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Removal of airborne nanoparticles by membrane coated filters

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ABSTRACT

The increasing amount of nanoparticles with the development of nanotechnology gives rise to concerns about potential negative impact on the environment and health hazards posed to humans. Membrane filter is an effective media to control nanoparticles. Three filters coated with polytetrafluoroethylene (PTFE) membrane were investigated in this study. A series of experiments on the filter efficiency and relevant parameters such as the particle size and face velocity were carried out. The data show that the efficiency curves for the membrane filters demonstrate the typical shape of "v" for particle sizes from 10 to 300 nm at face velocities from 0.3 to 15 cm/s. Membrane filters with larger pore sizes have larger Most Penetrating Particles Sizes (MPPS), and the MPPS decreases with increasing face velocity. The efficiencies decrease with increasing face velocity for particle sizes from 10 to 300 nm. We present the filtration efficiency data as a novel three-dimensional graph to illustrate its dependence on the particle size and face velocity. The membrane coated filter can be considered as two combined layers, one fibrous layer and one membrane layer. We develop a new filtration efficiency model which is a combination of the models for the two layers. Results from the model calculation agree with experimental data well. The study can help to optimize the filter product and to determine the operational parameters of filters, thus contributing to reduction of air pollution by rapidly emerging nanoparticles.

1. Introduction

In recent years, nanotechnology is becoming a revolutionary field due to its unique applications across a wide range of industries, from the field of medicine to alternative energy technology. Nanoparticles often possess unique electrical, optical, chemical, and biological properties. On the other hand, the special properties of nanoparticles can also potentially lead to new hazards or increased risks to the environment (McMurry et al., 2004; Oberdörster et al., 2005; Maynard and Pui, 2007; Wang et al., 2011a).

Filtration is the simplest and most common method for particle control and air cleaning (Maynard and Pui, 2007). Aerosol filtration is used in diverse applications, such as respiratory protection, air cleaning of smelter effluent, processing of nuclear and hazardous materials (Hinds, 1999), removal of asbestos fibers (Spurny, 1986) and diesel particles (Kittelson et al., 1984). However, the process of filtration is complicated, and although the general principles are well known there is still a gap between theory and experiments (Hinds, 1999).

Two major classes of filters exist, the fibrous filters and the membrane filters. Both types of filters have been widely used in different industrial fields. The membrane filters generally possess relatively high solid fractions and may provide high efficiency and excellent pressure drop features (Sutherland, 2008; Galka and Saxena, 2009; Kuo et al., 2010). The membrane filters rely more on the surface filtration than on the depth filtration for particles larger than the rated pore sizes in the membrane (Rubow and Liu, 1986; Ling et al., 2010).

The filtration performance of membrane filters depends on filter structures, particle properties and operation parameters (Marre and Palmeri, 2001; Cyrs et al., 2010). The research on the relationship between efficiency and particle size may help to optimize the filter product, and the research on the relationship of efficiency and face velocity may help to determine the operational parameters of filters. Our study is limited to clean membrane filters. Loading of particles on membranes is important in practical applications; however, it is out of the scope of this study.

Fibrous filtration has been extensively studied experimentally and theoretically; models based on the single-fiber efficiency are well developed and systematically documented by Brown (1993), Hinds (1999) and Lee and Mukund (2001). Studies on membrane filters are less compared to those on fibrous filters. While the capillary tube model has been shown to accurately predict the particle collection characteristics of Nuclepore membrane filters (Spurny et al., 1969; Manton, 1978, 1979;

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Marre and Palmeri, 2001; Cyrs et al., 2010), the fibrous filter model gives more accurate prediction for the conventional solvent-cast membranes (Rubow, 1981; Rubow and Liu, 1986). Good agreement can be found between the effective fiber diameter used in the model and the diameter of the fiber-like structures in the conventional membrane (Rubow and Liu, 1986). The samples in our study are coated with PTFE membrane, for which a model based on the effective fiber diameter is suitable.

In this study, a series of experiments on three commercial membrane filter samples were performed to study the effects of nanoparticle size and face velocity on filtration efficiency. The filtration efficiency data are shown as a novel three-dimensional graph with the particle size and face velocity as the axes. The graph gives an intuitive summary of the efficiency data and can better illustrate the dependence of the Most Penetrating Particle Size (MPPS) on the face velocity. Meanwhile a new theoretical model is developed combining the efficiencies of the fibrous layer and PTFE membrane layer. It is used to calculate the efficiency of the tested filters, and the results are compared to experimental ones.

2. Experimental method

2.1. Experimental setup

The experimental setup is shown in Fig. 1. An atomizer (TSI 3078) was used for generating aerosol particles with sodium chloride solution. A differential mobility analyzer (DMA, TSI 3080) was applied for particle classification according to the particle mobility sizes. A Po210 neutralizer was used to give Boltzmann equilibrium charging status to the classified particles. The filter holder was the supporter for filter samples. Two condensation particle counters (CPCs) were used for measuring the number concentrations of the particles upstream and downstream of the filter. A pressure gauge was used for measuring the pressure drop of the filter media. The filtration face velocity was controlled by the gas flow rate.

