# Investigation of the Performance of Airliner Cabin Air Filters throughout Lifetime Usage

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## ABSTRACT

The air supply from an airliner ventilation system is a mixture of outside air and recirculated air that passes through a high efficiency particulate air (HEPA) filter. The effectiveness of two commercial-available airliner cabin air filters were investigated in laboratory-based measurements due to the practical restrictions on airliner cabin filter testing during usage. The filtration efficiency and pressure drop were assessed at a particle size range of 20–500 nm under various airflow rates throughout the filter usage period. The Most Penetrating Particle Sizes (MPPS) were observed at ~150 and ~55 nm, where the filtration efficiency was 86% and 99% at the rated airflow rates (1600 $m^3$/h and 1970 $m^3$/h), respectively. The filtration efficiency decreased in response to the increased airflow rate from 1000 $m^3$/h to 2200 $m^3$/h, with the greatest reduction (~10%) occurring at MPPS. An increase of 250 Pa in the pressure drop across the filter was observed as the airflow rate increased from 1000 $m^3$/h to 2200 $m^3$/h. Increased filter usage led to increases in both filtration efficiency and the pressure drop. The actual filter usage was estimated using dust loading in the laboratory. Filtration efficiency increased ~10% and the pressure drop increased ~800% when 220 $g/m^2$ dust was loaded on the filer, corresponding to ~6000 hours filter usage at an in-cabin $PM_{10}$ concentration of 100 $\mu g/m^3$. Explicit relationships among filtration efficiency, pressure drop and filter usage under various in-cabin particle concentrations are presented as a reference to facilitate the use of more appropriate airliner cabin air filter exchange periods.

*Keywords:* In-cabin particles; Particle filtration; Dust loading; Filtration efficiency; Pressure drop.

## INTRODUCTION

A large number of epidemiological studies have shown positive associations between exposure to atmospheric particulate matter (PM) and various adverse health effects, including respiratory and cardiopulmonary effects (Delfino *et al.*, 2005; Pope and Dockery, 2006; Bai *et al.*, 2007). Previous experimental studies have reported a high PM concentration (50–200 $\mu g/m^3$) due to some routine activities (e.g., food serving) in the filter-equipped aircraft cabin environment (Nadga *et al.*, 1992; Dechow *et al.*, 1997; Lee *et al.*, 1999; Lindgren and Norback 2002). Besides PM, pathogenic aerosol particles (d < 300 nm) are more concerned in the enclosed airliner cabin environment. To reduce passengers' exposure to particulate pollutants, most of aircraft environmental control systems have been installed with

high efficiency particulate air (HEPA) filters (Hocking 2000). According to Federal Aviation Administration (FAA) and other organizations' instruction (FAA Title 14; ANSI/ASHRAE Standard 161), air filters are mandatory to be equipped for all the commercial aircrafts. According to different airliners' maintenance manuals, the cabin filters' change period varies from 3600–6000 hours without in-between tests. It is essential to investigate the effectiveness of aircraft cabin air filters for removing UltraFine Particle (UFP) that is the representative of pathogenic particle within the same size range along the filter usage period.

To our best knowledge, few studies were conducted to evaluate the performance of airliner cabin air filters on in-cabin UFPs removal. In nuclear industrial application, Alderman *et al.* (2008) studied the performance of HEPA filter at a variety of filter face velocities with different dust loadings. Only several studies reported the UFP filtration for the vehicle cabin filters in response to the increasing concern for exposure to air pollutants in the transportation environment. Pui *et al.* (2008) reported a significant UFP concentration decrease with recirculated air filtration inside vehicle in-cabins. Qi *et al.* (2008) and Xu *et al.* (2011) found

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that the vehicle cabin air filters' filtration efficiency varied from 20% to 70% with the most penetrating particle size at ~350 nm. The filtration efficiency decreased by 10–20% in response to the filter face velocity increase from 0.1 to 0.5 m/s (Qi *et al.*, 2008; Xu *et al.*, 2011). Although previous studies provided pioneer research regarding to UFP filtrations in closed vehicle cabin environment, the effectiveness of airliner cabin air filters on UFP removal is still unknown. The understanding of airliner cabin filter's performance during the filter usage lifetime is even less. Few studies measured the filtration efficiency or pressure drop as a function of the filter usage.

This study attempted to fill this important knowledge gap by characterizing UFP filtration efficiency and pressure drop in response to the various airflow rates and filter usage levels. These data provided a basis for further in-depth studies on aircraft cabin air quality and ventilation system adjustment.

