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A study on nanoparticle filtration characteristics of multilayer meltblown depth filters

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Abstract

Due to recent development in nanotechnology and increasing usage and production of nanomaterials, numerous studies related to environment, sanitation and safety handling of nanoparticle are being conducted. Since nanoparticles can be easily absorbed into human bodies through breathing process, based on their toxic substances and their large specific surface, these particles can cause serious health damage. Therefore, to reduce nanoparticle emissions, nanofiltration technology is becoming a serious issue. Filtration is a separation process during which a fluid passes through a barrier by removing the particles from the stream. Barrier filters can be made of various materials and shapes. One of the most common type of barrier filter is the fibrous filter. Fibrous filters are divided in two types: nonwoven and woven fabrics. Polypropylene is a thermoplastic material, used as a base material for melt blown nonwoven fabric. In this study, we examined filtration property of KCl nanoparticles with a mean particle diameter of 75 nm using multilayer meltblown filter samples. These experiments verify that the penetration of nanoparticle in the filter correlate with pressure drop; the meltblown layer MB1 has the greatest effect on dust collection efficiency of the filter. Among all tested samples, dust collection efficiency of 2-layer filter was best. However, when considering the overall pressure drop and dust collection efficiency, the 4-layer filter has the highest quality factor for particles smaller than 70 nm.

Keywords : Meltblown depth filter, nanoparticle, filtration, penetration, quality factor

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1. Introduction

Fibrous filters can be effectively used for removal of fine solid particles. Efficient removal of nanoparitcles though can be a challenge. Due to the toxic nature and large specific area of nanoparticles, only high efficiency filters with multilayer and fine fiber structures can be used for their removal.

Practically, the filter media can remove solid particles using the fibrous assembly structure, which has great air permeability and flexibility. Among them, the complex capturing mechanism of meltblown filter media, characterized by microporosity, are interception, inertial impaction, Brownian diffusion, gravitational settling, and etc. (Lokis and Motyl, 2001). Especially, the meltblown filter is widely used as light-weighted filter utilizing its large surface area that forms reticular structure of microfiber assembly (Zhang et al., 2004; Lifshutz, 2005). Polypropylene is a thermoplastic material, used as a base material for melt blown nonwoven fabric. Furthermore, polypropylene can be used for high efficiency filtration in combination with electrostatic charging. The Corona Charging is a typical method of electrostatic treatment (Tsai et al., 2002; Bruning et al., 2000; Cheung et al., 2005).

The quality of filter is defined as a function of pressure drop and filtration efficiency, meaning that a filter with low pressure drop and high filtration efficiency is characterized as a high performance filter and its performance can be easily compare with other filter samples. To develop a filter with high quality factor, the multi-layer meltblown filter is being used to increase the filtration efficiency and thermalbond layer (TB) is used as supporting layer and to increase the stiffness of pleated filter.

In this study, we observed the filtration performance of KCI particles within 17-600 nm range, and have conducted a comparative analysis of filter layer effect on filter performance based on number of layers by designing 3 types of 2-4 multilayer meltblown filters.

2. Experimental setup, method and materials

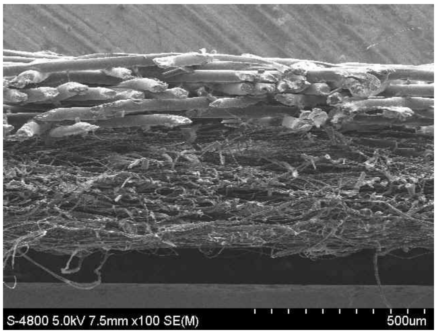
2.1 Test filter

For our study we have prepared multilayer filter samples. During the manufacturing process, the meltblown fabric is charges electrostatically by means of corona charging. In order to evaluate the mechanical filtration properties, we have used anti-static treatment followed by ISO/TS 21220 (ISO, 2009) method. This method describes the process of charge removal by soaking the filter sheet into isopropyl alcohol (IPA) and drying. The filter layers consist of supporting layer and fine fiber filter layer. In the Table 1, a summary of the physical properties of each layer is provided.