Our experimental method involved measuring filtration efficiency for monodisperse particles with the same electrical mobility. We have used this approach to study filtration of nanoparticles down to 3 nm (Kim et al., 2007; Wang et al., 2007), penetration through nanofiber composite filters (Wang et al., 2008a, 2008b), and filtration of nanoparticle agglomerates (Kim et al., 2009) and carbon nanotubes (Wang et al., 2011b, in press). This approach led to consistent results and easier data analysis compared to filtration tests using polydisperse aerosols.

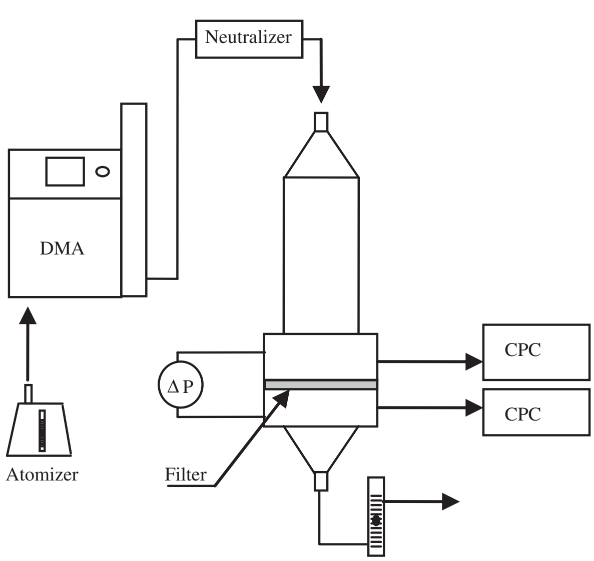

Fig. 1. The experimental setup.

Table 1
Parameters of three membrane coated filters.

Filter media	Filter A	Filter B	Filter C
Media	Non-woven nylon/ PTFE membrane	Non-woven polyester/PTFE membrane	Non-woven polyester/PTFE membrane
Thickness [mm@3.45 kPa]	0.43	0.38	0.15
Basis weight [g/m^2]	137.63	63.00	29.03
Permeability [cm/s @127 Pa]	3.24	2.43	2.20
Effective pore size [μm]	1.5	1.3	1.5

2.2. Experimental scheme

In the process of filtration, the aerosol flow goes through the filter media at a given face velocity, meanwhile the particles are captured by the filter. The parameters of filtration efficiency and pressure drop are two important factors for filters. In this study, the pressure drop of membrane filter samples at different face velocities were first measured, then a series of filtration efficiencies for different particle sizes at different face velocities was obtained.

The parameters of the three membrane coated filter samples are listed in Table 1. Fig. 2 shows SEM images of the PTFE membrane filter A, which consists of a series of interconnected fiber links between the adjacent void spaces.

For particle generation, 0.1% NaCl solution was used. The mean particle size was about 50 nm. In the experiments, the particles of 10,

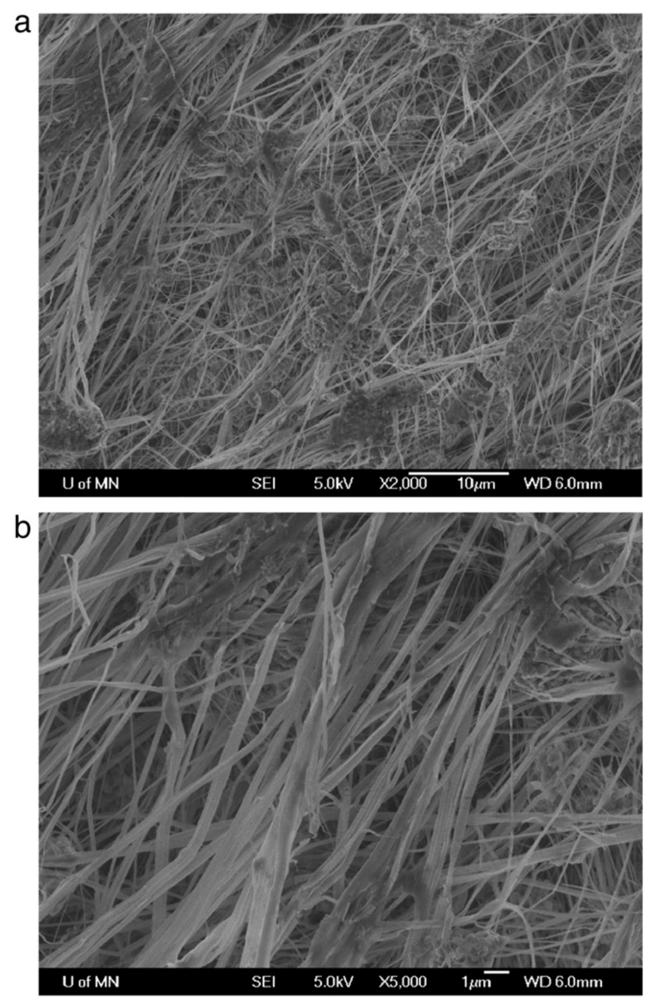

Fig. 2. SEM images of the PTFE membrane filter A.