Filtration Properties of Electrospinning Nanofibers

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ABSTRACT: Electrospinning is a relatively simple method to produce submicron fibers from solutions of different polymers and polymer blends. The extensive application in future of electrospinning nanofibers is filtration. In this article, the filtration properties of electrospinning nanofibers were investigated. During the experiments, nanofibers layers with different area weight were electrospun on the spunbonded or meltblown sublayers. Fiber diameter, pore diameter, filtration efficiency as well as filtration resistance of nanofibers web and sublayers were measured, respectively, through a series of experiments. The results show that the fiber diameter of nanofibers is much smaller than that of sublayers. It is also found that the pore diameter of nanofibers web is much smaller than sublayers and coefficient variation of the pore diameter of nanofibers web is much smaller than sublayers. Moreover, the filtration efficiency and filtration resistance of sublayers are lower than nanofibers webs. The balance between efficiency and press drop is also investigated in the article. © 2006 Wiley Periodicals, Inc. J Appl Polym Sci 102: 1285–1290, 2006

Key words: electrospinning; PVA; nanofibers; pore diameter; filtration properties

INTRODUCTION

Electrospinning is a relatively simple method to produce submicron fibers from solutions of different polymers and polymer blends. In general, fibers with diameter less than 1000 nm are called nanofibers in electrospinning. Electrospinning nanofibers are of interest in many applications.[1–6] These include filter media, composite materials, biomedical applications (tissue engineering, scaffolds, bandages, and drug release systems), protective clothing, optoelectronic devices, photonic crystals, and flexible photocells.

Filtration is necessary in many engineering fields. Fibrous materials used for filter media provide advantages of high filtration efficiency and low air resistance.[7] Filtration fineness is one of the most important concerns for the filter media performance. Since the channels and structural elements of a filter must be matched to the scale (as small as 0.3 μm) of the particles or droplets that are to be captured in the filter, one direct way of developing high efficient and effective filter media is by using nanometer-sized fibers in the filter structure.[8] In general, because of the very high surface area to volume ratio and resulting high surface cohesion, tiny particles of the order of <0.5 μm can be easily trapped in the electrospun nanofibrous structured filters and hence the filtration efficiency can be improved.

The strength of nanofibers web is too low to use for filter, and meltblown and spunbonded nonwoven are always as sublayers to support nanofibers web. Few articles have investigated the filtration properties of electrospinning nanofibers; in this contribution, the filtration properties of electrospinning nanofibers were tested and analyzed. Poly(vinyl alcohol) (PVA) was chosen to fabricate nanofibers.

PVA is a semicrystalline, hydrophilic polymer with good chemical and thermal stability.[9] PVA is highly biocompatible and nontoxic. It can be processed easily and has high water permeability.[10] PVA is a water-soluble polymer that readily reacts with different crosslinking agents to form a gel.[11] PVA solutions can form physical gels from various types of solvents. These properties have led to the use of PVA in a wide rang of applications in medical, cosmetic, food, pharmaceutical, and packing industries.

FUNDAMENTAL THEORY OF FILTRATION

Filtration process is theoretically divided into two stages. The first stage is called stable stage, and during this stage, filtration efficiency and resistance are unchanged with the time; the second stage is called unstable stage, and during this stage, filtration efficiency and resistance are independent of the particles properties and will change with the particles deposit, the gas corrosion and so on. As for the airflow with low particles concentration or for the high efficiency filters, the first stage is the main one for the filtration. Nanofibers filters belong to this stage, and it was investigated in following analysis.[12,13]

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According to classical filtration theory, there are mainly five mechanism effects to catch particles during the first stage, which are interception, inertial, diffusion, gravity, and static electricity effect, respectively. The efficiency of single fiber under every mechanism can be calculated, but the total efficiency of single fiber is not simply the total efficiency under every mechanism, but is the interaction effect of the five mechanisms. The filtration efficiency and resistance are expressed in following formulas (1) and (2).

