Particuology 28 (2016) 1–5

Contents lists available at ScienceDirect

Particuology

journal homepage: www.elsevier.com/locate/partic

Charged ultrafine particle filtration through vehicular cabin air filters

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ARTICLE INFO

Article history:
Received 4 December 2014
Received in revised form 8 September 2015
Accepted 24 September 2015
Available online 7 January 2016

Keywords:
Particle filtration
Electric charge
Filtration efficiency
Vehicular particle

ABSTRACT

Understanding the effectiveness of cabin air filters is important for assessing human exposure to ultrafine particles (UFPs) of vehicular origin. The filtration efficiency of vehicular UFPs with electric charges was investigated for different electric charge characteristics (charge state, charge polarity). The average filtration efficiency increased ∼10% as the electric charge state on the particles changed in distribution from lightly charged to highly charged. The enhancement of filtration efficiency due to electric charge was different at various filter-face air velocities. As electric charges increased, the filtration efficiency increased 12% and 9% at low air velocity (0.1 m/s) and high air velocity (0.5 m/s), respectively. The filter fiber material poses somewhat effect on the filtration efficiency change due to the electric charge. The effects of filter usage and charge polarity on filtration efficiency due to the electric charge were negligible. A coefficient was empirically derived and successfully accounts for the electric charge effect on UFP filtration efficiency.

Introduction

Recent studies have demonstrated that the concentration of ultrafine particles (UFPs) in on-road atmosphere is 100–1000 times greater than ambient air (Zhu, Hinds, Kim, & Sioutas, 2002; Westerdahl, Fruin, Sax, Fine, & Sioutas, 2005; Fruin, Westerdahl, Sax, Sioutas, & Fine, 2008; Quiros, Lee, Wang, & Zhu, 2013). On-road UFPs consist of substantially vehicle-emitted UFPs that are electrically charged (Yu, Lanni, & Frank, 2004; Maricq, 2006). Passengers and commuters are similarly exposed to these charged UFPs while traveling. Previous studies have reported that cabin air filters are the primary measure to reduce in-cabin UFP concentrations (Pui, Qi, Stanley, Oberdörster, & Maynard, 2008; Xu & Zhu, 2009; Xu & Zhu, 2013). It is important to quantitatively investigate the effectiveness of cabin air filters for charged particle filtration under different conditions.

The effectiveness of cabin air filters has been investigated previously. The most significant parameters that affect UFP filtration efficiencies were found to be the filter-face air velocity, dust loading, and fiber characteristics in the filter (Wang, Kim, & Pui, 2008; Xu, Liu, Liu, & Zhu, 2011; Xu & Zhu, 2013). Whereas filtration performance of cabin air filters has been assessed both theoretically and experimentally (Qi, Stanley, Pui, & Kuehn, 2008; Xu, Wu, Lin, & Chen, 2014), few studies have shown the effect of electric charges on filtration efficiency of cabin air filters. Although a theoretical understanding of electrical charge on particle filtration efficiency was presented (Brown, 1993), there are limited measurement data on cabin air filter for charged UFPs. Information on filtration effectiveness of cabin air filters against atmospheric charged particles is scant.

In this study, the filtration efficiency of cabin air filters was investigated with various particle charging characteristics. The objective of the present study is to perform a parametric study to identify the key parameters that affect charged UFP filtration. An empirical expression was derived to correlate the filtration efficiency and the UFP charging state at different UFP sizes.

Materials and methods

Test filters

Four new cabin air filters that were manufactured for the Toyota Prado were used as test filters. Two of the filters were made of glass fiber (Serial No. PQ35 SVW, Mann + Hummel Inc., Shanghai, China) and the other two were made of polymer fiber (Serial NO. 1706496504, Blaross Inc. Shanghai, China). Three filters (Serial No. 1706496504, Blaross Inc. Shanghai, China) that had been used for

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http://dx.doi.org/10.1016/j.partic.2015.09.012
1674-2001/

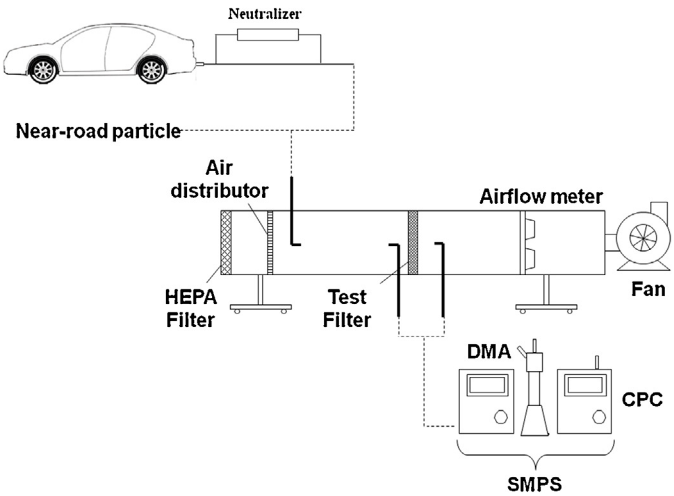

Fig. 1. Schematic of the filtration efficiency test systems for ultrafine particles (UFPs) of different charge states.

