Published in final edited form as:

Sci Total Environ. 2011 October 15; 409(22): 4868–4874. doi:10.1016/j.scitotenv.2011.08.011.

Removal of Airborne Nanoparticles by Membrane Coated Filters

Jingxian Liu¹, David Y. H. Pui², and Jing Wang^{3,4}

¹Filter Test Center, Northeastern University, Shenyang, Liaoning, China ²Particle Technology Laboratory, Mechanical Engineering, University of Minnesota, Minneapolis, Minnesota, USA

³ETH Zurich, Institute of Environmental Engineering, 8093 Zurich, Switzerland ⁴Empa, Analytical Chemistry, 8600 Dübendorf, Switzerland

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.

Keywords

nanoparticle; membrane filter; filtration efficiency; face velocity; model

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).

© 2011 Elsevier B.V. All rights reserved.

Publisher's Disclaimer: This is a PDF file of an unedited manuscript that has been accepted for publication. As a service to our customers we are providing this early version of the manuscript. The manuscript will undergo copyediting, typesetting, and review of the resulting proof before it is published in its final citable form. Please note that during the production process errors may be discovered which could affect the content, and all legal disclaimers that apply to the journal pertain.

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, 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 Figure 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 S.C. et al. 2007, Wang et al. 2007), penetration through nanofiber composite filters (Wang et al. 2008 a, b), and filtration of nanoparticle agglomerates (Kim S.C. et al. 2009) and carbon nanotubes (Wang et al. 2011 b, c). This approach led to consistent results and easier data analysis compared to filtration tests using polydisperse aerosols.

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 were obtained.

The parameters of the three membrane coated filter samples are listed in Table 1. Figure 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, 20, 50, 100, 200, and 300 nm sizes were selected using the DMA and used to challenge the filter with face velocities of 0.3, 1, 5.3, 10, and 15 cm/s.

3. Result analysis

3.1 Pressure drop features

Pressure drop is an important parameter to evaluate the performance of filters. High pressure drop means high energy consumption, which usually leads to high efficiency. Pressure drop is related to the face velocity, and increases with increasing face velocity linearly. The pressure drop values of the three filter samples are shown in Figure 3.

Filter A had the lowest pressure drop. In contrast, Filter C had the highest one. Filter B was in the middle and close to Filter C. At the face velocity of 1cm/s, the pressure drop values of Filters A, B and C were 39.2 Pa, 52.3 Pa and 57.8 Pa, respectively. Permeability is related to the pressure drop; higher permeability leads to lower pressure drop. The data in Figure 3 are consistent with the data of filter permeability.

3.2 Efficiency at different face velocities

As air penetrates a filter, the trajectories of particles deviate from the air streamlines due to several mechanisms. As a result, particles may collide with the filter surface and become deposited on them. The important mechanical mechanisms causing particle deposition include diffusion, inertial impaction, interception, and gravitational settling. Because Brownian motion generally increases with decreasing particle size, the diffusive deposition of particles is stronger when the particle size is reduced. Inertial impaction mechanism becomes stronger with increasing particle size and increasing air velocity. Interception and gravitational settling are also related to the particle size. The curve for the total efficiency

for all capture mechanisms vs. the particle size takes a typical “v” shape as shown in Brown (1993), Hinds (1999), Lee and Mukund (2001).

The filtration efficiencies for different particle sizes at different face velocities were measured in the experiments. The efficiency data of Filters A, B and C are shown in Figures 4, 5, and 6, respectively.