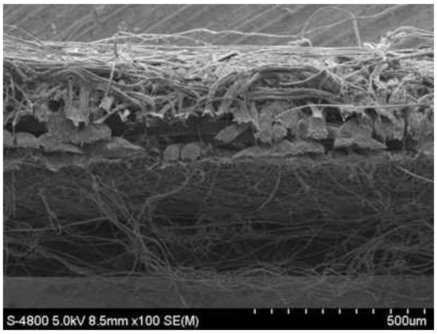
Table 1. Physical properties of single layers.

	Thermalbond (TB)	Meltblown 1 (MB1)	Meltblown 2 (MB2)
Basis weight, g/m^2	70 ± 10 %	10 ± 10 %	14 ± 10 %
Thickness, mm	0.3 ± 15 %	0.07 ± 15 %	0.17 ± 15 %
Initial pressure drop at 5.3 cm/s, mmH_2O	0.13	1.81	0.223
Initial efficiency at 5.3 cm/s, %	15.742	50.735	32.627
Air permeability (125 Pa at 20 cm^2), CFM	700	157	350

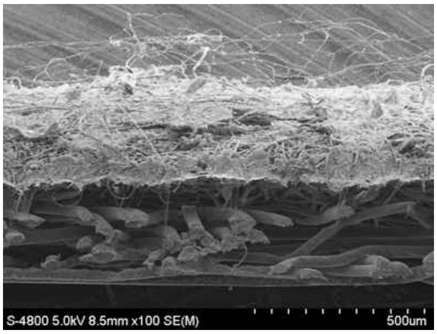
Supporting layer filter, which is thermalbond layer is made of polyethylene terephthalate fibers, and MB layer is all made by polypropylene fibers.



(a) 2-layer filter



(b) 3-layer filter



(C) 4-layer filter

Fig. 1. SEM images(5,000×) of multilayer meltblown depth filters

Figure 1 shows cross section SEM images of multi-layer meltblown depth filters magnified 5000 times. In the Figure 1 (a), cross section SEM image of 2-layer filter is displayed. Upstream layer is the TB layer with effective fiber diameter of 77.6 ❍m. Below TB layer there is a layer made of fine MB1 fibers with an effective fiber diameter of 3.9 ❍m. Upstream layer in the Figure 1 (b) is made of MB2 fibers with an effective fiber diameter of 11.4 ❍m and is supported by TB layer similar to the one of 2-layer filter. Downstream layer is MB1 layer with fiber of same diameter as MB1 of 2-layer filter. In the Figure 1 (c), a four layer filter with two MB1, one MB2, and one supporting TB layer is shown. First and third layer are MB1 and the second layer is MB2.

2.2 Experimental material

In this study, the particles were generated from the diffusion dryer (Model 3062, TSI Inc., USA) filled with silica gels, by spraying and passing 1.0wt% KCI solution using the pressure atomizer (Model 9302A, TSI Inc., USA). The generated particles are neutralized by passing through aerosol neutralizer (GRIMM Model 5.621, Germany). Figure 2 shows the particle size distribution, and the mean particle diameter is 75nm.

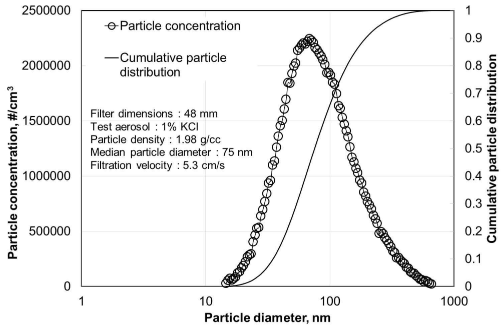


Fig. 2. Particle size distribution

2.3 Experimental setup and method

Figure 3 shows the schematic diagram of lab-scale filter test unit. In this study, the dust collection efficiency was evaluated by measuring the particle concentration at inlet and outlet of filter chamber. The Mass Flow Controller (Model 5850E, Brooks

Instrument, USA) was used to control the air flow rate. Generally for the purpose of filtration performance evaluation the filtration velocity was set as 5.3 cm/s. Accordingly, the air flow rate was set 4.4 slpm.

TSI SMPS composed of DMA (Model 3080, TSI Inc., USA) and Condensation Particle Counter (CPC, Model 3025A, TSI Inc., USA) was used in this experiment to measure the concentration of nanoparticles. Table 2 shows the experimental conditions.

