenger exposure to PM at the airport, especially in terminal buildings, has seldom been the focus of those studies. It is valuable to carry out an in-depth investigation of passengers’ exposure at terminal buildings since they always spend a relatively long time (more than 1 h) waiting aboard.

In this study, the characteristics of indoor PM pollution in the TSN (Tianjin Binhai International Airport, IATA: TSN) terminal buildings were explored and the sources of indoor particles were quantified through the on-site monitoring of PM in 31-size bins from 0.25 to 32 µm. Moreover, combined with the standard parameters of the population breathing zone, the PM exposure of passengers and employees staying in the terminal buildings was quantitatively evaluated. We would (1) analyze the characteristics of indoor and outdoor particle concentrations. (2) acknowledge the relationship between indoor and outdoor particle concentrations. (3) conduct source identification of indoor particle pollution. (4) calculate particle pollution exposure and RDD of passengers in the airport terminal buildings.

2 MATERIAL AND METHODS

2.1 Sampling Method

Measurements were conducted at TSN (Tianjin Binhai International Airport, IATA: TSN, ICAO: ZBTJ), which is one of the major air traffic centers in China. In 2019, the passenger throughput in TSN was 23.81 million (http://www.tbia.cn/). TSN extends 364000 m² with two terminal buildings. Terminal 1 (T1) extends 116,000 m² with 19 stands and a single runway; Terminal 2 (T2), located eastside of T1, extends 248,000 m² with 40 stands and dual parallel runways (Fig. 1). Both of the terminal buildings have two floors with the upper floor being the departure hall and the lower floor being the arrival hall.

The measurements were performed simultaneously in the indoor and outdoor environments using 21 instruments. The sampling locations are shown in Fig. 1. One instrument was set up on the first floor between the T1 and T2 terminal buildings, and others were set up in the departure halls and arrival halls of the T1 and T2 terminal buildings. 4 instruments were placed in the arrival hall (first floor) of T1 terminal building, 4 instruments were placed in the departure hall (second floor) of T1 terminal building; 6 instruments were placed in the arrival hall (first floor) of T2 terminal building, 6 instruments were placed in the departure hall (second floor) of T2 terminal building. The indoor sampling sites were away from the dining area and gathering area, and the outdoor site was located away from vehicle emissions. All sites were away from entrances and exits, as is recommended by GB/T18204.6-2013 (“Examination methods for public places—Part 6: Technical specifications of health monitoring”), more than 3 sampling sites in public place whose surface area is more than 1000 m². The sampling height was set to ~1.3 m above ground, which is close to the breathing zone for adults (~1.6 m) and children (~1 m). The Portable Laser Aerosol spectrometer and Dust Monitors (Model 11A, Grimm Corporation, Germany) combined with an optical particle sensor were used to measure the concentrations of PM₁, PM₂.₅ and PM₁₀ at 1-min counting interval. The Grimm 11-A quantifies particles in 31-size bins from 0.25 to 32 µm with a maximum mass concentration detection limit of 10⁹ µg m⁻³. The C-factor of 1 was set as the default value. The sampling parameter settings are shown in Table 1. Two sampling periods were selected to represent the winter (January 6–12, 2020) and summer (August 25–31, 2020). The HVAC system was on during the whole sampling periods. The daily sampling started from 8:00 am to 7:00 pm, covering the peak periods of airport flights.

2.2 Quality Assurance and Quality Control (QA/QC)

In this study, we collected both indoor and outdoor samples using the same types of equipment so that the results were readily comparable thus I/O ratios could be reliably estimated. The comparability of the indoor and outdoor samplers had been tested before the sampling campaigns, and the substantial similarity of the measurements had been confirmed. To verify the accuracy of the data recorded by the instruments, we compared it with the data measured by a sampling station (117°21′54.84″, 39°8′35.08″), which is around Tianjin Airport Traffic Station (TATS).
Fig. 1. (a) Locations of the indoor and outdoor sampling sites in the TSN terminal buildings. Blue dot: outdoor sampling site; red dot: indoor sampling sites (ten sampling sites on each floor). (b) The Outdoor sampling site. (c) Sampling device No. 4 in departure hall of T1 terminal building. (d) Vertical layers of T1 and T2 terminal buildings.