Filtration efficiency (η) can be expressed by the particles concentration of inlet and outlet airflow:

$$\eta = \frac{G_1 - G_2}{G_1} = \frac{Q(N_1 - N_2)}{N_1 Q} = 1 - \frac{N_2}{N_1} \qquad (1)$$

where G_1 and G_2 are the quantity of particles in inlet and outlet airflow (mg/h); N_1 and N_2 are the particles concentration of inlet and outlet airflow (mg/m^3); and Q is the speed of wind (m^3/h).

Filtration resistance (ΔP) can be expressed as

$$\Delta P = \frac{2C' v^2 H \alpha \rho_a}{\pi d_f^2}(\mathrm{Pa}) \qquad (2)$$

where C' is the resistance coefficient; v is the filtration velocity (m/s); H is the thickness of filtration layer (m); and ρ_a is the gas density (kg/m^3); d_f is the fiber diameter (m).

As far as three main factors concerned with air filtration, particles, medium (air), and filter character, the most important parameters that affect filtration properties of air filter are the diameter of particles, air current velocity, diameter of fibers, as well as filling rate. In general, filtration efficiency will be higher and smaller particles diameter will be filtrated with smaller fibers diameter, close and uniform filling, but the filtration resistance will be higher at the same time.

EXPERIMENTAL

Materials

Poly(vinyl alcohol) (PVA, molecular weight $M = 70 \times 10^3$ g/mol) was purchased from Shanghai Chemical Fibers Institute of China. PVA was dissolved in distilled water at concentrations 10 wt %. The solution was stored at room temperature. The experiments were carried out at room temperature in air.

Polypropylene (PP) spunbonded sublayer and PP meltblown sublayer were purchased from Chinese Nonwoven Company. The square meter weight of spunbonded sublayer and meltblown sublayer is 18 g/m^2. In electrospinning (Fig. 1), two kinds of sublayers were put in the collecting screen and were used to collect PVA nanofibers web, respectively.

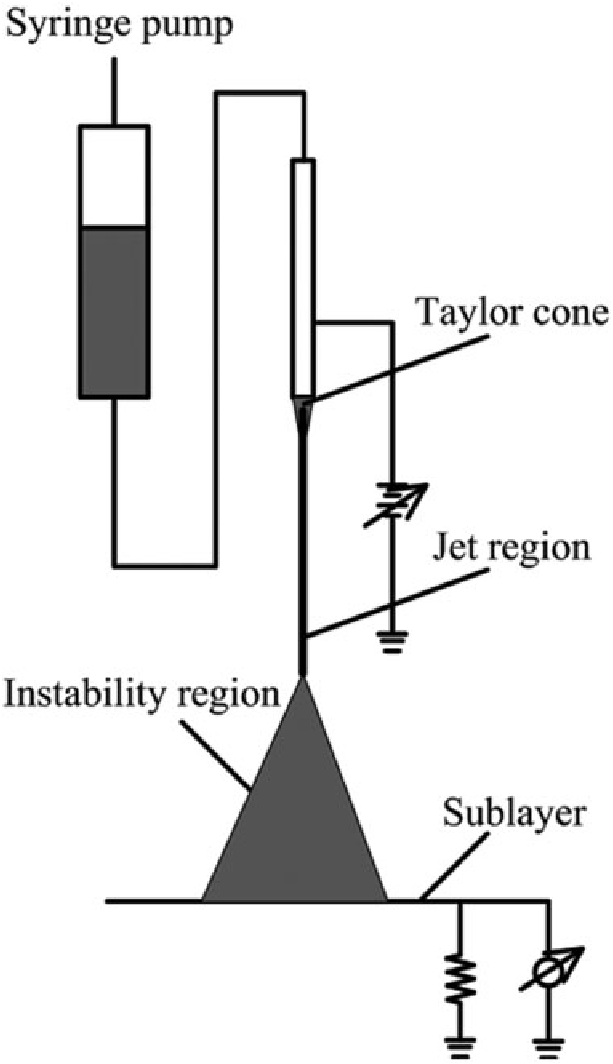

Figure 1 Experiment set-up.