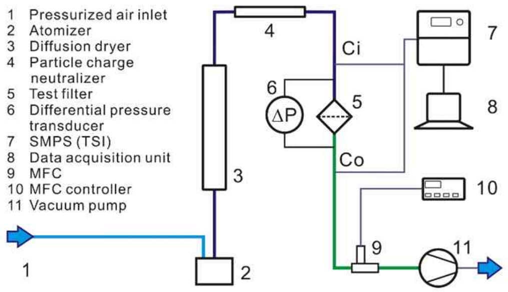


Fig. 3. Schematic diagram of Lab-scale filter test unit

Table 2. Experimental conditions

Conditions	Value
Filter media	Meltblown depth filters
Sample dimension	42 mm
Test aerosol	1 % KCl
Particle density	1.98 g/cc
Mean particle diameter	75 nm
Filtration velocity	5.3 cm/s

3. Results and discussion

3.1 Single filter layer test results

Pressure drop is the difference of the pressure measured upstream and the pressure measured downstream the filter sample. This difference is duo to the resistance of the media to the air flow. Pressure drop is an important parameter to evaluate the filter performance. The theoretical calculation of pressure drop is described in the equation (1) from Lee and Liu (Lee and Liu, 1982).

$$\triangle P_{th} = 16 \mu \alpha UL/Kd^2_f \quad (1)$$

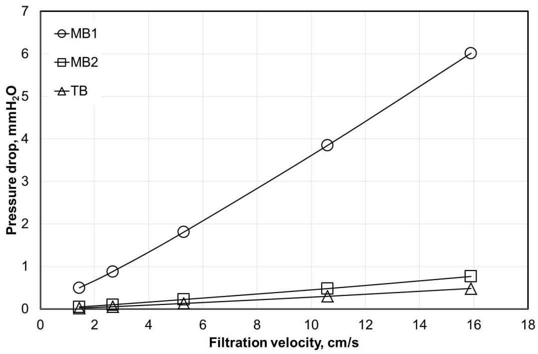


Fig. 4. Pressure drop of single layers

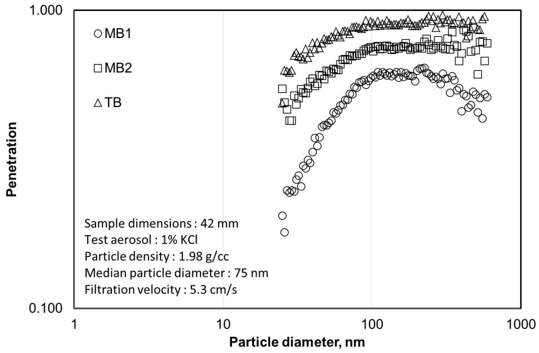


Fig. 5. Penetration of single layers

where, μ is air viscosity, α the solidity or packing density of the filter, U the average air velocity inside the filter medium, L the filter depth or thickness, K the hydrodynamic factor, and d_f the fiber diameter.

The filter pressure drop is direct proportional to thickness of the filter, and inverse proportional to the square of the fiber diameter according to the equation (1). According to this equation the pressure drop is a function of filtration velocity. Therefore the pressure drop increases with the air velocity. Figure 4 shows the pressure drop of single layers. Highest pressure drop is recorded during the tests with MB1 layer. This is mainly due to the dense packing of fine MB1 fibers.

The particle penetration is defined as the ratio of inlet and outlet particle concentration. The Figure 5 describes single layer filter penetration. Dense packing of MB1 filter layer is the main reason for low particle penetration. The particles are collected by means of mechanical mechanisms. The smaller the fiber diameter of filter the higher is the probability of fine particles to be collected within the fibrous layer structure.

According to the result of the pressure drop and the penetration of filter layer, MB1 layer exhibits the biggest effect on the actual filtration performance of the filter.

