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Characteristics of Nylon 6 nanofilter for removing ultra fine particles

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Abstract−Electrospinning is a fabrication process that uses an electric field to make polymer nanofibers. Nanofibers have a large specific surface area and a small pore size; these are good properties for filtration applications. In this paper, the filtration characteristics of a Nylon 6 nanofilter made by electrospun nanofibers are tested as a function of the fiber diameter. Nanofilter media with diameters in the range of 100-730 nm can be produced in optimized conditions. The pressure drop of a Nylon 6 nanofilter linearly increases with the increasing face velocity. An electrospun Nylon 6 filter (mean fiber diameter: 100 nm) shows a much lower pressure drop performance relative to the commercial HEPA filter media when the filtration efficiency of the Nylon 6 nanofilter and the HEPA filter are over 99.98% with test particles of 0.02-1.0 μm in diameter. The pressure drop at 5 cm/s of the face velocity is measured as 27 mmAq for the Nylon 6 nanofilter media, and 37.1 mmAq for the HEPA filter media. The particle size with minimum efficiency decreases with the decreasing fiber diameter. And the minimum efficiency becomes greater as the fiber diameter is decreased.

Key words: Electrospinning, Nanofibers, Nanofilter, MPPS, Nano-particle

INTRODUCTION

According to recent researches, nano-scale fibers can be easily produced for many different applications and research fields. Nanofibers have a large specific surface area and a small pore size. Polymer nanofibers are being used or finding uses in filtration, protective clothing, biomedical applications, including wound dressings and drug delivery systems, as structural elements in artificial organs, and in reinforced composites [1,2]. A nanofilter made of nanofibers creates an impressive improvement in the filter performance, such as in the particle capture ability, pressure drop, filter longevity and weight. The compact design and long service life of a nanofilter should offer many benefits and can be designed to occupy a smaller overall space when installed [3]. Lee and Liu [4] derived the relation among the particle size with minimum efficiency, particle diameter, and the minimum efficiency of fibrous filters. Generally all filters have most penetrating particle sizes and the filters show minimum filtration efficiency in that range of particle sizes.

Electrospinning is a fabrication process that uses an electric field to make polymer nanofibers. Generally, the suspended drop starts to stretch and form a Taylor cone as a result of an electric field being applied to the solution. The distortion of this solution drop is caused by the balance of the repulsive forces induced on the drop due to the charge distribution and the surface tension of the liquid. When the voltage reaches a critical value, the electric force overcomes the surface tension of the deformed drop in the suspended polymer solution formed at the tip of the syringe. Then a jet can be produced. After the jet travels through the air, the polymer fibers are produced by the evaporation of the solvent and are collected at an electrically grounded target. The surface morphology of the electrospun fiber is affected by many parameters, such as the polymer concentration, the applied voltage, the spinning distance, the air friction, the gravity, the temperature, and the ambient parameters [5-7].

In this study, an optimum condition to form Nylon 6 nanofilters with a different diameter is used in the electrospinning process. The filtration characteristics of a Nylon 6 nanofilter made by electrospun nanofibers and a high efficiency particulate air (HEPA) filter are tested as a function of the fiber diameter in regard to the pressure drop, the filtration efficiency and the MPPS (most penetrating particle size).

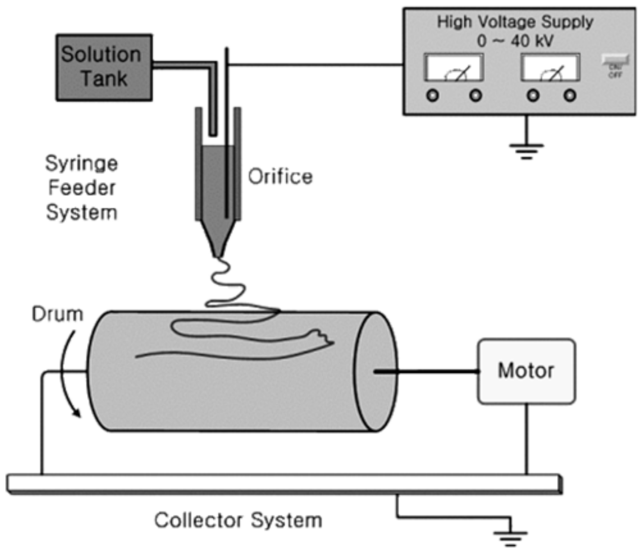

Fig. 1. Schematic diagram of the electrospinning apparatus.