Electrospinning setup

Experimental set-up device used for electrospinning process is shown in Figure 1. Variable high voltage power supply was used for the electrospinning. It was used to produce voltages ranging from 0 to 50 kV, and the voltage used in the experiment was about 20 kV and the current was adjusted to be constant. PVA solution was poured in a syringe attached with a capillary tip of 1 mm diameter, and the flow rate was uniform, 0.5 mL/h.

Measurements

The morphology of the eletrospinning nanofibers and sublayers were observed with a scanning microscope manufactured by Japan Electron Optical Laboratory. The results are shown in Figure 2.

The nanofibers webs are weighed with the electron balance manufactured by Shanghai Apparatus Company.

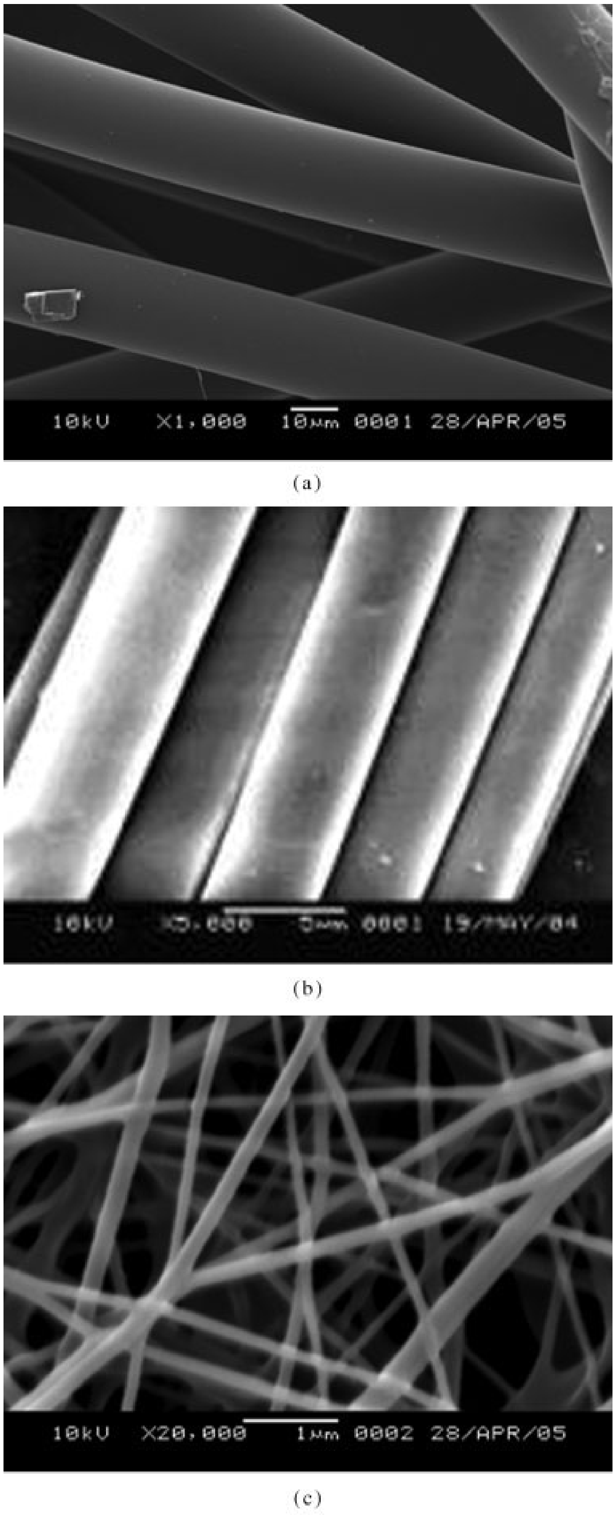

Figure 2 Structure comparison among spunbonded sublayers, meltblown sublayers, and nanofibers. (a) The morphology of spunbonded sublayers, (b) the morphology of meltblown sublayers, and (c) the morphology of nanofibers webs.