3.2 Multi-layer depth filter test results

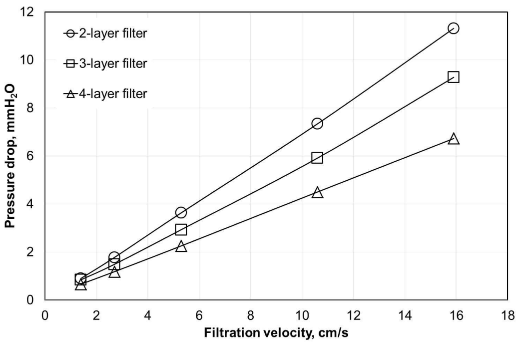


Fig. 6. Pressure drop of multilayer depth filters

Figure 6 shows the result of pressure drop as function of filtration velocity for multi-layer depth filter samples. With increased of filtration velocity, the pressure drop increased linearly. When increase of layer number, the pressure drop of the filter exhibited a decreasing tendency. According to equation (1), the pressure drop is also a function of filter thickness. However, by measurement of filter thickness shows that 2-layer filter has an average of 0.55 mm, 3-layer filter has an average of 0.48 mm and 4-layer filter has an average of 0.45 mm thickness. Which means that not the layer number but the filter thickness is an important factor for pressure drop.

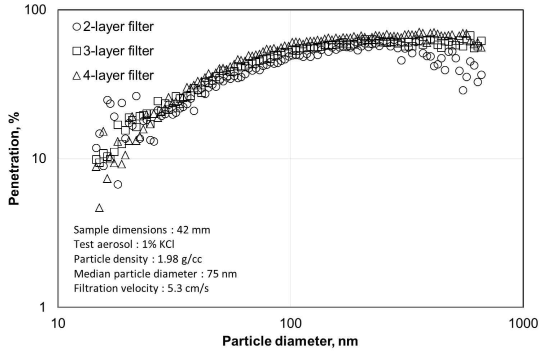


Fig. 7. Penetration of multilayer depth filters

Figure 7 describes nanoparticle penetration of multi-layer filter samples. Depending on the pressure drop differences of the filter, nanoparticle penetration appeared the lowest in case of 2-layer filter, and the highest in case of 4-layer filter. Generally, the filter with higher dust collection efficiency rate has higher pressure drop. Equation (2) describes the Quality factor (Q), which is defined as function of penetration P and pressure drop ΔP.

$$Q = \ln(1/P)/ \Delta P \quad (2)$$

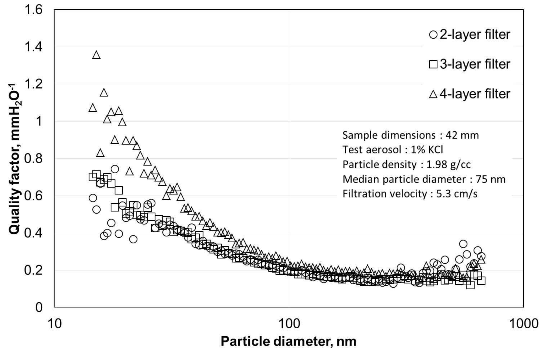


Fig. 8. Quality factor of multilayer depth filters

In the equation (2), P represents filter penetration, and ΔP stands for pressure drop. Therefore, when filter penetration and the pressure drop become lower, the quality factor increases. Figure 8 presents the quality factors of three filter samples as function of particle size.

The difference in quality factor values is significant only for the range of particles smaller than 70 nm. Whereas, the performance of 4-layer filter was better than 2-layer and 3-layer filters in the rage of under 70 nm. In this rage of particle size the best performance exhibits the filter with four layers.

4. Conclusion

In this study we have observed the filtration property of various filter samples under the following test conditions such as filtration velocity of 5.3 cm/s, KCl particle size range of 17- 600 nm and by using three different types of meltblown filter samples with different layer arrangement.

Based on the thickness of each layer of filter sample, the pressure drop appeared to be different for same test conditions at filtration velocity of 5.3 cm/s. For particle size in the range between 40 nm to 200 nm, the nanoparticle penetration is almost similar. MB1 layer has the greatest effect on the nanoparticle collection efficiency. Furthermore, the nanoparticle collection efficiency of the 2-layer filter was the most superior.

If we consider the quality factor, the performance of 4-layer filter was the best for nanoparticles smaller than 100nm. As a result, the filter has high dust collection efficiency with low pressure drop for particles smaller than 70 nm.

Finally, we can conclude that a multilayer filter composed of fine fiber meltblown layers can be effectively used for removal of nanoparticles.

Acknowledgement

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