Influence of Electric Field Interference on Double Nozzles Electrospinning

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ABSTRACT: The low production rate of electrospinning process may limit the industrial use of single needle system. To meet high yield requirement and uniform fibers, a bottom-up multiple jets electrospinning nozzle was designed, each nozzle can emit 6–18 jets. The influence of electric field interference on jet path, membrane shape, and fiber morphology were investigated. Experiment finds that electrical field strength in the closer part of two nozzles is weakened because of electric field interference when the distance between two nozzles is 30 mm, making the jet hard to emit in this section, and closer part of electrospun fiber webs has fewer fibers. The spinning in far side part of two nozzles is similar to that of single nozzle. While in middle part of one nozzle, the jet path is short, elongation of jets smaller, the formed fibers thicker, solvent evaporation less sufficient. When the distance of two nozzles is increased to 50 mm, influence of electric field interference is weaker, the electrospun fiber web and average diameter of fibers are almost the same as that of single nozzle electrospinning. © 2010 Wiley Periodicals, Inc. J Appl Polym Sci 116: 3688–3692, 2010

Key words: electrospinning; nanofiber; polymer; electric field

INTRODUCTION

Electrospinning is a straightforward and cost effective method for fabricating submicron fibers. In general, fibers with diameter less than 1000 nm are called nanofiber in electrospinning.[1,2] Because of unique properties such as high surface area to volume ratio, small pore sizes, high porosity and so on, the ultrafine fiber membranes prepared by electrospinning process have been extensively studied and widely used for its potential applications in filter media, composite materials, and biomedical applications.[3–7] The major technical barrier for manufacturing electrospun fibers for applications is the production rate. To achieve high throughput industrial production, several researchers investigated multiple jets electrospinning. Yarin and Zussman[8] provided a new approach using a ferromagnetic liquid sub layer. With the external electric field, the perturbations of the free surface became sites of jetting directed upward. Dosunmu et al. and Varabhas et al.[9,10] used a porous hollow tube. The mass production rate from the porous tube is 250 times greater than from a typical single jet. Liu and He[11,12] used bubble electrospinning. Multiple jets are observed during the electrospinning process as predicted for it is easy to form many bubble-induced cones on the solution surface.

In addition to the increase of production rate, multiple nozzles have been used in electrospinning. The technical problem for mass production of electrospun fibers is the assembly of nozzles during electrospinning. A straightforward multijet arrangement as in high-speed melt spinning cannot be used because adjacent electrical fields often interfere with one another, making the mass production scheme by this approach very impractical.[13] Chu[14,15] guided the design of multijet electrode arrays by a two-dimensional finite element analysis (FEA) for electromagnetic, through the use of software by Field Precision. Yang et al.[16] calculated and analyzed Electrical field distribution of a special aligned multiple jets setup. The results demonstrate that the special setup with different heights of the 7 needles could produce uniform fibers according to SEM images. Theron et al.[17] describe the results of the experimental investigation and modeling of multiple jets during the electrospinning of polymer solutions. The results demonstrate how the external electric fields and mutual electric interaction of multiple charged jets influence their path and evolution during electrospinning. Kim et al.[18] fabricated nanosize fibers using an extra-cylindrical electrode connected with single and multiple nozzles of an electrospinning process to stabilize the initial spun jets. The result indicates that the modified electrospinning technique shows a possibility as a useful method for increasing the production

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rate of nanofiber manufacturing. Tomaszewski and Szadkowski[19] tested three types of multijet electrospinning heads, series, elliptic, and concentric. The concentric electrospinning head was selected as the best type with respect to both the efficiency and quality of the process. Kim and Park[20] invented a bottom-up multiple nozzles electrospinning device to improve the productivity and quality of nonwoven webs. Although lots of literature was on multiple nozzles electrospinning, fewer works were about electric field interference on multiple nozzles electrospinning. In this work, we designed a bottom-up multijet nozzle to improve the yield of electrospinning. The influence of electrical field on jet path, membrane shape, and fiber morphology were also investigated when the distance of the two nozzles was changed.