As the particle size increases from 10 nm to 300 nm, the efficiency curves demonstrate the typical shape of “v” for all samples. As the face velocity increases from 0.3 to 15 cm/s, the efficiency decreases and the bottom of the v-shaped curve drops. The lowest point of the v-shaped curve is the minimum efficiency and corresponds to the MPPS. At 5.3 cm/s, for Filters A, B and C, the minimum efficiencies are 99.800%, 99.997% and 99.993%, respectively and the MPPS values are 100 nm, 70 nm and 100 nm, respectively. Membrane filters with larger pore sizes allow more penetration of large particles. The data of MPPS are consistent with the pore sizes of the three filter samples. The theoretical model of Lee and Liu (1980) shows that the MPPS decreases with increasing face velocity. It can be seen from the efficiency curves that the bottom point is moving to the left as the face velocity increases. For Filter A, the MPPS values are 100 nm, 90 nm and 75 nm for the face velocities of 5.3, 10 and 15 cm/s, respectively.

If we compare the efficiencies of the three filter samples, Filter A has the lowest one, Filter B and Filter C have almost the same values, with Filter B slightly higher. This can be seen from Figure 7, in which the efficiencies of the three filter samples at the face velocity of 5.3 cm/s are compared.

The quality factor (QF) is a parameter to evaluate the filter performance, which is defined as:

$$Q_f = \frac{\ln(1/P)}{\Delta P}$$

where P is the penetration and ΔP is the pressure drop.

The quality factor changes with the particle size and face velocity. The quality factor curves of the three filter samples at the face velocity of 5.3 cm/s are shown in Figure 8. Generally, Filter B has higher QF compared to the others. For 50 nm particles, Filter B and Filter C have the same QF; for 100 nm particles, filter B has the highest QF and Filter A has the lowest one; for 300 nm particles, Filter C has the lowest QF.

3.3 Efficiency for different particle size

The collection efficiency is related to various filtration mechanisms, which depend on the particle size. The data show that for small particles (such as 10 or 30 nm) and large particles (such as 200 or 300 nm), the filtration efficiencies are higher than for the intermediate sizes (such as 50 and 100 nm). An increase in the particle size causes increased filtration by interception and inertial impaction mechanisms, whereas a decrease in the particle size enhances collection by Brownian diffusion. As a consequence, there is an intermediate particle size region where two or more mechanisms are simultaneously operating, yet none is dominant. This is the region where the particle penetration through the filter is a maximum and the filter efficiency a minimum. All filters have specific particle sizes for which the efficiencies are the lowest and the efficiency decreases sharply. The MPPS values for the three samples are between 50 and 100 nm. At low velocities, the efficiency decreases slowly with increasing velocity; but at high velocities, the efficiency decreases sharply.

3.4 Efficiency surface analysis

In order to better describe the filtration efficiency as a function of both the particle size and face velocity, a three-dimensional graph of efficiency surface with the particle size and face velocity is generated, as shown in Figures 9, 10 and 11 for Filters A, B and C, respectively.

The graphs for the three samples are similar, which indicates that all the three membrane filter samples possess similar characteristics. The shape of the efficiency graph is like a half funnel. The efficiency is relatively high for small and large particles at all face velocities; it is also relatively high at very low face velocities for the particle size range in our study. As the face velocity increases, the efficiency for intermediate particle sizes (50 – 100 nm) is becoming significantly smaller than those for smaller and larger particles. Thus a trough region is formed on the efficiency surface and it becomes deeper as the face velocity increases. The trough region represents the MPPS for different face velocities. The three-dimensional efficiency surface gives a summary of the data and shows the MPPS intuitively.

4 Model calculation

4.1 Filtration efficiency model

The membrane filter samples used in the experiment were made by surface coating technology. The filters included two layers: a non-woven fibrous layer and a PTFE membrane layer. Thus the function of filtration was due to the two layers. The total efficiency of the membrane coated filter is:

$$E=1-P_mP_s=1-(1-\eta_m)(1-\eta_s), \quad (1)$$

where P_m and P_s are the penetrations for the membrane layer and non-woven layer, respectively; η_m and η_s are the efficiencies of the membrane layer and non-woven layer, respectively. Such a model for composite filters with multiple layers has been used by Wang et al. (2008 a, b) to study composite nanofiber filters.