## METHODS

### Sample Filters and Testing System

The filtration efficiency and pressure drop were measured with two commercially-available cabin air filters that were manufactured for a McDonnell-Douglas aircraft (Model MD-82): a plate type filter with aluminum mini separator (Model KK2972941, Filter A, Donaldson Inc. USA) and a V shape filter without separator (Model CD00973F2, Filter B, Pall Inc. USA), as shown in Fig. 1. The test filters were 592 mm in width and 592 mm in length. The thicknesses of filters were 149 mm. Detailed characteristics of the test filters were shown in Table 1. Filter surface areas were calculated by multiplying the pleat number and the pleat

surface areas. Both of the test filters were made of glass fibrous media. Measurements were conducted in a Europe Standard EN-1822 classified testing system (European Standard High Efficiency Air Filters: EN 1822-5). Fig. 2 illustrated the schematic diagram of the testing system. A blower was used to extract ambient air through cabin air filter. Diethylhexylsebacate (DEHS) particles were generated from a three-jet Collison nebulizer (Model CN24j, BGI Inc. USA) and injected into the testing system. Arizona dust (A2), which is the standard dust for filter loading test, was generated by a dust generator (Model RBG 1000 CF, PALAS Inc. Germany) to load particle on the filters in order to investigate the effect of dust load on the filtration efficiency and pressure drop. A mesh air distributor was used to uniformly distribute the airflow and particle concentration on the cross section area of the test tunnel. Nine spots uniformly distributed on the filter surface were selected to check the uniformity of filter face velocity and UFP concentration. The data were collected until the filter face velocities and UFP concentrations were observed to be stabilized within 5% and 10% difference, respectively.

A nozzle airflow meter was used to measure and monitor the airflow rate. The nozzle airflow meter was calibrated according to ISO9300-2005 standard before the measurements. The airflow rate was recorded until the differences from 5 continuous measurements were less than 5%. A Scanning Mobility Spectrometer (SMS, Model PA1500, MSP Co. USA), which consists of a Differential Mobility Analyzer (DMA) and a Condensation Particle Counter (CPC), was used to measure particle concentrations in the 20–500 nm range alternately upstream and downstream of the test filter. When measuring the upstream particle concentration, an aerosol dilutor (Model 3302A, TSI Inc.



(a)                                                                                                      (b)
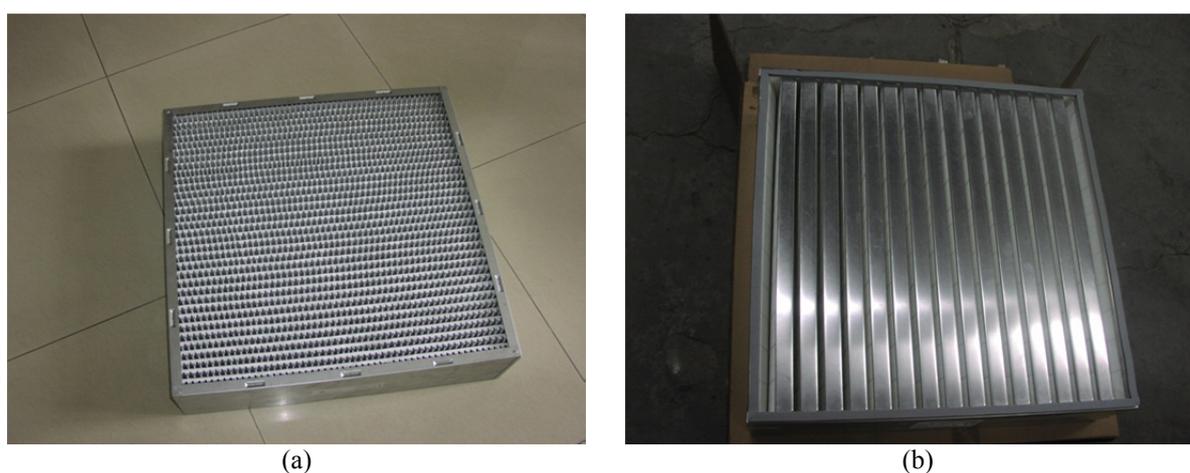
**Fig. 1.** Photographs of the measured filters: (a) plate type filter with aluminum mini separator (Model KK2972941, Filter A, Donaldson Inc. USA) and (b) V shape filter without separator (Model CD00973F2, Filter B, Pall Inc. USA).