Table 1. Grimm11-A sampling parameter settings.

<table>
<thead>
<tr>
<th>parameter</th>
<th>Value or range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sampling flow (L min$^{-1}$)</td>
<td>1.2</td>
</tr>
<tr>
<td>PTFE Filter membrane (mm)</td>
<td>47</td>
</tr>
<tr>
<td>Sampling interval ()</td>
<td>60</td>
</tr>
<tr>
<td>Operating temperature ($^\circ$C)</td>
<td>4-40</td>
</tr>
<tr>
<td>Mass concentration range ($\mu$g m$^{-3}$)</td>
<td>$0.1-1 \times 10^5$</td>
</tr>
<tr>
<td>Particle number concentration range</td>
<td>$1-2 \times 10^5$</td>
</tr>
</tbody>
</table>

The station is located on the northeast side of the airport runway, about 200 m away from the nearest runway as shown in Fig. S1. The area around the sampling site is open with no other pollution sources but aircraft emissions. The temperature, relative humidity (RH), wind speed
(WS), and wind direction (WD) at the sampling station during the measuring periods are shown in Fig. S2. The comparability between the hourly concentrations outdoor instrument and the sampling site passed correlation check.

2.3 Indoor-outdoor Relationship Methods

Indoor measurements reflect contributions from both particles generated indoors and particles of outdoor sources that infiltrate indoors. The research on the indoor-outdoor relationship methods of PM began in the 1990s by means of measuring the mass concentration of PM. Correlation analysis, I/O ratio and \( F_{\text{inf}} \) are three commonly used methods to analyze the indoor-outdoor relationship methods of PM (Chen and Zhao, 2011).

I/O ratio is a simple and useful parameter to qualitatively analyze the level of indoor PM affected by outdoor sources. I/O ratio is calculated as follows:

\[
\frac{I}{O} = \frac{C_{\text{in}}}{C_{\text{out}}}
\]

where \( C_{\text{in}} \) is the indoor PM mass concentration, \( C_{\text{out}} \) is the outdoor PM mass concentration.

\( F_{\text{inf}} \) is the equilibrium fraction of ambient particles that penetrate indoors and remains suspended which avoids the mixture with indoor particle sources. Eq. (2) is derived from a more complex mass-balance model including parameters taking the indoor-outdoor air exchange rate, penetration efficiency, and particle deposition rate into account (Chen and Zhao, 2011; Hänninen et al., 2004). After measuring the indoor and outdoor particle concentrations under different conditions, \( F_{\text{inf}} \) (the slope) and \( C_s \) (the intercept) can be calculated using the regression of indoor concentration against the outdoor concentration (Ott et al., 2000; Hoek et al., 2008).

\[
C_{\text{in}} = \frac{\rho \cdot \alpha}{\alpha + k_d} C_{\text{out}} + \frac{S/V}{\alpha + k_d} = F_{\text{inf}} \times C_{\text{out}} + C_s
\]

where \( \rho \) denotes the particle penetration factor, \( \alpha \) denotes the air exchange rate due to infiltration; \( k_d \) denotes the particle deposition rate; \( S \) denotes the indoor particle emission rate; \( C_{\text{in}} \) denotes the indoor particle concentration; \( V \) denotes the volume of the room; \( C_{\text{out}} \) denotes the outdoor particle concentration; \( F_{\text{inf}} \) denotes the infiltration factor; \( C_s \) denotes the indoor particle concentration which is contributed by indoor sources.