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EXPERIMENTAL

1. Electrospinning Apparatus for Producing Nanofilters

Fig. 1 shows a schematic diagram of the electrospinning setup. It consists of three components, such as a syringe feeder, a high voltage supply, and a collector. The spinning occurs from the droplet of solution protruding from the 0.7 mm internal diameter of the tip. A positive electric potential is applied to the polymeric solution by attaching the lead from the variable high voltage power supply (Chungpa EMT Inc.). All experiments are conducted with the voltage at 15-25 kV. It is directly connected to the copper wire located inside the solution. A drum collector is placed 10-20 cm vertically from the tip of the syringe as a grounded collector. Nylon 6 solution is prepared by a pellet (Aldrich Co.) dissolved in formic acid (Junsei Co.) in the ultrasonicator.

Table 1 shows the conditions for making nanofilters. The concentration of the Nylon 6 is 25, 30, 35 wt%. These optimized conditions that produce nanofibers by using Nylon 6 are investigated and the Nylon 6 nanofilters using nanofibers of 100-730 nm in diameter are designed and evaluated for filtration efficiency. The temperature is 20 °C and the relative humidity is 40%. All experiments are performed in a constant temperature-humidity chamber which can control the temperature and the humidity automatically.

The surface morphology of the electrospun fiber is observed with a scanning electron microscope (HITACHI 4200). The Sauter mean diameter of the electrospun fiber is measured by an image analyzing processor (IMT, 2000) based on SEM.

Table 1. Experimental conditions to produce Nylon 6 nanofibers by electrospinning

Parameters	Values
Polymer	Nylon 6
Solvent	Formic acid
Concentration (wt%)	25, 30, 35
Electric voltage (kV)	15-25
Tip to collector distance (cm)	10-20
Collector	Steel Mesh
Capillary diameter (mm)	0.7
Temperature (°C)	20
Relative humidity (%)	40

2. Performance Evaluation of Nanofilters

Fig. 2 is a schematic diagram of the filter testing apparatus used. The system is composed of an atomizer, a diffusion dryer, a charge neutralizer, a filter holder and a condensation particle counter. The PSL (polystyrene latex) particles, which have known sizes, are dissolved in distilled water and are atomized through the atomizer. A great deal of moisture is on the surfaces of the monodisperse particles; however, they are eliminated when they pass through the diffusion dryer. In order to avoid unwanted electrostatic effects, a charge neutralizer (TSI, 3054) is used. Electrical charges on the aerosol are neutralized by exposing the aerosol to a cloud of bipolar ions produced by a radioactive source. The 10 mCi Kr85 source is placed inside an aluminum tube and the aerosol passes through the tube. The particles are thus brought to a state of equilibrium by a Boltzmann charge. The filter to be tested is placed in a filter holder and the particle concentration at the upstream and the downstream of the filter is measured with the condensation particle counter (TSI, 3010). The condensation particle counter can measure the number concentration of nano-sized particles that grow to micro-sized droplets in a supersaturated environment [8,9].

RESULTS AND DISCUSSION

1. Morphology of the Test Nanofilters

The morphology of electrospun fiber is affected by the polymer concentrations, the applied voltage, and the tip to collector distance. But the most important factor is the concentration of Nylon 6. Fig. 3 shows the SEM images of Nylon 6 nanofibers as a function of the Nylon 6 concentration. When the concentration is 25 wt%, electrospun fibers have an average diameter of 100 nm, but as the concentration of Nylon 6 increases to 35 wt%, the mean fiber diameter gradually thickens to 730 nm. The higher concentration of the polymer solution tries to form thicker fibers by preventing the stretching of fibers and the high electric field strength makes thinner fibers by the increased repulsive force on the polymer surface. All other parameters are adjusted in order to make uniform nanofibers [10,12].