**Table 1.** Information of the test filters in this study.

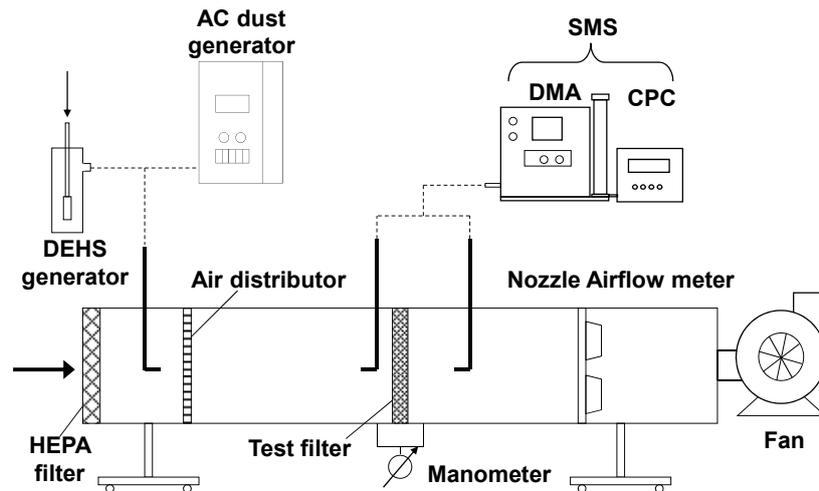|  | Make, Model | Rated airflow rate, m³/h | Marked filtration efficiency | Filter surface area, m² | Weight, kg |
|---|---|---|---|---|---|
| Filter A | Donaldson Inc. KK2972941 | 1600 | 90%-95% | 4.6 | 3.6 |
| Filter B | Pall Inc. CD00973F2 | 1970 | 99.99% | 8.9 | 6.3 |

**Fig. 2.** Experimental schematic of the filtration efficiency test systems.

USA) was employed at the sampling inlet of the SMS since the concentration was over the SMS's measure upper limit. The aerosol dilutor was calibrated at the sampling airflow rate of 0.5 L/m. The dilution ratios at different particle sizes were shown in Fig. 3. The filter efficiency, defined as "1 – downstream concentration/upstream concentration", was then calculated. SMS data were collected in 90-s intervals. The pressure drop across the filter was continuously monitored by a manometer (Manometer 475 Mark III, Dwyer Instruments Inc. USA) during the experiment. Prior to each measurement, the air tightness of the system was checked to verify that there is no particle leaking into the system from the ambient.

### Test Protocols and Data Analysis

The filtration efficiencies and pressure drops across the test filters were tested at five airflow rates (1000, 1300, 1600, 2000, and 2200 m³/h). This airflow range was selected to cover the most likely recirculated air flow rates under the actual flying conditions. The actual airflow rate through the filters varies due to the inconsistent engine power (e.g., flight ascending or descending) and uncontrolled recirculated air system press drop (e.g., additional personal air supply inside cabins). Dividing the airflow rates by filter surface area, the filter face air velocities of Filter A and B were calculated. For all five airflow rates, data collection started after particle concentrations reached a stable condition with a < 10% differences between two consecutive readings. Five consecutive concentrations were measured for either downstream or upstream under all experimental conditions. In the result section, the symbols in Figures represent the sample means, and the error bars represent the standard deviations.

The filtration efficiencies and pressure drop across the filter were measured continuously as the dust load increased. To investigate the filter performance throughout the filter usage lifetime, the filtration efficiency and pressure drop were expressed as a function of filter usage time. The filter usage time corresponding to the dust load levels was calculated by modifying a previously developed equation

for vehicle cabin filter (Xu *et al.*, 2011), as

$$T = P/(C \times Q \times \eta) \tag{1}$$

where T is the filter usage time (h), P is the dust load on the filter (g), C is the in-cabin particle concentration (g/m³), Q is the airflow rate (m³/h), and η is the filtration efficiency (-).

The measurement result of filtration efficiency and pressure drop were then linked to the filter usage time. It should be noted that the rapid dust loading characteristics in this study may be different from a steady loading in real-world condition. Thus, T represents estimated filter usage rather than exact practical flight time.