2.4 Exposure Assessment Method

Comprehensive exposure refers to the total exposure of humans to PM in different environments over a given period. The PM concentrations in the environment and the duration of exposure have a significant impact on the amount of exposure. Considering longer wait-times (usually 1 hour or more) of the passengers in the terminal buildings and the premature death problems due to PM exposure, the potential health risks are supposed to be quantified. In this study, the comprehensive exposures of PM (EP) in different indoor microenvironments (arrival halls and departure halls) were estimated using a modified version of the previous approach (Boisa et al., 2014; Liu et al., 2019):

\[
EP = \int_{t_1}^{t_2} PM(t) \times dt \times TR
\]

where \( PM \) is the concentration of airborne particles in the indoor microenvironment, and PM\(_{2.5}\) concentrations in TSN terminal buildings were used for calculation; \( TR \) is the tracheobronchial retention, and a value of 75% (SFT, 1999) was used in this research; \( t_2 - t_1 \) is the exposure duration, and a value of 2 h was applied according to passengers’ waiting time on average in terminal buildings (Hafizogullari et al., 2002).

Respiratory deposition dose (RDD) has been intensively used to assess the health risks of human exposure to PM ambient atmosphere. Here we used RDD to examine the level of exposure.
of passengers to PM during waiting for the plane. RDD is an integrated exposure-risk function of the exposure concentration, deposition fraction (DF), and duration time (T) spent in each activity as well as breathing frequency (f) and tidal volume (TV) for the different activities. Calculation of RDD is as follows:

$$RDD = PM_i \times DF_i \times V_T \times f \times T$$  \hspace{0.5cm} (4)$$

$$DF = IF \times \left[ 0.058 \frac{0.911}{1 + \exp(4.77 + \ln(dp))} + \frac{0.943}{1 + (\exp(0.508 - 2.58 \ln(dp)))} \right]$$  \hspace{0.5cm} (5)$$

$$IF = \left[ 1 - 0.5 \left( 1 - \frac{1}{1 + 1.00076 \cdot dp^{1.8}} \right) \right]$$  \hspace{0.5cm} (6)$$

where PM$_i$ represents the mass concentration of PM with particle size < i µm (i = 1, 2.5, 10); DF$_i$ represents the deposition fraction of PM$_i$, which is calculated as the median particle size (dp) of the particulate matter of interest (He and Gao, 2021), the mean dp diameter is 0.4, 0.45, and 4 µm; VT is the tidal volume of people, which is set as 1250 cm$^3$ per breath for adults (Sanchez-Soberon et al., 2015); the breath frequency; f, is set as 20 breaths per minute for adults, respectively; T is the duration of exposure.

3 RESULTS AND DISCUSSION

3.1 Pollution Characteristics

The average indoor and outdoor concentrations of PM measured at the TSN terminal buildings in winter and summer are illustrated in Fig. 2. The indoor average concentrations and standard deviations (SD) of PM$_{1}$, PM$_{2.5}$ and PM$_{10}$ during the whole sampling periods were 22.0 ± 13.9, 25.3 ± 16.2 and 33.6 ± 22.4 µg m$^{-3}$, respectively. The PM$_{2.5}$ (25.3 µg m$^{-3}$) and PM$_{10}$ (33.6 µg m$^{-3}$) concentrations on average exceeded the limit values set by the World Health Organization (WHO, 2021), which are 5 and 15 µg m$^{-3}$, respectively, by 5.03 and 2.24 times. The averaged concentrations of outdoor PM$_{1}$, PM$_{2.5}$, and PM$_{10}$ were 38.9 ± 25.6 µg m$^{-3}$, 45.8 ± 28.1 µg m$^{-3}$ and 67.5 ± 32.1 µg m$^{-3}$, respectively, about 2 times more than the indoor concentrations. The outdoor PM concentrations in winter were generally higher than those in summer, which can be observed in Table S1. This depends on many factors, such as heating and unfavorable meteorological conditions (referring to meteorological conditions that were not conducive to the diffusion of pollutants, and were
Fig. 3. Particle size distribution in the terminal buildings and outdoors. (a) Arrival halls; (b) Departure halls.

favorable for pollutant accumulation or secondary formation) in winter. Moreover, the seasonal difference in concentrations was more pronounced indoors, with indoor PM concentrations approximately doubling in winter than in summer (Table S1). It is worth noting that the averaged indoor concentrations in summer are relatively low. The reason could be the reduction in the number of passengers and the closure of catering services in terminal buildings due to the lockdown during COVID-19 (a 44.2% decrease in passenger turnover and a 31.0% decrease in take-offs and landings in TSN in 2020 (CAAC, 2021).