Table 2 shows the experimental conditions for the performance evaluation of the nanofilters. The diameter of the test filters is 47 mm and the face velocity is 5 cm/s. Nylon 6 nanofilters are prepared in three samples according to the mean fiber diameter of 100

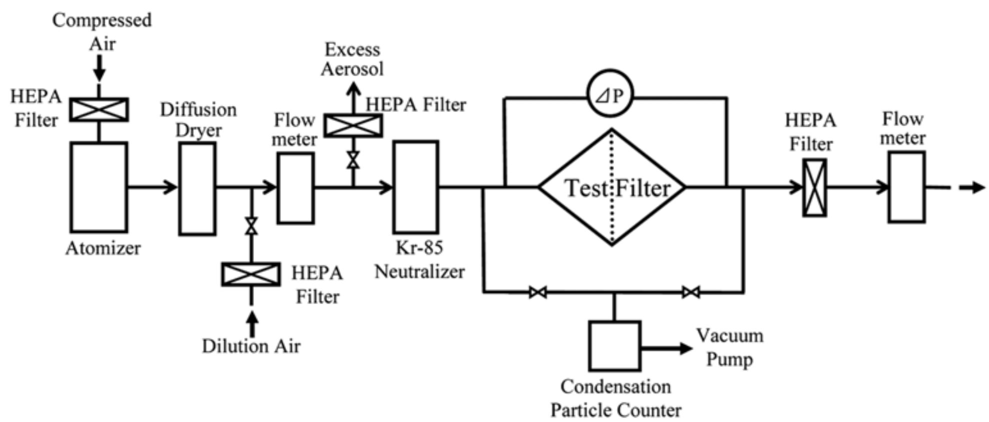
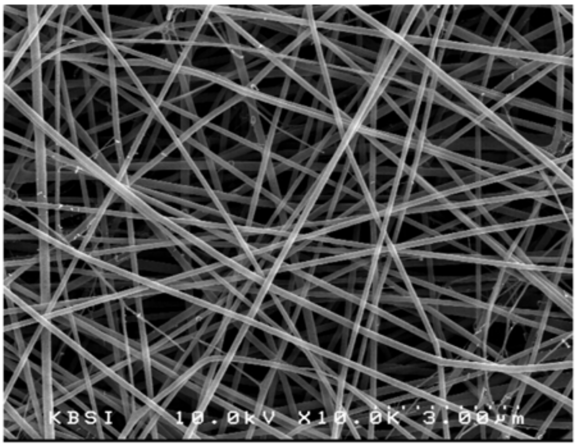
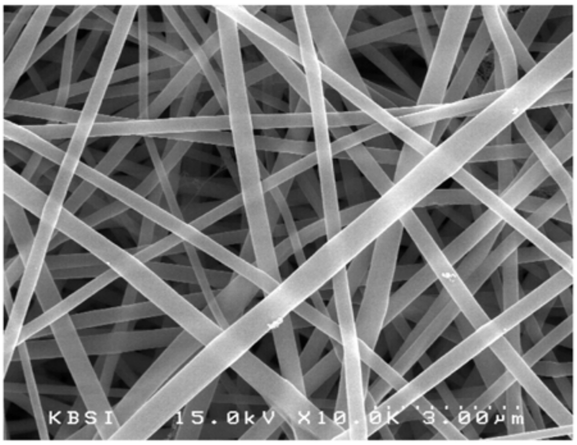


