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State-space analysis of influencing factors on airborne particle concentration in aircraft cabins

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ABSTRACT

Epidemiological studies have shown that exposure to airborne particles is strongly associated with human health. Air quality concerns in aircraft cabins increase as air travel is becoming more common. Analyzing factors that influence the concentrations of airborne particles and taking mitigating measures will protect human health during air travel. In this study, concentrations of particles larger than 0.3 μm were measured in aircrafts' supply air in 9 flights. Air change rates were evaluated by the concentration of CO_2 in supply air and recirculation air. Human emission, deposition and resuspension of particles were analyzed with our previously published results. The state-space method was used to calculate time-dependent particle concentration in different particle diameter intervals. Afterwards, with variation ranges of the 5 factors above, deviation rates of particle concentration were defined to evaluate the importance of those factors. This study determined: 1) resuspension is not an important factor, especially as time elapses; 2) varied deposition rate slightly influences particles smaller than 5.0 μm; 3) air change rate and human emission rate strongly impact the concentration of particles smaller than 2.0 μm; 4) supply air concentration generally affects the concentration of larger particles.

1. Introduction

As air travel is getting very common, the risk of transmitting infectious diseases becomes a more important public health issue [1–3]. Numerous epidemiological studies have found a strong exposure–response relationship between particulate matter (PM) and health effects including morbidity, lung cancer, cardiovascular and cardiopulmonary diseases [4–8]. The environment in aircraft cabin is susceptible to infections from particles such as droplets exhaled by an infected passenger [1,9]. Decreasing the airborne particle concentration may lower the risk of disease transmission. Thus, obtaining a clear understanding of important factors on particle concentrations is essential for improving cabin air quality and decreasing the risk of infection.

Air cabin studies conducted when smoking was allowed showed that the main particle source was cigarettes [10–12]. Although currently smoking is forbidden and no longer a major factor on air quality, other pollutant sources need to be investigated. In the aircraft cabin's ventilation system, outside air (bleed air) is ventilated into the cabin and mixed with filtered recirculation air. We find that the outside air is unfiltered and contains pollutants such jet engine exhaust. Thus particles originating from the aircraft engines [13] and ambient air may be delivered to the cabin. O'Donnell et al. [14] studied 45 flights of the same aircraft type. The total particulate levels (average 105 $\mu g/m^3$) exceeded the comfort criteria (75 $\mu g/m^3$), including non-smoking flights. Measurements in 2012 also indicated that the air quality in aircraft cabins may not be satisfactory [15].

The important parameters (air exchange rate, particle concentration of supply air, etc.) and their variation ranges in the cabin have not been measured or investigated in depth; hence the purpose of this study is to evaluate the importance of determining factors for particle concentrations in aircraft cabins. The results of this study will aid in developing appropriate mitigating measures to improve the comfort and health of passengers and crew.

2. Measurements and parameters

Particle concentrations in supply air are determined by conducting field tests during 9 different flights. CO_2 concentrations in both supply air and exhaust air are also measured during 5 of the 9 flights. The CO_2 measurements are used to determine air change rate. Particle deposition, resuspension, and people's emission rate are based on our previous research as below. The variation ranges of parameters are substituted into the state-space model to calculate the general particle concentrations in the cabin.

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Nomenclature

A (m^2)	Floor area of cabin
$\boldsymbol{A}$	State matrix
$\boldsymbol{B}$	Input matrix
$\boldsymbol{C}(t_k)$	Concentration vector of particles at time t_k, state vector
$C_i(t_k)$ (N/L)	Concentration of particle with index i at time t_k
$\dot{C}_i\ (t_k)$ (N/(L s))	Change rate of concentration of particle with index i at time t_k
$C_{R,CO_2}(t)$ (ppmv)	CO_2 concentration of recirculation air at time t
$C_{S,CO_2}(t)$ (ppmv)	CO_2 concentration of supply air at time t
$C_{S,i}(t_k)$ (N/L)	Particle (size i) concentration of supply air
d_p (μm)	Particle diameter
$D_{j,\max}$	Deviation rate due to maximal parameter symbol j (including k_d for deposition, k_m for air change rate, s for particle concentration of supply air, N_i for human emission, R for resuspension)
$D_{j,\min}$	Deviation rate due to minimal parameter symbol j
i	Size index of particle
j	Index of parameters
$k_{d,i}$ (1/s)	Deposition rate of particle with size index i
k_m (1/s)	$k_m = Q(t)/V$, air change rate
$\dot{m}$ [m^3/(s·person)]	CO_2 generation rate per person
m_i (N/L)	$m_i = M_iA/V$
M_i (N/m^2)	Particle load of the cabin floor
n	The number of passengers and crews in cabin
N_i (N/(L s))	Human emission rate of particle with size index i
$\boldsymbol{p}$	Parameter vector
$Q(t)$ (m^3/s)	Total airflow rate at time t
$R(t)$ (1/s)	Particle resuspension rate
t (s)	Time
u_* (m/s)	Friction velocity of airflow
$\boldsymbol{u}$ (t_k)	Input vector
V (L)	Cabin volume
z_0 (m)	Aerodynamic roughness length
ρ_p (kg/m^3)	Particle density

Each field test was conducted in a Boeing 737-800 airplane. Personalized air supply outlets are located on the top of each seat, and air outlets at the bottom of the cabin.