The departure halls of T1 and T2 are connected by a gallery and are more available for air exchange. Thus, the difference in PM concentrations between the two terminal buildings was smaller in the departure halls (the concentrations in T2 are 0.33–0.41 times higher than in T1) than in the arrival halls (the concentrations in T2 are 0.43–0.53 times higher than in T1) during the whole sampling periods. For different halls, the average concentrations of PM1, PM2.5 and PM10 were higher in arrival halls (25.0 ± 16.5 µg m⁻³ for PM1, 34.5 ± 21.2 µg m⁻³ for PM2.5, 35.8 ± 21.4 µg m⁻³ for PM10) than in departure halls (19.1 ± 15.2 µg m⁻³ for PM1, 26.5 ± 17.2 µg m⁻³ for PM2.5, 31.4 ± 20.9 µg m⁻³ for PM10) during the whole sampling periods, as the arrival halls are located in the first floor of the terminal buildings so vehicle and airliner activities contribute to the air pollution to a larger extent (Fig. 2).

As for number concentration, the particle size distribution less than 1 µm of indoor and outdoor particle concentrations in the TSN terminal buildings is shown in Fig. 3. Significant differences in the distribution of particles less than 1 µm in size of indoor and outdoor PM were observed. The outdoor number concentration decreased with the increasing particle size, with a peak number concentration at a particle size of about 0.25 µm (the smallest size bin of our instruments). For indoor terminal buildings, sharp variation of indoor PM number concentrations existed in particles within the range of 0.25–0.40 µm in size, with a peak number concentration at a particle size of about 0.30 µm in the departure and arrival halls of the TSN terminal buildings.

In the departure halls, the averaged indoor number concentration was 46.9% higher than outdoor, the concentration was 26.7% lower in the arrival halls than outdoor. The maximum value of number concentration (Dp = 0.30 µm) was 1.958 × 10⁵ cm⁻³ in the departure hall, 46.8% lower than that in the arrival hall, with the number concentration of 3.685 × 10⁵ cm⁻³. The minimum number concentration appeared in particle size around 1.0 µm, suggesting that particles with a particle size < 1 µm had a more significant impact on indoor air quality. For different halls, the number concentrations of particles of the same size in the arrival halls were generally higher than those in the departure halls, providing further evidence of the significant impact of aviation and vehicle emissions.

3.2 Source Identification in TSN Terminal Buildings

The correlation heatmap of indoor and outdoor concentrations of different particulate matters in different sampling periods is illustrated in Fig. 4. Indoor and outdoor PM concentrations were highly correlated, with the Spearman correlation coefficient (r) in the TSN terminal buildings varying from 0.62 to 0.98 in each sampling period, especially during summer sampling period (r = 0.97
for PM₁ and r = 0.98 for PM_{2.5}, respectively). Furthermore, the correlation coefficient of PM_{2.5} and PM₁₀ between the outdoor site and TATS were 0.85 and 0.65 with p value less than 0.01 (Fig. S3), indicating aircraft activity should be the potential source of pollution. For different halls, the r between arrival/departure halls and outdoor PM concentrations were generally above 0.5 with p value less than 0.05, except for those involving PM₁ and PM_{2.5} concentrations between arrival halls and outdoors in winter, which showed a relatively poor correlation (PM₁: r = 0.42; PM_{2.5}: r = 0.45). Furthermore, higher correlation rates between arrival/departure halls and outdoor PM concentrations were observed in summer compared to those in winter.