## RESULTS AND DISCUSSION

### Filtration Efficiency and Pressure Drop for Clean Test Filters

Fig. 4 shows their filtration efficiencies at five airflow rates (1000, 1300, 1600, 2000, and 2200 m³/h). Filtration efficiency demonstrated a characteristic "U" shape with a Most Penetrating Particle Size (MPPS) at approximately 150 nm for Filter A and 55 nm for Filter B, respectively. The U-shape curves were similarly observed from previous experimental studies (Qi *et al.*, 2008; Xu *et al.*, 2011) and theoretical simulation (Lee and Liu, 1982). Impaction and interception are the dominant filtration mechanisms for larger particles while diffusion is the dominant one for smaller particles. For Filter A, particles at a size of 150 nm are too large to be collected by diffusion but too small for interception and impaction to be effective (Hinds, 1999). The same principle applied to Filter B for the MPPS occurred at ~55 nm. These MPPSs were smaller than the previously reported results from building ventilation and vehicle cabin measurement studies (Xu *et al.*, 2011; Podgórski *et al.*, 2006; Leung *et al.*, 2010). This is because the fiber solidity of aircraft cabin air filter is higher than the filters that are used in building ventilation or vehicle ventilation systems. Larger solidity enhanced the particle collection by impaction but posed a negligible effect on the particle collection by
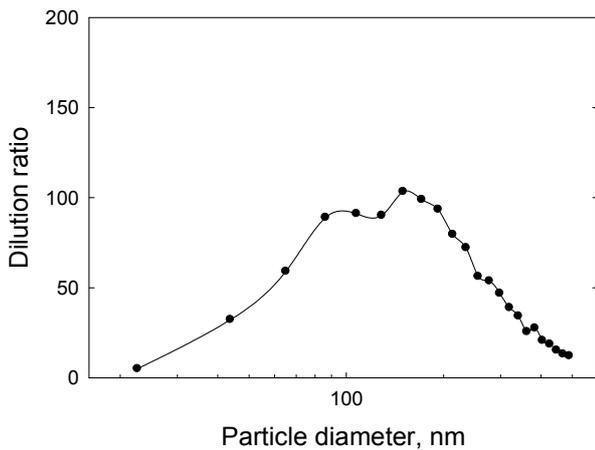
**Fig. 3.** Dilution ratios of the aerosol dilutor (Model 3302A, TSI Inc.) as a function of particle size.
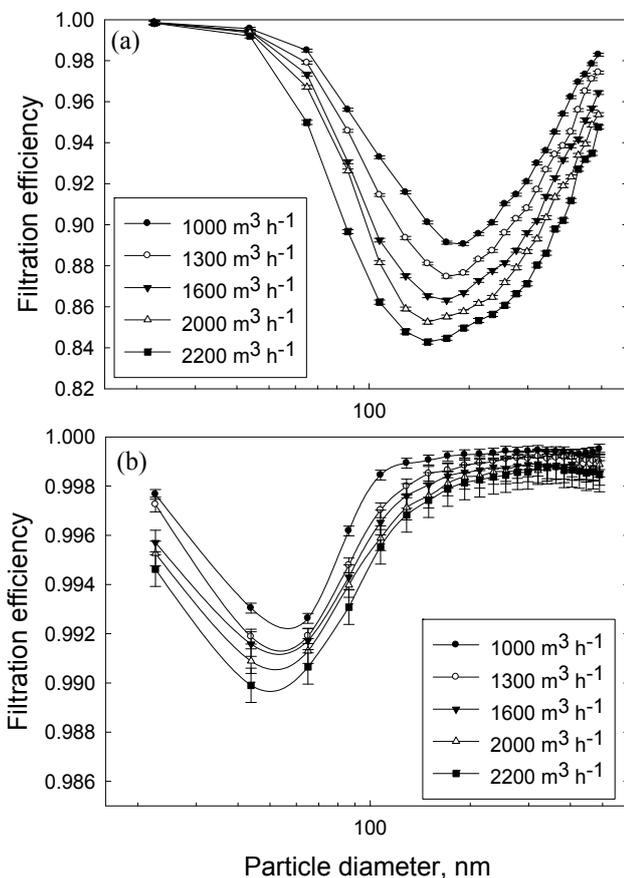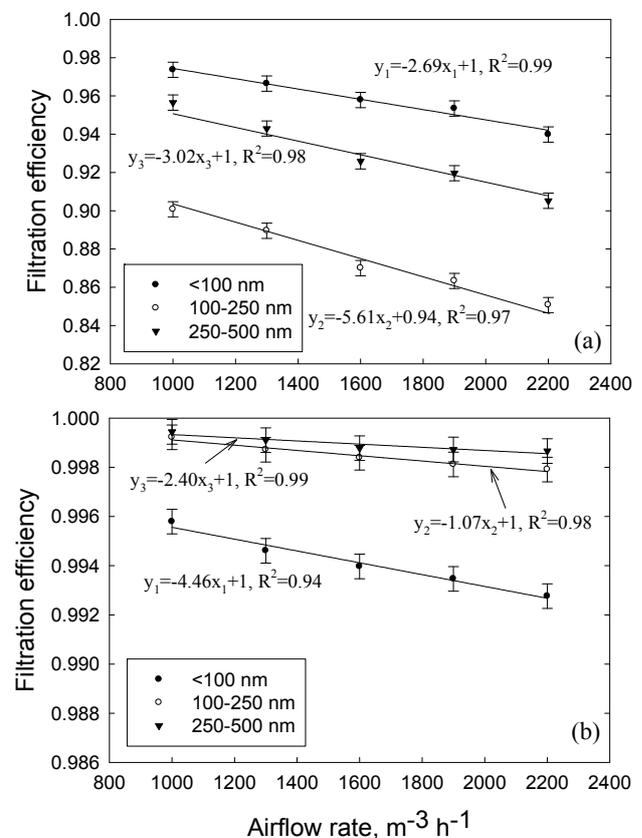