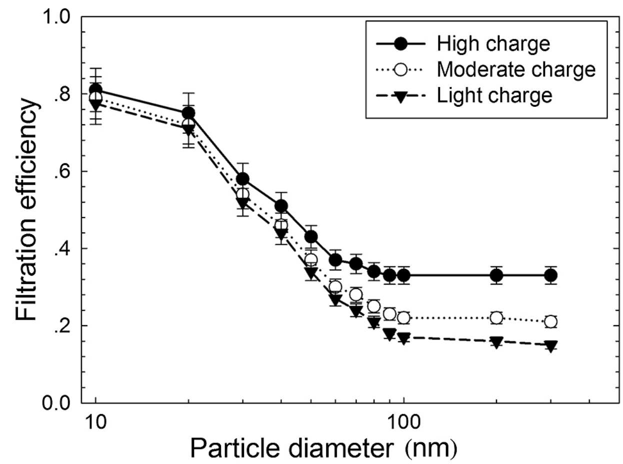

Fig. 2. Filtration efficiencies of test cabin filters for UFPs with different electric charges. The filter-face air velocity was 0.3 m/s. New glass–fiber filters were used in this measurement.

6 months were used to study the effect of electric charge on filtration efficiency for used filters. The test filters were 190 mm in width, 200 mm in length, and 30 mm in thickness. The solid volume fraction (SVF) of each test filter was between 6% and 15%. The fiber diameters of the filters were examined using a scanning electron microscope (SEM, JEM-ARM200F, JEOL, Japan) and ranged from 4 to 20 μm.

Testing system and protocol

All the filtration measurements were conducted in the same testing system. Fig. 1 presents a schematic of the experimental setup. The emission from the tailpipe of a Toyota Prado 2009, which ran idle in the experiments, was the source for the highly charged particles. It was found that 55%, 28%, 14%, and 3% of the directly emitted UFPs had electric charges of 1, 2, 3, and 4, respectively (Maricq, 2006). The emitted UFPs in the exhaust air at an airflow of $80 \pm 15\,m^3/h$ passing through an aerosol neutralizer (Model 3077, TSI Inc., USA) was used as a moderately charged particle source. By passing through the neutralizer, the electric charge distribution on the UFPs was brought to a well characterized Boltzmann equilibrium where more than 90% of the charged UFPs were singly charged (Wiedensohler & Fissan, 1991). To measure the filtration efficiency for lightly charged UFPs, the test system was located 200-m downwind of the traffic road. Lee, Xu, and Zhu (2012) found that 5% of UFPs were singly charged similar to the ambient state at a far distance (>100 m) downwind of the traffic road. The road where measurements were taken is a main thoroughfare with a traffic volume of 40–60 vehicles/h that was experienced throughout the whole measurement. This was typical of traffic conditions on this road. During the measurement, there was a consistent downwind breeze (1.5 ± 0.69 m/s) carrying UFPs in air flow over the road directly to the measurement site. A fan was used to extract ambient air through a high-efficiency particulate air (HEPA) filter into the testing system. A steel mesh distributor was used to uniformly distribute the airflow on the tunnel cross-section area. Fixed filter-face air velocities (0.1 ± 0.02, 0.3 ± 0.02, 0.5 ± 0.02 m/s) were maintained during the experiment. Particle size distributions in the 10–300 nm range were measured both upstream and downstream of the test filter using a universal scanning mobility particle sizer (U-SMPS Model 2700, Palas Karlsruhe, Germany). The measurement was started once the upstream UFP concentration was stabilized to within 10% difference.

Theoretical filtration efficiency

A well-accepted theoretical expression for particle filtration efficiency (Brown, 1993) was used in the analysis of this study. In its derivation inertial impaction, interception, and diffusion were considered as primary mechanisms. Denoting the filtration efficiency by η, it takes the form

$$\eta = 1 - \exp\left(-\frac{4\alpha Eh}{(\pi d_f)}\right), \tag{1}$$

where α is the SVF, E the total single fiber efficiency (SFE), h filter thickness, and d_f fiber diameter. Noted that Eq. (1) does not take the effect of electric charge into consideration. For electrically charged particles, the image force between particles and fibers is the additional driver for particle attachment on filter fibers (Xu, Liu, & Zhu, 2010). To extend the theoretical calculation of the filtration efficiency to charged UFPs, a coefficient B, defined as the ratio of the filtration efficiency with electric charge to the filtration efficiency without electric charge, is introduced in Eq. (1) and discussed below.

Results and discussions

Filtration efficiencies of test cabin filters

Fig. 2 shows the UFP filtration efficiencies of the cabin filters with different electric charge states. New glass–fiber filters were used in this measurement. The filtration efficiency is larger for smaller particles. For all electric charge states, filtration efficiency as a function of particle size exhibits a similar trend. Although the filtration curves with different charge states are similar, the electric charge affects the filtration efficiency differently at various particle sizes. While the electric charge causes a 3–12% increase of the filtration efficiency for small UFPs (<100 nm), a larger filtration efficiency increase (13–20%) was observed for large particles (>100 nm) as charge state increased from low to high. This might be because stronger Brownian motion for the small particles somewhat balanced the electric force on the UFP. Another reason is, for smaller particles (diameter < 100 nm), a single charge is the predominant charge state (Maricq, 2006) whereas the number and proportion of electric charge both increase as UFP size increases. Larger UFPs can carry high electric charge states and hence exhibit a larger electric force on other UFPs. This in turn accelerates a larger particle along the electric force direction, resulting in greater electric mobility.