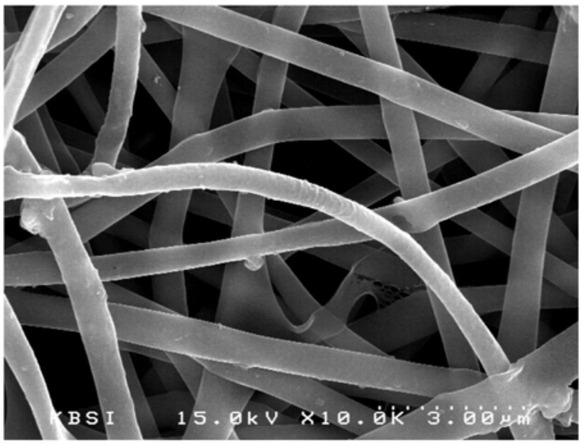
Fig. 2. Schematic diagram for the performance evaluation of the nanofilters.



(a) Concentration 25 wt%: Mean Diameter 100 nm: Sample 1



(b) Concentration 30 wt%: Mean Diameter 430 nm: Sample 2



(c) Concentration 35 wt%: Mean Diameter 730 nm: Sample 3

Fig. 3. Scanning electron micrographs of Nylon 6 nanofibers as a function of the concentration.

(Sample 1), 430 (Sample 2), 730 (Sample 3) nm and filtration efficiency is evaluated using test particles of 0.02-1.0 μm in diameter.

2. Pressure Drop Across the Test Filters

Three test filters and one HEPA filter are evaluated for the performance of the pressure drop and the filtration efficiency. The HEPA filter is used as a commercialized filter (Hollingsworth & Vose, HB5443), and the Nylon 6 nanofilters are prepared by electrospinning. The HEPA filter is used for measuring the reference values. Fig. 4 shows the SEM image of the test HEPA filter made of glass fibers with diameters in the range of 100-1,500 nm.

Table 2. Experimental conditions for evaluating the filtration efficiency of nanofilters

Parameters	Values		
	Sample 1	Sample 2	Sample 3
Face velocity (cm/s)	5	5	5
Test particle size (μm)	0.02-1.0	0.02-1.0	0.02-1.0
Test filter size (mm)	47	47	47
Mean fiber diameter (nm)	100	430	730
Pore size (μm)	0.24	0.55	0.94

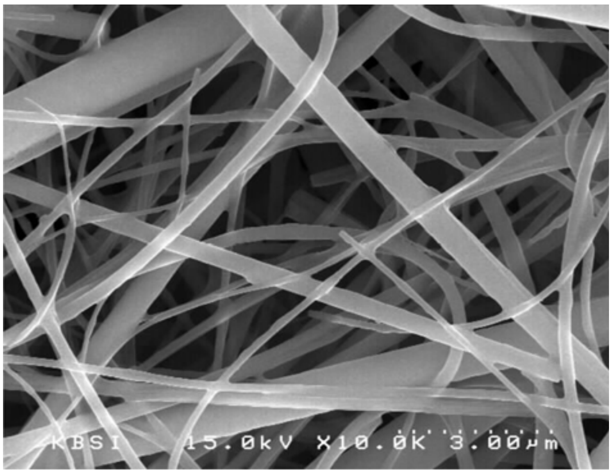


Fig. 4. Scanning electron micrograph of the HEPA filter: Fiber diameters range from 100 to 1,500 nm.

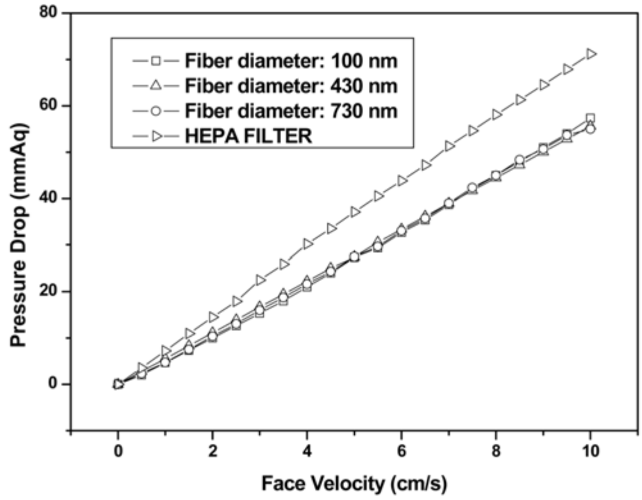


Fig. 5. Pressure drop of the Nylon 6 nanofilters and the HEPA filter as a function of face velocity for various fiber diameter.