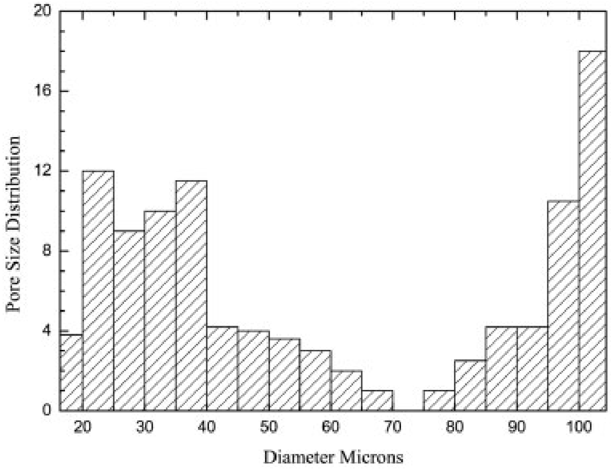

Figure 3 Pore distribution histogram versus diameter of PP spunbonded sublayer outputted directly by capillary flow porometer.

Capillary flow porometer *CFP-1100-AI*, manufactured by American PMI company, was used to test the pore diameter of spunbonded sublayers and nanofibers webs supported by sublayers. According to apparatus standard, three samples were tested in every group. The final results are shown in Figures 3 and 4 and Table I.

NJL-3 Sodium flame method, manufactured by Donghua University, was used to test the filtration efficiency and filtration resistance of nanofibers webs and sublayers (Fig. 5). The method is based on the NaCl aerosol particles with the mean size 0.6 μm, which penetrate into the test samples. The penetrating velocity of NaCl particles is 5 m/min and the area of the sample is 100 cm^2. All the experiments were made according to the British Standard BS 4400.

RESULTS AND DISCUSSION

Structure comparison

From Figure 2, the average fibers diameter of spunbonded sublayers [Fig. 2(a)] is about 13 μm, the aver-

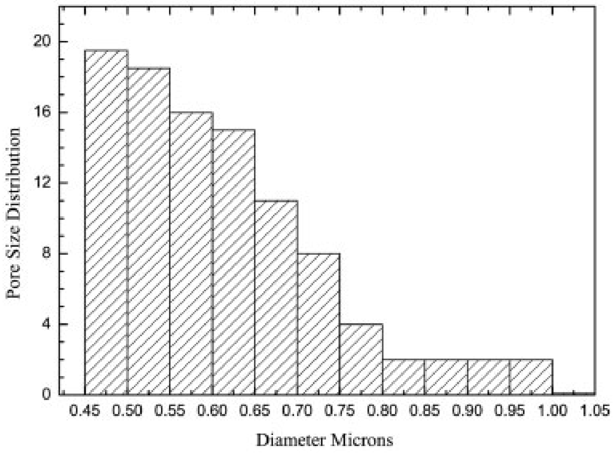

Figure 4 Pore distribution histogram versus diameter of nanofibers webs outputted directly by capillary flow porometer.

TABLE I
Measurement Value of PP Spunbonded Sublayers and Nanofibers Webs

PP spunbonded sublayers	
Average pore diameter(μm)	41.99
The least pore diameter(μm)	18.06
The biggest pore diameter(μm)	96.40
Standard deviation of pore diameter(μm)	23.12
Coefficient variation	55
Nanofibers webs	
Average pore diameter(μm)	0.74
The least pore diameter(μm)	0.60
The biggest pore diameter(μm)	1.73
Standard deviation of pore diameter(μm)	0.26
Coefficient variation	35%

age fibers diameter of meltblown sublayers [Fig. 2(b)] is about 4 μm, and the average fibers diameter of nanofibers webs [Fig. 2(c)] is about 0.2 μm. It is obvious that the diameter of fibers in Figure 2(c) is much smaller than that of fibers in Figure 2(b). The diameter of fibers in Figure 2(b) is smaller than that of fibers in Figure 2(a). The diameter decreases sharply, which leads to the enhancement of filtration efficiency.