In addition, the I/O ratios and infiltration factors are applied to investigate the indoor-outdoor relationship in the TSN terminal buildings. During the whole sampling periods, the average values of I/O ratios were 0.55 ± 0.27, 0.47 ± 0.25, 0.47 ± 0.24 for PM₁, PM_{2.5}, and PM₁₀, respectively, indicating the I/O of PM₁ was higher than PM_{2.5} and PM₁₀. Generally, the I/O ratios of PM₁₀ were always lower than those of PM₁ and PM_{2.5} during the whole sampling periods, due to the characteristics of penetration coefficient and deposition rate, which is shown in Table S2. Fig. 5 shows the boxplots of I/O ratios for PMs in different halls of the TSN terminal buildings in different periods. The I/O ratios were generally higher in winter than those in summer, which is consistent with previous findings (Ferrero et al., 2011a, 2011b, 2010). The average I/O ratios of the terminal buildings were 0.48–0.70 in winter and 0.33–0.54 in summer (Fig. 5), indicating that indoor PM concentrations in the TSN terminal buildings could possibly be affected by the outdoor air pollution sources. During winter sampling period, the I/O ratio of PM₁₀ (0.62 ± 0.28) was slightly higher than that of PM₁ and PM_{2.5} (0.59 ± 0.31, 0.59 ± 0.26). However, apparently higher I/O ratios of PM₁ compared with PM_{2.5} and PM₁₀ emerged during the summer period, as foreseen by previous studies (Hussein et al., 2005; McAuley et al., 2010). The I/O ratios of PM_{2.5} were generally higher in the arrival halls (0.68 and 0.54 on average in winter and summer, respectively) than those in the departure halls (0.58 and 0.44 on average in winter and summer, respectively) in the TSN terminal buildings, which is consistent with the mass concentrations discussed in Section 3.1. For the I/O ratios of PM₁₀, a similar trend was observed, with 0.62 (winter) vs. 0.46 (summer) in the departure halls and 0.56 (winter) vs.0.44 (summer) in the arrival halls.

To further explore the sources of indoor pollutants and quantify the contribution of outdoor sources to indoor PM₁, PM_{2.5}, and PM₁₀ concentrations, the infiltration factor (F_{inf}) method was applied. Fig. 6 illustrates the results of linear regression with the observed concentrations in TSN terminal buildings. In general, F_{inf} (i.e., the slope of the linear regression line) were 0.85 ± 0.15, 0.62 ± 0.16, and 0.51 ± 0.22 for PM₁, PM_{2.5} and PM₁₀ in the TSN terminal buildings during the whole sampling periods (Fig. 6(a)). As for another important measure, R^2, in determining the degree of linear correlation of variables (“goodness of fit”), the values are 0.87, 0.87 and 0.71. This means that 87%, 87%, and 71% of the variation in total indoor PM₁, PM_{2.5}, and PM₁₀ concentrations can be explained by outdoor sources. Generally, PM₁ had the highest absolute F_{inf} and PM₁₀ had the lowest absolute F_{inf} (Fig. 6(a)), indicating that PM with smaller particle sizes were more likely to enter the indoor environment from the outdoor, which is consistent with the I/O ratios results.
Fig. 5. Box-plots of I/O for PMs in (a) winter and (b) summer. AH: arrival halls; DH: departure halls.