The efficiency of the non-woven fibrous layer η_s is related to the single fiber efficiency η_{sf} (Hinds 1999):

$$\eta_s=1-\exp\left(-\frac{4\alpha L\eta_{sf}}{\pi D_f}\right), \quad (2)$$

where α is the solidity of the filter, L is the thickness, η_{sf} is the single fiber efficiency, D_f is the fiber diameter.

The efficiency of the membrane layer η_m is related to the pore structures, and the so-called effective single fiber efficiency η_{mf} . The relation is the same as Equation (2), but with η_{sf} replaced by η_{mf} :

$$\eta_m=1-\exp\left(-\frac{4\alpha L\eta_{mf}}{\pi D_f}\right). \quad (3)$$

4.1.1 Single fiber efficiency of the non-woven fibrous layer—Particles in the flow are captured by fibers in non-woven fibrous filter. For a single fiber, the four major

mechanical capture mechanisms are Brownian diffusion, interception, inertial impaction and gravitational settling. The total filtration efficiency of a single fiber is the sum of the efficiencies by the individual filtration mechanisms. The overall single fiber efficiency η_{sf} can be written as:

$$\eta_{sf} \approx \eta_{sfDiff} + \eta_{sfInter} + \eta_{sfImp} + \eta_{sfGrav} \quad (4)$$

where η_{sfDiff} , $\eta_{sfInter}$, η_{sfImp} , η_{sfGrav} , are the single fiber efficiencies due to Brownian diffusion, interception, inertial impaction and gravitational settling mechanisms, respectively. These individual efficiencies can be computed by (Lee and Mukund 2001, Wang and Pui 2009):

$$\eta_{sfDiff} = 2.58 \left(\frac{1-\alpha}{K} \right)^{1/3} Pe^{-2/3}, \quad (5)$$

$$\eta_{sfInter} = \frac{1-\alpha}{K} \frac{R^2}{(1+R)}, \quad (6)$$

$$\eta_{sfImp} = \frac{1}{(2K)^2} \left[(29.6 - 28\alpha^{0.62}) R^2 - 27.5 R^{2.8} \right] Stk, \quad (7)$$

$$\eta_{sfGrav} = \frac{V_g/U}{1 + V_g/U}, \quad (8)$$

where U is the face velocity; K is the hydrodynamics factor, $K = -0.5 \ln \alpha - 0.75 - 0.25\alpha^2 +$

α ; Pe is the Peclet number, $Pe = \frac{d_f U}{D}$ with D the particle diffusion coefficient; R is the ratio of particle diameter to fiber diameter $R = d_p/d_f$; Stk is the Stokes number, and V_g is the settling velocity. Calculation results show that the efficiencies due to impaction and gravitational settling are negligible compared to those due to diffusion and interception for the particle size range in our study.

4.1.2 Effective single fiber efficiency of the membrane layer—The PTFE membrane consists of a series of interconnected fiber links between the adjacent void spaces. The filtration mechanisms are similar to those of the non-woven fibrous filters, also with the same four mechanical mechanisms. In application of the fibrous filter model to membrane filters, the actual filter thickness and solidity values are used in the model. The effective fiber diameter is dependent of the micro-structure in the membrane filter. Rubow and Liu (1986) found that the effective fiber diameter agreed well with the average diameter of the fiber-like structures in membrane filters. We found that in our samples the fiber-like structures have similar dimension as the pores. Thus the effective diameter is set to be 1.5 μm , the same as the average pore size in Filter A. The Knudsen number based on this effective fiber diameter is about 0.09, which is considered to be in the slip flow regime. The Kuwabara flow field in the slip flow regime is used (Pich 1965). In the particle size range of

our experiments, diffusion and interception are the dominant capture mechanisms. Thus we only include these two in the calculation of the overall single fiber efficiency. The overall single fiber efficiency can be written as (Rubow 1981):

$$\eta_{mf}=2.86\left(\frac{1-\alpha}{K}\right)^{1/3}Pe^{-2/3}\left(1+0.389\xi'\left(\frac{(1-\alpha)Pe}{K}\right)^{1/3}\right)+\frac{1-\alpha}{K}\frac{R^2}{1+R}\left(1+\frac{2\xi'}{R}\right) \quad (9)$$

where ξ' is a dimensionless coefficient used to present the degree of flow slippage at the solid surface boundary. The other terms are defined same as above.