**Fig. 4.** Particle filtration efficiencies as a function of particle size at various airflow rates using (a) Filter A and (b) Filter B. Two filters were measured without dust loading.

increased airflow rate from 1000 m³/h to 2200 m³/h. Both Qi *et al.* (2008) and Xu *et al.* (2011) found the similar results in the wind tunnel and laboratory testing system.

To further evaluate the effectiveness of airliner cabin air filter for UFP filtration and extend the application of the result from this study to estimate the filtration performance of other airliner cabin air filters, the filtration efficiency as a function of airflow rate were linearly regressed in various UFP size ranges, as shown in Fig. 5. The filtration efficiency at the MPPS range (100–250 nm for Filter A; < 100 nm for Filter B) decreases in response to the increased airflow rate. Besides filtration efficiency, pressure drop (defined as the pressure gradient along the airflow direction across the filter) is another important parameter. Pressure drop directly affects the performance of the aircraft supply air system and the quantity of cabin fresh air intake. Fig. 6 illustrated the relationship between pressure drops and the airflow rate. The pressure drop increases in response to the increased airflow rate for both of the test filters. As the airflow rate increases from 1000 to 2200 m³/h, the increases of pressure drop across Filter A and B were 100 Pa and 250 Pa, respectively. It suggests that the cabin recirculated airflow rate might be decreased due to the increased filter pressure drop under some routine operation circumstances, like flight ascending with larger airflow rate introduced from the engine compressor.



**Fig. 5.** The relationship between filtration efficiency and airflow rate for different particle diameter ranges for (a) Filter A and (b) Filter B. Two filters were measured without dust loading.
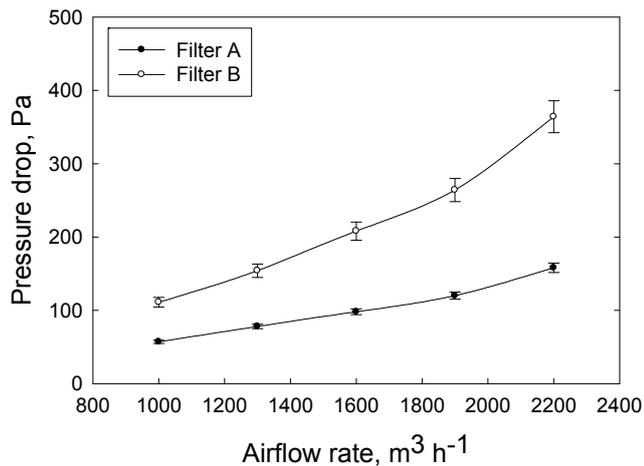
diffusion (Hinds, 1999). Therefore, the MPPS that represents the combined effect of impaction and diffusion decreased in response to the larger solidity. Fig. 4 also indicated that the total filtration efficiency is related to the airflow rate, which suggests that airflow rate is a primary contributor that affects the aircraft cabin UFP concentration levels. The filtration efficiency decreases up to 10% in response to

**Fig. 6.** Pressure drop across the cabin filter as a function of airflow rate. Two filters were measured without dust loading.