Fig. 6. Linear Regression Plots of indoor and outdoor concentrations for PM$_{1}$, PM$_{2.5}$, and PM$_{10}$. The slope of the linear regression line represents $F_{in}$ and the intercept of the linear regression line represents $C_{s}$; (a, d, g) The whole sampling periods; (b, e, h) Winter; (c, f, i) Summer; (a, b, c) indoor of TSN terminal buildings; (d, e, f) arrival halls; (g, h, i) departure halls.
Significantly higher $R^2$ were observed in summer than those in winter in the TSN terminal buildings (Figs. 6(b) and 6(c)), indicating that outdoor sources contributed more to the indoor environment compared to indoor sources during summer sampling period. This phenomenon was more pronounced in the departure halls, with $R^2 (F_{in})$ of 0.97 ($0.75 \pm 0.12$), 0.97 ($0.66 \pm 0.18$), and 0.89 ($0.50 \pm 0.26$) for PM$_{1}$, PM$_{2.5}$ and PM$_{10}$ (Fig. 6(g)) during summer sampling period. As a result, more than half of outdoor PM with particle size less than 2.5 µm could enter the departure halls. Moreover, the negative $C_s$ (i.e., the intercept of the linear regression line, indicating the indoor-generated particles, with the values of $-6.9 \pm 5.8$, $-3.8 \pm 3.7$, and $-3.5 \pm 3.2 \mu g m^{-3}$ for PM$_{1}$, PM$_{2.5}$, and PM$_{10}$, respectively) in the departure halls during summer sampling period (Fig. 6(i)) also indicated that indoor sources had a very limited contribution to the PM mass concentration. Nevertheless, the $R^2$ were always less than 0.3 in different halls of the TSN terminal buildings during winter sampling period, suggesting that the indoor sources contributed more to the indoor environment than the outdoor sources. This was also proved by the higher $C_s$ and lower $F_{in}$ in winter than in summer (Figs. 6(b), 6(e), and 6(h)). One of the main reasons for this phenomenon was the heating and unfavorable ventilation conditions in winter.

### 3.3 Exposure Assessment

In view of the high PM pollution caused by heating and unfavorable ventilation conditions, the PM exposure in winter had a greater impact on passengers and employees staying in the terminal buildings. Therefore, taking winter as an example, the PM$_{2.5}$ exposure of passengers in the TSN terminal buildings was derived, and the comprehensive exposure of PM$_{2.5}$ in the TSN terminal buildings was compared with other indoor areas investigated in related studies, as shown in Table 2. The comprehensive exposures of PM$_{2.5}$ in TSN terminal buildings were 65.3 and 78.8 µg m$^{-3}$ in the departure halls and arrival halls during winter sampling period, respectively. The comprehensive exposures in the TSN terminal buildings are higher than those in the transportation microenvironments ($18.6 \mu g m^{-3}$), residences ($20.1$–$40.4 \mu g m^{-3}$), a research center ($45.5 \mu g m^{-3}$), and offices ($31.8$–$43.8 \mu g m^{-3}$). Moreover, PM$_{2.5}$ maximum exposure can reach $112.9 \mu g m^{-3}$ in winter, which may lead to potential respiratory diseases for passengers and employees staying in the terminal buildings for a long time. Variable ventilation conditions are a direct factor affecting exposure, mainly affecting indoor PM concentrations by affecting the indoor and outdoor air exchange rates (Morawska et al., 2001; Cyrys et al., 2004). In a naturally ventilated indoor environment, pollutants are more likely to enter the room with the ventilation airflow due to the active indoor and outdoor air circulation and higher air exchange rate (Klinmalee et al., 2009). Nevertheless, ventilation mainly relies on indoor air circulation in a mechanically ventilated environment, resulting in a relatively lower air exchange rate and infiltration factor (Ho et al., 2004; Goyal and Kumar, 2013).

To further quantify the health risks of long-time exposure to PM$_{1}$, PM$_{2.5}$, and PM$_{10}$, RDD has been applied. Given that adults are assumed to breathe a total of 20 times per minute and on average when waiting aboard. The exposure to PM concentrations will be different when passengers wait aboard for varied durations. Owing to these parameters, the RDD values for PM$_{1}$, PM$_{2.5}$, and PM$_{10}$ during five exposure durations (40 min, 60 min, 80 min, 100 min, and 120 min) in winter and summer periods were collected, as illustrated in Fig. 7. Considerable variation in RDD of PM$_{1}$, PM$_{2.5}$, and PM$_{10}$ during the longer exposure durations (100 min, 120 min) were observed.