The pressure difference between the front and the back side is relative to many parameters. The pressure difference is caused by the combined effect of each fiber resisting the flow of air past it.

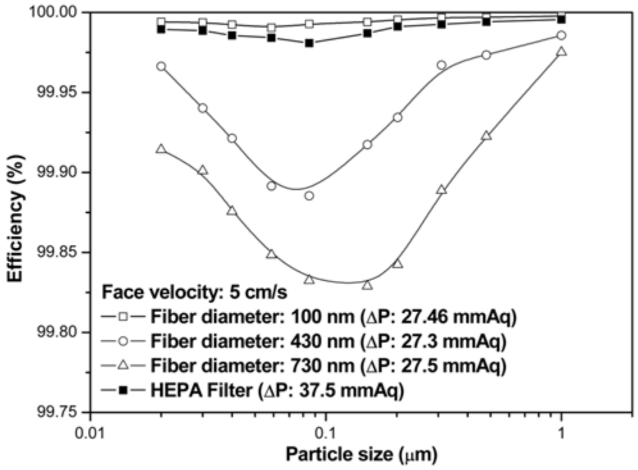


Fig. 6. Filtration efficiency of the Nylon 6 nanofilters and the HEPA filter as a function of particle size for various fiber diameter.

Usually, the pressure drop is directly proportional to the flow velocity, the fluid viscosity, the solidity, and the thickness of a filter media [9,13]. The pressure drop of the test filters is measured with various face velocities. Fig. 5 shows the pressure drop change of the Nylon 6 nanofilters and HEPA filter as a function of the face velocity. The face velocity represents the averaged air velocity which passes through the surface area facing to the upstream. When the velocity increases, the pressure drop is linearly increased. All test filters with different diameters have almost the same pressure drop changes. It shows that the homogeneity of the Nylon 6 nanofilters is confirmed. The pressure drop at 5 cm/s of the face velocity is measured as 27 mmAq for the electrospun Nylon 6 nanofilters, and 37.1 mmAq for the HEPA filter (Filtration efficiency >99.98%, at 0.02-1 μm Particle).

3. Filtration Efficiency and MPPS

The collection efficiency (η) of the nanofilters is calculated as follows:

$$\eta=\left[1-\frac{C_{downstream}}{C_{upstream}}\right]\times 100\% \qquad (1)$$

where $C_{upstream}$ is the particle number concentration in the upstream and $C_{downstream}$ is the particle number concentration in the downstream. Fig. 6 shows the results for the filtration efficiency as a function of the particle size for nanofilters. Sample 1 shows the best filtration efficiency compared to Sample 2 and Sample 3. The filtration efficiency of Sample 1 is over 99.99% at 0.02-1 μm particles. The filtration efficiency increases with the decreasing of the fiber diameter of the filter media (at the same pressure drop). Also, Sample 1 appears to have better filtration efficiency than the commercialized HEPA filter, even if Sample 1 has a lower pressure drop.

The relationship between the filter quality in the single-fiber efficiency and the fiber diameter is obscured by the complex dependence of the overall filtration efficiency. The overall air filtration occurs via direct interception, inertial impaction, diffusion, gravitational settling and electrostatic attraction. The electrostatic attraction is too weak to affect the collection efficiency. More particles are traveling near the fibers at the slip flow condition, so the only important mechanisms in the range of minimum efficiency are interception, diffusion and impaction in the electrospun nanofilters. Because of the slip on the fiber surface for the fibers with diameters smaller than 0.5 μm, Sample 1 has a lower pressure drop than the HEPA filter even the Sample 1 has a high filtration efficiency.