4.2 Model calculation

According to the theoretical models listed above, the total efficiency of Filter A is calculated. Table 2 gives the parameters used in the calculation. We list the values of the filtration efficiency from the experiment and model in Table 3 for the face velocity of 5.3 cm/s. The total efficiency from the model has contributions from both the membrane and fibrous layers (Equation 1). The model indicates that the efficiency by the membrane layer is dominant for Filter A. Figure 12 is the comparison of the efficiencies between model calculation and experimental results. Figure 13 gives the efficiency surface graph from model calculation compared with experimental points. The figures show that the data from model calculation and experiments agree very well, and the theoretical model is suitable for predicting efficiency of membrane coated filters.

Pressure drop is inversely proportional to the square of the fiber size if the slip effect is not considered (Davies 1973, Hinds 1999). Since the effective fiber size in the membrane layer is significantly smaller than the fiber size in the fibrous layer (Table 2), the pressure drop of the membrane layer is substantially higher than that of the fibrous layer. Therefore, the membrane makes the major contribution in terms of both filtration efficiency and pressure drop for Filter A.

5. Conclusion

Based on the experiments, analysis and model calculation, the following conclusions are obtained:

1. The efficiency curves for all membrane coated filter samples show a typical shape of “v” for face velocities from 0.3 to 15 cm/s and the particle sizes from 10 to 300 nm.
2. The MPPS values of filter samples are related to the pore sizes; larger MPPS corresponds to larger pore size. The MPPS decreases with increasing face velocity.
3. Under our experimental conditions, the efficiency decreases with increasing face velocity for all particle sizes and decreases sharply at high velocities.
4. The efficiency surface graph presents a typical half funnel shape with high efficiency plateau for small and large particles and low face velocities. The trough region represents the MPPS at different face velocities.
5. The membrane coated filter can be modeled with a fibrous layer and a membrane layer. The efficiency results of model calculation agree well with experimental data.

Acknowledgments

The work was partially supported by the National Institute of Environmental Health Sciences grant # 1RC2ES018741-01 (sub-grant 100029-D) on “Hazard Assessment and Risk Estimation of Inhaled Nanomaterials Exposure”. The authors thank the support of members of the Center for Filtration Research: 3M Corporation, Boeing Company, Cummins Filtration Inc., Donaldson Company, Inc., Entegris Inc, Hollingsworth & Vose Company, Samsung Semiconductor Inc., Shigematsu Works CO., LTD, TSI Inc., and W. L. Gore & Associates and the affiliate member National Institute for Occupational Safety and Health (NIOSH).