Pore diameter comparison

In this part, the pore diameters of PP spunbonded sublayer and nanofibers webs were tested. Pore distribution histogram versus diameter (Figs. 3 and 4), average pore diameter, least pore diameter, and biggest pore diameter (Table I) were outputted directly by capillary flow porometer. According to the following formula (3 and 4),[14] we utilized some software to calculate standard deviation of pore diameter and coefficient variation (Table I). It is analyzed that coefficient variation of sublayers pore diameter is much bigger than that of nanofibers webs pore diameter. The former pore diameter coefficient variation value is 55%, and the latter is only 35% (Table I).

$$s^2 = \frac{1}{n}\sum_{i=1}^{n}(x_i - \bar{x})^2 \tag{3}$$

$$\text{Coefficient variation} = \frac{S}{\bar{X}} \times 100\% \tag{4}$$

In addition, the least pore diameter of sublayers is 18 μm, and the biggest one is 96 μm (Table I). But after nanofibers mats were electrospun on the sublayers, the values diminish to 0.60 and 1.73 μm, respectively. The results prove that the pore diameter of nanofibers webs is much smaller than sublayers pore diameter and the particles are much easier to be captured in the nanofibers webs. So, nanofibers webs are more efficient and effective than sublayers as filter media.

Comparison of filtration efficiency

The filtration efficiency of meltblown sublayers is 30%, and the filtration efficiency of spunbonded sublayers is 6% [Fig. 5(a)]. It is obvious that filtration efficiency of complex is much higher than sublayers after 0.5 g/m^2 nanofibers web was electrospun on the sublayers. Moreover, filtration efficiency of complex is about 100% when 2.4 g/m^2 nanofibers web was electrospun on the meltblown sublayers. At the same condition, 2.9 g/m^2 nanofibers web was needed for electrospinning on the spunbonded sublayers, and 95% of filtration efficiency of complex can only be achieved. The results prove that nanofibers webs can improve filtration efficiency effectively. The reason is that the diameter of nanofibers is smaller than sublayers and the

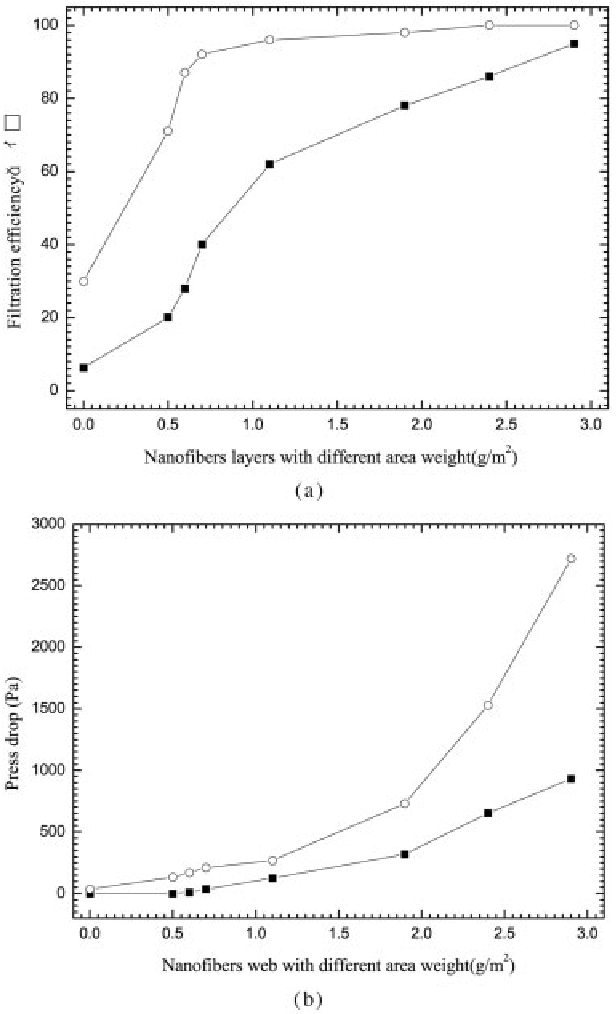

Figure 5 Comparison of filtration efficiency and press drop. (a) Comparison of filtration efficiency. The top line shows that nanofibers mats electrospun on the meltblown sublayer; the bottom line shows that nanofibers mats electrospun on the spunbonded sublayer. (b) Comparison of press drop. The top line shows that nanofibers mats electrospun on the meltblown sublayer; the bottom line shows that nanofibers mats electrospun on the spunbonded sublayer.

pore diameter of nanofibers webs is smaller than sublayers. Particles with small diameter are easier to be filtrated in nanfibers webs.