### *Filter Characteristics Change along Filter Usage Period*

The particles were consistently loaded in the filter during the filter usage which leads to the changes of various filter characteristics, including filtration efficiency and pressure drop. Filter A was used in this study to investigate these changes along the filter usage. Fig. 7 was the Scanning Electron Microscope (SEM) micrographs of the filters before (a) and after (b) 1000 g dust loading. The filter usage was determined by adopting the measured dust load into Eq. (1). The dust load on the test filter (P in Eq. (1)) was measured periodically; the upstream $PM_{10}$ concentration (C in Eq. (1)) in the aircraft cabin environment was adopted at a range of 50–250 µg/$m^3$ from the reported results (Nadga *et al.*, 1992; Dechow *et al.*, 1997; Lee *et al.*, 1999; Lindgren and Norback 2002). The airflow rate (Q in Eq. (1)) was set as the rated airflow rate at 1600 $m^3$/h from the filter manufacturers. Filtration efficiency (η in Eq. (1)) was measured as 100% for $PM_{10}$ mass concentration. An example calculation for in-cabin $PM_{10}$ concentration (C) of 100 µg/$m^3$ indicates that the cabin filter usage of 6000 h (T) reflects 1000 g dust loaded (P) on the filter. Various

filter usages were calculated according to different dust loads using Eq. (1). Fig. 8 illustrated that the estimated filter usage is proportional to the mass of loaded dust under various in-cabin particle concentrations. A linear relationship was found between filter usage and dust loading by assuming the filter upstream dust concentration is relative consistent. However, in the real situation, the upstream concentration varies due to weather, location, passenger number, etc. It is a limitation of the experiment in this study that will be further investigated in the next study.

In this study, the particle loading on the filter was faster than the slow dust loading characteristic under the actual flying condition. This experimental approach can be reasonably applied to estimate the filter usage level since the filtration mechanisms are the same. However, some unknown phenomenon (e.g., particle loading close to the upstream filter surface) may lead to potential difference between experimental dust loading method and real dust loading condition. Since the airliner cabin filter is not allowed to be measured during usage, this is the optimal method to investigate the filter performance throughout the filter usage lifetime.

Overall, nine sets of filtration efficiency and pressure drop experimental data, under nine dust loadings, were collected in the present study. For clarity, only five dust loadings were shown in Fig. 9. Fig. 9 showed the variability of filtration efficiency with different dust load levels. As the filter was loaded more dust, the collected particles protruded the surface of the fibers and develop chains of particles extending from fibers, which led to the increased filtration efficiency. More dust loading led to smaller air paths among the fibers that result in larger filtration efficiency by diffusion. Meanwhile, more dust loading led to a larger projected area of the fibers that increases particle collection by impaction mechanism. Therefore, the dust loading posed the positive effect on the enhancement of overall filtration efficiency. This finding is consistent to the theoretical result (Lee and Liu, 1982) but slightly different from the previous result on vehicle cabin air filter (Xu *et al.*, 2011), in which the filtration efficiency increases most for smallest particles.
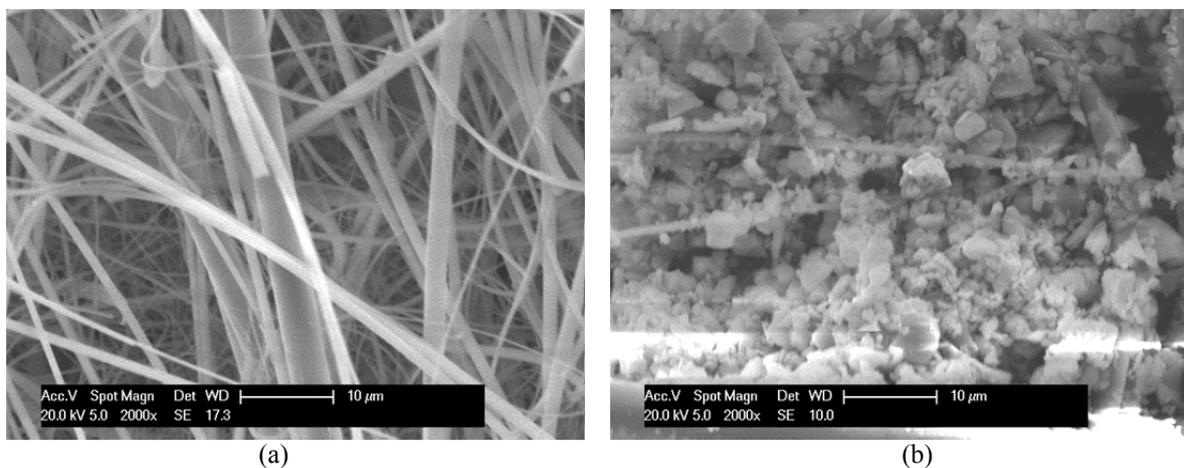