The parameters are evaluated in 5 particle size intervals (0.3–0.5 μm, 0.5–1.0 μm, 1.0–2.0 μm, 2.0–5.0 μm, 5.0–10.0 μm). Accordingly, the representative diameters of particles are 0.4 μm, 0.75 μm, 1.5 μm, 3.5 μm, 7.5 μm as Zhou et al. [16].

2.1. Measuring equipment

Particle concentration of supply air, CO_2 concentrations of supply air and recirculation air were measured. Particle concentrations were measured with Fluke 983 Airborne Particle Counter (FLUKE Corporation, USA) which is able to simultaneously measured and recorded number particle concentrations in six different channels of particle sizes (0.3–0.5 μm, 0.5–1.0 μm, 1.0–2.0 μm, 2.0–5.0 μm, 5.0–10.0 μm and ≥10.0 μm). To meet the equipment's optimal operation criteria, during measurement the pressure was maintained at more than 48 kPa and the humidity is less than 95%. The setting flow rate of the Fluke 983 was 2.83 L per minute.

TELAIRE 7001 CO_2 Monitor (General Electric Company, USA), insensitive to pressure, was used to test CO_2 concentration. Detection limit and threshold of the monitor are 0 and 10,000 ppm, respectively.

2.2. Measurements of particles and CO_2 concentration

Field measurements of particle and CO_2 concentrations in domestic flights were conducted from Sept. 17, 2012 to Mar. 10, 2013. Nine randomly selected domestic flights were tested, and the flights' information is provided in the Supplementary information Table SI.1. Among these flight routes, the northernmost and easternmost city is Harbin, the southernmost city is Shenzhen, the westernmost city is Urumchi; thereby, the large scope represents diverse locations within China. See Fig. 1. The flight durations range from 1 h 27 min to 3 h 50 min. Particle concentration of supply air was measured during the 9 flights. In addition, CO_2 concentrations in the supply air and recirculation air were tested in 5 of 9 flights.

Throughout the duration of the flight, particle concentrations were collected approximately every 85 s. Linear interpolation is used to estimate values for every second to calculate particle concentrations in the cabin of each flight. CO_2 measurements were recorded every 30 s. See Section 2.4 for procedure for using the CO_2 concentrations to calculate the air change rate.

2.3. Evaluation of particle concentration of supply air

The variation of particle concentration of supply air was determined using the maximum, minimum and the arithmetic average of the test results. An overall average for the 9 flights was derived using each individual flight's average. This assumes the weight of each flight is equal despite differing flight durations. The results are shown in Table 1.

The frequency distribution of the supply air particle concentration is similar for all 5 particle size groups. The supply air particle concentration for 0.3–0.5 μm particles is shown in the Supplementary information Fig. SI.1 as a representative for all particle intervals. These results show that the distribution is left-skewed. That's because higher concentrations occur only as the aircraft ascends and descends through the clouds, but those two phases are relatively shorter than the cruising phase. As shown in

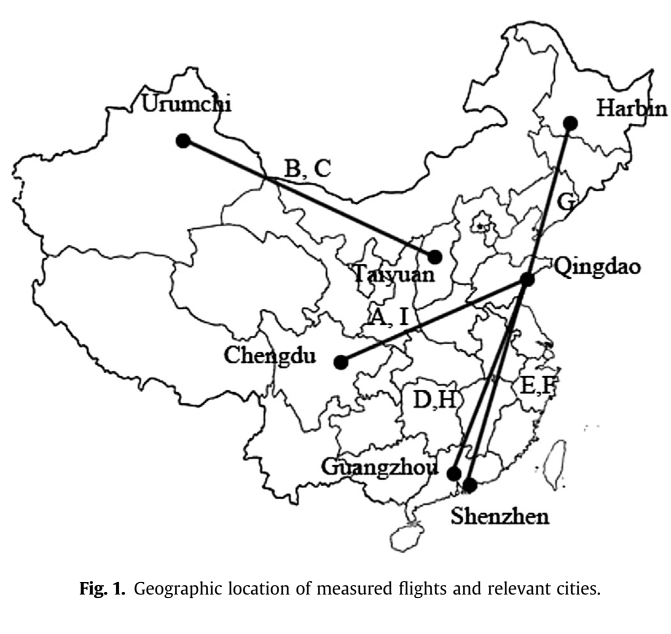

Fig. 1. Geographic location of measured flights and relevant cities.