Comparison of press drop

The press drop of meltblown sublayers is 0 Pa, and the press drop of spunbonded sublayers is 35 Pa [Fig. 5 (b)]. It is obvious that the press drop of complex is much higher than sublayers after nanofibers web was electrospun on the sublayers. Moreover, the press drop of nanofibers web that was electrospun on the meltblown sublayer increases sharply than the same square meter weight of nanofibers web that was electrospun on the spunbonded sublayer. The results illuminate that nanofibers webs enhance press drop and filtration resistance. According to formula (2), when the diameter of fibers is smaller, the press drop is bigger.

The balance of properties

In general, filtration efficiency will be higher when the fibers diameter is small and the pore diameter is small. So the filtration efficiency of nanofibers web is higher than that of sublayers. But higher efficiency results on higher press drop (Fig. 5). In fact, big press drop makes against filtration. An excellent filter requires higher filtration efficiency and lower press drop. In practice, different applications require different properties. So, one should choose balance of properties.

In this article, we try to find the balance of properties. In Figure 5, it is found that there is an optimum region for maximum filtration efficiency at minimum pressure drop and that this optimum is at a lower is add-on weight for meltblown webs than for sponbonded webs. Figure 6 is the graph of pressure drop versus efficiency. It is obvious that the filtration efficiency at 0.5–1.0 g/m^2 add-on nanofiber webs for meltblown webs is much higher than that for sponbonded webs when the press drop is lower (200−400 Pa).

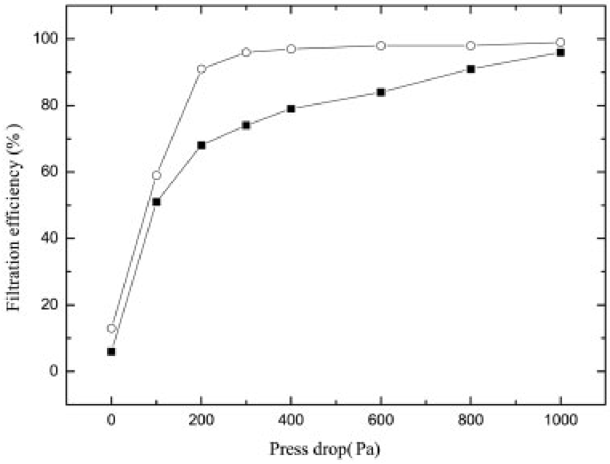

Figure 6 Pressure drop versus efficiency. The top line shows that nanofibers mats electrospun on the meltblown sublayer; the bottom line shows that nanofibers mats electrospun on the spunbonded sublayer.

CONCLUSIONS

Electrospinning nanofibers are provided with good adsorbability and excellent filtration properties because of its smaller diameter (about 200 nm in this article) and the very high surface area-to-volume ratio. Fiber diameter, pore diameter, filtration efficiency as well as filtration resistance of nanofibers web and sublayers were measured through a series of experiments. Conclusions are drawn as following:

1. The fiber average diameter of nanofibers web is about 0.2 μm. The average fiber's diameter of meltblown sublayers is about 4 μm. The average fiber's diameter of spunbonded sublayers is about 13 μm. The filtration efficiency is higher when the diameter of fibers is smaller.
2. After nanofibers web was electrospun on the sublayers, the pore diameter of the complex is much smaller than sublayers and has much smaller coefficient variation of pore diameter than sublayers. Filtration efficiency and press drop are bigger when the pore diameter is smaller.
3. Filtration efficiency and press drop increase obviously after nanofibers web was electrospun on sublayers. The filtration efficiency of complex can almost achieve 100%, but correspondingly press drop is up to 1530 Pa when 2.4 g/m^2 nanofibers web was electrospun on meltblown sublayer that filtration efficiency is 30% and press drop is 35 Pa. In fact, big press drop makes against filtration. It is found in this article that there is an optimum region for maximum filtration efficiency at minimum pressure drop and that this optimum is at a lower add-on weight for meltblown webs than for sponbonded webs.

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