**Fig. 7.** SEM micrographs of the cabin air filter: (a) before dust loading and (b) after dust loading. Filter A was used for dust loading in the test.
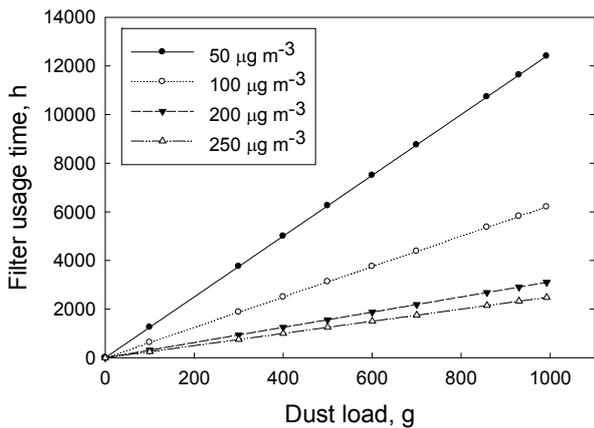
**Fig. 8.** Estimated filter usage as a function of loaded dust mass under various in-cabin particle concentrations. Filter A was used in this test. The filter airflow rate was 1600 $m^3/h$. The filter usage was estimated by loading Arizona dust on the filter in testing system shown in Fig. 3.
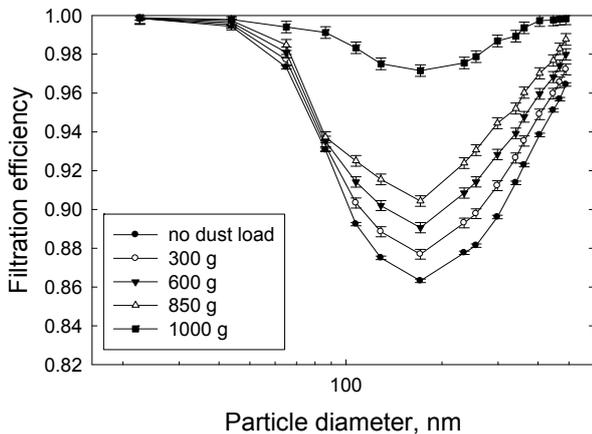


**Fig. 9**. Filtration efficiencies at different dust load levels. Filter A was used in this test. The filter airflow rate was 1600 $m^3/h$. The filter usage was estimated by loading Arizona dust on the filter in testing system shown in Fig. 3.

This is because the filter solidity ($30 \pm 5$ $g/m^2$) of the vehicle cabin air filters is lower than the solidity ($80 \pm 10$ $g/m^2$) of the aircraft cabin air filters. The increased projected area of the fibers by the loaded dust is too small to affect the particle collection by impaction. Only small particle collection by diffusion was enhanced significantly.

From Fig. 9, it can be also seen that the filtration efficiency increases approximately linearly as the loaded dust mass rises until 850 g. As the dust load increased from 850 g to 1000 g, the filtration efficiency increased more significantly. The approximate linear relationship curves below 850 g dust load indicated that the dust was loaded uniformly in the filter. After loading 850 g dust in it, filters captured particles more rapidly due to the particle clogging effect discussed above.

Fig. 10 illustrates the relationship between pressure drop and the dust loading on the test filter. Dust load showed a significantly impact on the pressure drop across the filter.

The pressure drop increases approximately 8 times more (~100 Pa to 800 Pa) as 1000 g dust was loaded on the filter. To generalize this finding to other aircraft cabin air filters, the relationship between pressure drop and dust loads on unit filter area was also explicitly shown in Fig. 10. It can be seen that, as the filter was loaded with more dust, the pressure drop increased more rapidly due to the clogging led by more attached particles. For example, the pressure drop only increased 100 Pa when the dust load increases from 0 to 50 $g/m^2$. However, a 350 Pa increase of the pressure drop was observed when the dust load increases from 150 to 200 $g/m^2$. This suggests that, to avoid dramatic pressure drop increase, this specific filter should be changed every 4500-hour filter usage that corresponds to 150 $g/m^2$ dust loading in the filter at the $PM_{10}$ concentration of 100 $\mu g/m^3$.