References

- Brown, RC. Air Filtration. Pergamon Press; London: 1993.
- Cyrs WD, Boysen DA, Casuccio G, Lersch T, Peters TM. Nanoparticle collection efficiency of capillary pore membrane filters. *Journal of Aerosol Science*. 2010; 41(7):655–664.
- Davies, CN., editor. Air Filtration. Academic Press; London: 1973.
- Galka N, Saxena A. High efficiency air filtration: The growing impact of membranes. *Filtration & Separation*. 2009; 46(4):22–25.
- Hinds, WC. Aerosol technology: Properties, behavior, and measurement of airborne particles. Second. Wiley-Interscience; New York, USA: 1999.
- Kim CS, Bao L, Okuyama K, Shimada M, Niinuma H. Filtration efficiency of a fibrous filter for nanoparticles. *J Nanoparticle Research*. 2006; 8:215–221.
- Kim SC, Harrington MS, Pui DYH. Experimental study of nanoparticles penetration through commercial filter media. *J Nanoparticle Research*. 2007; 9:117–125.
- Kim SC, Wang J, Emery M, Shin WG, Mullholand G, Pui DYH. Structural Property Effect of Nanoparticle Agglomerates on Particle Penetration through Fibrous Filter. *Aerosol Sci & Technology*. 2009; 43(4):344–355.
- Kittelson DB, Moon KC, Liu BYH. Filtration of diesel particles. *Science of The Total Environment*. 1984; 36:153–158.
- Kuo YM, Huang SH, Lin WY, Hsiao MF, Chen CC. Filtration and loading characteristics of granular bed filters. *Journal of Aerosol Science*. 2010; 41(2):223–229.
- Lee, KW.; Mukund, R. Filtration Collection. In: Baron, PA.; Willeke, K., editors. *Aerosol Measurement - Principles, Techniques, and Application*. 2nd. John Wiley and Sons; 2001.
- Lee KW, Liu BYH. On the minimum efficiency and most penetrating particle size for fibrous filters. *Journal of the Air Pollution Control Association*. 1980; 30:377–381.
- Ling TY, Wang J, Pui DYH. Measurement of Retention Efficiency of Filters against Nanoparticles in Liquids using an Aerosolization Technique. *Environmental Science & Technology*. 2010; 44:774–779. [PubMed: 20000703]
- Manton MJ. The impaction of aerosols on a nuclepore filter. *Atmospheric Environment*. 1978; 12:1669–1675.
- Manton MJ. Brownian diffusion of aerosols to the face of a nuclepore filter. *Atmospheric Environment*. 1979; 13:525–531.
- Marre S, Palmeri J. Theoretical study of aerosol filtration by nucleopore filters: The intermediate crossover regime of Brownian diffusion and direct interception. *Journal of Colloid and Interface Science*. 2001; 237:230–238. [PubMed: 11334538]
- Maynard, AD.; Pui, DYH. Nanoparticles and Occupational Health. Springer; 2007. p. 186
- McMurry, PH.; Shepherd, M.; Vickery, JS. Particulate Matter Science for Policy Makers: A NARSTO Assessment. Cambridge University Press; Cambridge, UK: 2004. p. 660
- Oberdörster G, Oberdörster E, Oberdörster J. Nanotoxicology: An emerging discipline evolving from studies of ultrafine particles. *Environmental Health Perspectives*. 2005; 113:823–839. [PubMed: 16002369]
- Pich, J. The filtration theory of highly dispersed aerosols. *Staub Reinhalt, Luft*. Vol. 5. 1965. p. 16-23.
- Rubow, KL. PhD thesis. University of Minnesota; 1981. Submicrometer Aerosol Filtration Characteristics of Membrane Filters.