Usually, all filters have an MPPS that gives the minimum efficiency in the particle size range of 0.1-0.5 μm. The particles in the size are too large for diffusion to be effective and too small for impaction or interception to be effective. When the fiber diameter of the filter media is 100 nm, the minimum efficiency of nanofilters is shown to be near 58 nm particle size with a filtration efficiency of 99.991%. But as the diameter of the filter media is increased to 730 nm, the MPPS is 150 nm with a filtration efficiency of 99.829%. Decreasing the fiber size in a nanofilter media provides for improvement in the MPPS situation. When the nanofilters are designed for the same pressure drop, the nanofilter with small size fiber diameters has small MPPS and high filtration efficiency at the MPPS.

The particle size for minimum efficiency is proportional to the diameter of the fibers, which suggests that the diameter of the particle will decrease as the fiber diameter is decreased. And the minimum efficiency becomes greater as the fiber diameter is decreased.

CONCLUSIONS

Most of the studies on electrospun nanofibers are focused on the morphology of fibers and materials. In this study, Nylon 6 nanofilters are prepared in three samples with a mean fiber diameter of 100, 430, 730 nm by electrospinning. The filtration efficiency is evaluated by using test particles of 0.02-1.0 μm in diameter. When the concentration of the polymer solution increases from 25 to 35 wt%, the diameter of the fibers increases from 100 to 730 nm. The fiber diameter of the filter can be controlled by changing the parameters. All three of the test samples are prepared to have the same pressure drop by controlling the diameter and the thickness of nanofilter media. The characteristics of the nanofilters are examined as a function of the fiber diameter. When the face velocity increases, the pressure drop is linearly increased. The particle size of the minimum efficiency decreases as the fiber diameter is decreased. And the minimum efficiency becomes greater as the fiber diameter is decreased. The electrospun Nylon 6 filter (mean fiber diameter: 100 nm) exhibits much less pressure drop performance relative to the commercial HEPA filter media.

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REFERENCES

1. S. M. Jo, W. S. Lee and S. W. Chun, *Fiber Technology and Industry*, **6**(1/2), 61 (2002).
3. K. Graham, M. Ouyang, T. Raether, B. McDonald and P. Knauf, *Polymeric nanofilters in air filtration applications*, 15th Annual Technical Conference, Texas, April 9 (2002).
2. D. H. Reneker and I. Chun, *Nanotechnology*, **7**, 216 (1996).

4. K. W. Lee and B. Y. H. Liu, *J. Air Poll. Control Assoc.*, **30**, 377 (1980).
5. D. H. Reneker, A. L. Yarin, H. Fong and S. Koombhongse, *Journal of Applied Physics*, **87**, 9, 4531 (2000).
6. J. M. Deitzwl, J. D. Kleinmeyer, D. Harris and N. C. Becktan, *Polymer*, **42**, 261 (2001).
7. Y. C. Ahn, S. K. Park, G. T. Kim, Y. J. Hwang, C. G. Lee, H. S. Shin and J. K. Lee, *Current Applied Physics*, **6**, 1030 (2006).
8. ASHRAE Standard 52.1, Method of Testing General Ventilation Air-Cleaning Devices for Removal Efficiency by Particle Size (1999).
9. W. C. Hinds, *Aerosol technology*, John Wiley & Sons, New York (1999).
10. G. T. Kim, Y. C. Ahn, J. K. Lee, N. Kattamuri and C. M. Sung, *J. Ilass-Korea*, **8**, 31 (2003).
11. G. T. Kim, Y. J. Hwang, Y. C. Ahn, H. S. Shin, J. K. Lee and C. M. Sung, *Korean J. Chem. Eng*., **22**, 147 (2005).
12. H. S. Park and Y. O. Park, *Korean J. Chem. Eng*., **22**, 165 (2005).
13. R. C. Brown, *Air filtration: An integrated approach to the theory and applications of fibrous filters*, Pergamon Press (1993).