The results shown in Figs. 9 and 10 demonstrated that the aircraft cabin air filter characteristics changed as the particles were continuously loaded in the filter. However, it cannot explicitly indicate the relationship between the filter usage and filtration efficiency and pressure drop. By substituting the dust load with corresponding filter usage time in Figs. 9 and 10, Fig. 11 illustrated the filtration efficiency and pressure drop as a function of the filter usage. For filtration efficiency, filter usage time of 2000, 4000, and 8000 hours (according to above test result of 180 $g/m^2$ dust load in the filter) under in-cabin concentrations of 200, 100, 50 $\mu g/m^3$ are the turning points, beyond which the filtration efficiency begins to increase dramatically. In contrast, there is no obvious turning point for pressure drop change along filter usage time. Filter usage posed a consistent effect on the pressure drop throughout the studied filter usage period. This is because the particles loaded inside the filter are uniformly distributed that leads to a gradual airstream velocity/direction change among fibers. Thus, pressure drop across the filter increases faster as the filter usage continuously increases in a gradual manner instead of an obvious turning point.
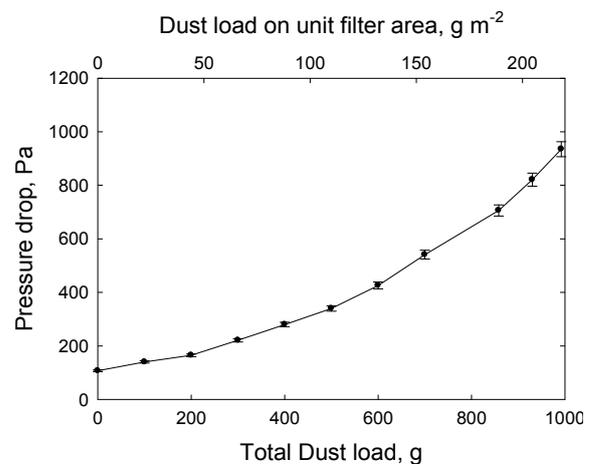


**Fig. 10.** Pressure drop across the cabin filter as a function of loaded dust mass on the filter. Filter A was used in this test. The filter airflow rate was 1600 $m^3/h$. The filter usage was estimated by loading Arizona dust on the filter in testing system shown in Fig. 3.
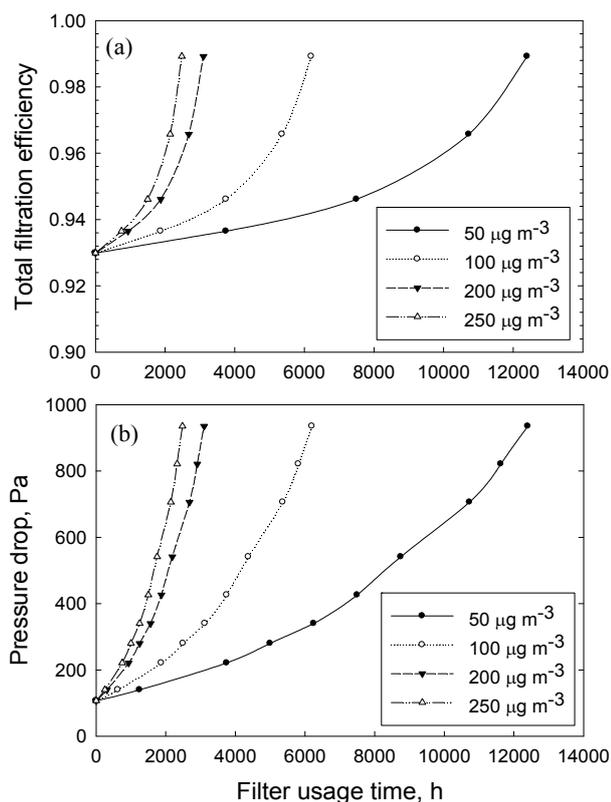
**Fig. 11.** Total filtration efficiencies and pressure drops as a function of filter usage time. For comparison, various in-cabin particle concentrations reported in previous field measurements (Nadga *et al.*, 1992; Dechow *et al.*, 1997; Lee *et al.*, 1999; Lindgren and Norback, 2002) were used to illustrate the filtration efficiency and pressure drop change as the filter usage increases.

## CONCLUSIONS

In summary, the performance of aircraft cabin air filter was evaluated and investigated under various filter usage time. For two test aircraft cabin air filters, MPPS varies from 55 nm to 150 nm that is smaller than the MPPS of normal building ventilation and vehicle cabin air filters. Slight decrease of filtration efficiency (up to 10%) and increase of pressure drop (100 Pa to 250 Pa) were observed as the airflow rate increased from 1000 m³/h to 2200 m³/h. Filtration efficiency of particles at MPPS was affected (~10%) most by the airflow rate change. Filter usage contributes to a slight filtration efficiency increase (~10%) and a significant pressure drop increase (~800%). The dust load on unit filtration area of 180 g/m² was observed as the turning point beyond which the filtration efficiency increased more rapidly. Explicit relationships among filtration efficiency, pressure drop and filter usage under various in-cabin particle concentrations were presented as a reference to facilitate airliner air filter change decisions.

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## DISCLAIMER

Reference to any companies or specific commercial products does not constitute its endorsement or recommendation by the National Science Foundation of China.

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