- Rubow, KL.; Liu, BYH. Characteristics of Membrane Filters for Particle Collection, Fluid Filtration: Gas, Volume I, ASTM STP 975. In: Raber, RR., editor. American Society for Testing and Materials; Philadelphia: 1986.
- Spurny KR. On the filtration of fibrous aerosols. *Science of the Total Environment*. 1986; 52:189–199.
- Spurny KR, Lodge JP, Frank ER, Sheesley DC. Aerosol filtration by means of nucleopore filters: Structural and filtration properties. *Environmental Science and Technology*. 1969; 3:453–464.
- Sutherland K. Filtration overview: A closer look at depth filtration. *Filtration & Separation*. 2008; 45(8):25–28.
- Wang J, Pui DYH. Numerical Investigation of Filtration by Fibers with Elliptical Cross-sections. *J Nanoparticle Research*. 2009; 11(1):185–196.
- Wang J, Asbach C, Fissan H, Hülser T, Kuhlbusch TAJ, Thompson D, Pui DYH. How can nanobiotechnology oversight advance science and industry: Examples from Environmental, Health and Safety Studies of Nanoparticles (nano-EHS). *J Nanoparticle Research*. 2011a; 13:1373–1387.
- Wang J, Chen DR, Pui DYH. Modeling of filtration efficiency of nanoparticles in standard filter media. *J Nanoparticle Research*. 2007; 9:117–125.
- Wang J, Kim SC, Pui DYH. Carbon Nanotube Penetration through a Screen Filter: Numerical Modeling and Comparison with Experiments. *Aerosol Science & Technology*. 2011b; 45:443–452.
- Wang J, Kim SC, Pui DYH. Measurement of Multi-wall Carbon Nanotube Penetration through a Screen Filter. *J Nanoparticle Research*. 2011c in press. 10.1007/s11051-011-0415-y
- Wang J, Kim SC, Pui DYH. Investigation of the Figure of Merit for Filters with a Single Nanofiber Layer on a Substrate. *J Aerosol Science*. 2008a; 39:323–334.
- Wang J, Kim SC, Pui DYH. Figure of merit of composite filters with micrometer and nanometer fibers. *Aerosol Science & Technology*. 2008b; 42:722–728.

Highlights

- Experiments and model calculation were carried out to study removal of airborne nanoparticles in the range of 10 – 300 nm by PTFE coated membrane filters
- The most penetrating particle size (MPPS) was related to the pore sizes; larger MPPS corresponds to larger pore size. The MPPS decreases with increasing face velocity.
- Under our experimental conditions, the efficiency decreases with increasing face velocity for all particle sizes and decreases sharply at high velocities.
- The filtration efficiency data was plotted as a novel three-dimensional graph to illustrate its dependence on the particle size and face velocity.
- The membrane coated filter was modeled with a fibrous layer and a membrane layer. The efficiency results of model calculation agreed well with experimental data.

Figure 1.
The experimental setup.

(a)

(b)

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

Figure 3.
Pressure drop as a function of the face velocity for the three filter samples.

Figure 4.
Efficiencies of Filter A at different face velocities.

Figure 5.
Efficiencies of Filter B at different face velocities.

Figure 6.
Efficiencies of Filter C at different face velocities.

Figure 7.
Comparison of the efficiencies of samples at 5.3 cm/s.

Figure 8.
The quality factor of the three filter samples for different particle sizes at 5.3 cm/s.

Figure 9.
The efficiency surface for Filter A.

Figure 10.
The efficiency surface for Filter B.

Figure 11.
The efficiency surface for Filter C.

Figure 12.
Comparison of the filter efficiency curves from the model calculation and experimental data.

Figure 13. Comparison of the efficiency surface graph. The results from model calculation are represented by the surface and the experimental data are represented by the points.

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@3.45kPa]	0.43	0.38	0.15
Basis weight [g/m ²]	137.63	63.00	29.03
Permeability [cm/s @127Pa]	3.24	2.43	2.20
Effective pore size [μm]	1.5	1.3	1.5

Table 2
Parameters used in model calculation

Parameters	Fibrous layer	Membrane layer
(Effective) fiber size [μm]	20	1.5
Solidity	0.2	0.3
Filter thickness [mm]	0.3	0.14
Particle density [g/cm^3]	2.165	
Mean free path [μm]	0.066	
Viscosity [$\text{g}/\text{cm}\cdot\text{s}$]	0.000181	

Table 3

Filtration efficiency from the experiment and model for Filter A at 5.3 cm/s.

Particle size (nm)	10	20	50	100	200
Experiment efficiency (%)	100	99.9980	99.9135	99.800	99.9664
Model efficiency η (%)	100	100	99.9910	99.7817	99.9744
Efficiency of the fibrous layer η_s (%)	64.4964	34.1619	12.2050	5.8535	5.3602
Efficiency of the membrane layer η_m (%)	100	100	99.9898	99.7681	99.9730