### Table 2. Indoor comprehensive exposures of PM$_{2.5}$ in summer in this study and other related studies

<table>
<thead>
<tr>
<th>Sampling site</th>
<th>Exposure [µg m$^{-3}$]</th>
<th>Ventilation</th>
<th>Reference</th>
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<td>TSN airport</td>
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<td></td>
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<tr>
<td>Departure Hall</td>
<td>65.3</td>
<td>HVAC</td>
<td>This study</td>
</tr>
<tr>
<td>Arrival Hall</td>
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<td></td>
</tr>
<tr>
<td>6 households in Harbin</td>
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<td>40.4</td>
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<td>Liu et al., 2022</td>
</tr>
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<td>Deng et al., 2017</td>
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Fig. 7. Variations in PM$_1$, PM$_{2.5}$, and PM$_{10}$ RDD for different exposure durations in the TSN terminal buildings during the sampling periods. X-axis: Exposure start time; y-axis: Exposure duration; z-axis: Respiratory deposition dose (RDD).
Nevertheless, the variation of PM1, PM2.5, and PM10 during the shorter exposure durations remained stable. The average RDD in winter (87.5, 105.4, and 145.2 for PM1, PM2.5 and PM10 when waiting for 120-min) were 67–97% higher than those in summer (50.9, 54.8, and 74.0 for PM1, PM2.5, and PM10 when waiting for 120-min). In addition, significant diurnal variations of RDD were observed under various exposure durations. In winter, the maximal RDD for PM2.5 and PM1 appeared at 8:00 LST, while the maximal RDD for PM10 appeared at 16:00 when passengers’ exposure duration reached 120 min. In summer, the maximal RDD for PM1, PM2.5, and PM10 appeared at 9:00 LST. It is suggested that passengers could reduce their waiting duration to reduce the PM exposure if possible. Moreover, passengers could choose to take flights at noon in winter and at night in summer when the RDD reached the minimum.

4 CONCLUSIONS

In this study, the characteristics of indoor PM pollution in the TSN terminal buildings were explored and the indoor particles were quantified through the on-site monitoring of PM. Combined with the standard parameters of the population breathing zone, the PM exposure of passengers and employees staying in the terminal buildings was quantitatively evaluated during two cases in winter and summer 2020. Our conclusions are as follows. During the whole sampling period, the indoor PM2.5 and PM10 concentrations on average exceeded the WHO limit values by 5.03 and 2.24 times. Higher indoor PM concentrations occurred were observed in winter than in summer. During winter sampling period, the indoor sources contributed more to the indoor environment than the outdoor sources with relative higher $C_s$ and lower $F_{inf}$, whereas the opposite was found during summer case. Sharp variation of indoor PM number concentrations existed in particles within the range of 0.25–0.40 µm in size, with a peak number concentration at particle size of about 0.30 µm. PM with smaller particle sizes (less than 2.5 µm) were more likely to enter the indoor environment from outdoors. The comprehensive exposure in the TSN terminal buildings was higher than those in the transportation microenvirons, residences, and other buildings. Moreover, considerable variation in RDD of PM1, PM2.5, and PM10 during the longer exposure durations existed. The averaged RDD in winter were 67—97% higher than those in summer. The maximal RDD for PM2.5 and PM1 appeared at 8:00 LST, while the maximal RDD for PM10 appeared at 16:00 when passengers’ exposure duration reached 2h in winter, however, the maximal RDD for PM1, PM2.5, and PM10 appeared at 9:00 LST in summer.

Several suggestions are offered in this study. First, passengers should select to take flights at noon in winter and at night in summer when the RDD reached the minimum, and reduce the waiting duration if possible. Secondly, due to the impact of COVID-19, the passenger flow is significantly lower than in other years (especially in T1), so that greater uncertainty existed during the summer sampling period. Moreover, additional episodes are required for statistical significance. Nevertheless, this study still provides valuable information on the impacts of PM on indoor air quality in airport terminal buildings, which is helpful for decision-making in heavy pollution emergencies.

ACKNOWLEDGMENTS

This work was financially supported by the National Natural Science Foundation of China (No. U2133206, U1933110) and the Fundamental Research Funds for the Central Universities (No. 3122022PT04).

SUPPLEMENTARY MATERIAL

Supplementary material for this article can be found in the online version at https://doi.org/10.4209/aaqr.220357

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