EXPERIMENTAL

Material preparation

Polyvinyl alcohol (PVA) powder (M_w = 88,000 g mol^{-1}, 88% hydrolyzed), purchased from J & K Chemical®, was used to prepare a solution that was used as the working fluid. The polymer powder was dissolved in distilled water at 10% weight concentration with the aid of mechanical stirring. The viscosity of polymer solution was 240 mPa s. The electric conductivity of polymer solution was 26 μS/cm.

Experimental set up

The multiple-nozzle electrospinning apparatus is schematically shown in Figure 1. As shown in the figure, the electrospinning apparatus used in this study consist of a fluid reservoir (4) in which polymer solution was stored, a pump (5) pressurizing and supplying the solution in the fluid reservoir (4) to each nozzle (2). The nozzles manufacturing the solution into fibers of a fine diameter, a collector (1) for piling the electrospun fibers, and a high voltage power supply (3) for supplying electric charge required during the spinning process. The polymer solutions were electrospun at a positive voltage of 20 kV, a tip-to-collector distance of 10 cm. When the tip-to-collector distance was close, the influence of electric field on spinning was easy to observe. The flow rate of single nozzle electrospinning was 4.6 mL/h, and flow rate of double nozzle electrospinning was 8.3 mL/h.

The morphology of PVA nanofibers were observed by JSM-5600LV scanning electron microscopy (SEM). A small piece of fiber web was placed on the SEM sample holder and sputter coated with gold. Accelerating voltage of 10 kV was used to take the SEM photographs. Jets were observed by SONY

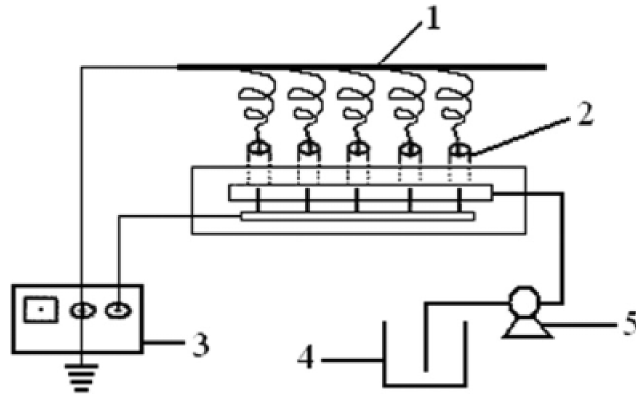

Figure 1 Schematic of a multinozzle electrospinning apparatus. (1) collector; (2) nozzle; (3) high voltage power supply; (4) fluid reservoir; and (5) pump.

DSC-F717 digital camera. The electric conductivity of the polymer solution was measured using a DDSJ-308A Intelligent Conductivity Meter. The viscosity of the polymer solution was measured using a HAAKE RS150 Rheometer.

RESULTS AND DISCUSSION

The electric field of electrospinning was analyzed by a three-dimensional FEA (Ansoft Maxwell) for electromagnetic. The yz plane which passes through axis of nozzles and collector is chosen to describe the distributing of electric field; results are shown in Figure 2. Applied voltage of nozzles was all 20 kV; the collector was connected to ground. The density of equipotential lines indicates the strength of the electric field in a particular region. The field is stronger where the lines get closer together. The arrow in Figure 2 is electric intensity vector (E vector), which denotes the direction of electrostatic field. Figure 2(a) shows electric field of single nozzle electrospinning. The equipotential lines near the nozzle are closer, near the collector are sparser. The equipotential lines near the edge on the top of nozzle are closest, which means electric field there is strongest. Electric field lines that start from edge on the top of nozzles are declining at fist then turning to be perpendicular to collector. Electric field lines that start from middle on the top of nozzle are perpendicular to collector. Figure 2(b) shows electric field of double nozzles electrospinning with the distance of two nozzles is 30 mm. The equipotential lines near the right edge on top of left nozzle are sparser than that near the left edge, which means electric field strength near the right edge on top of left nozzle is weaker than that near the left edge. The interference of electric field makes the electric field strength weaker at the top of nozzles. The equipotential lines are sparser and the electric field lines are almost perpendicular to collector between two nozzles, which

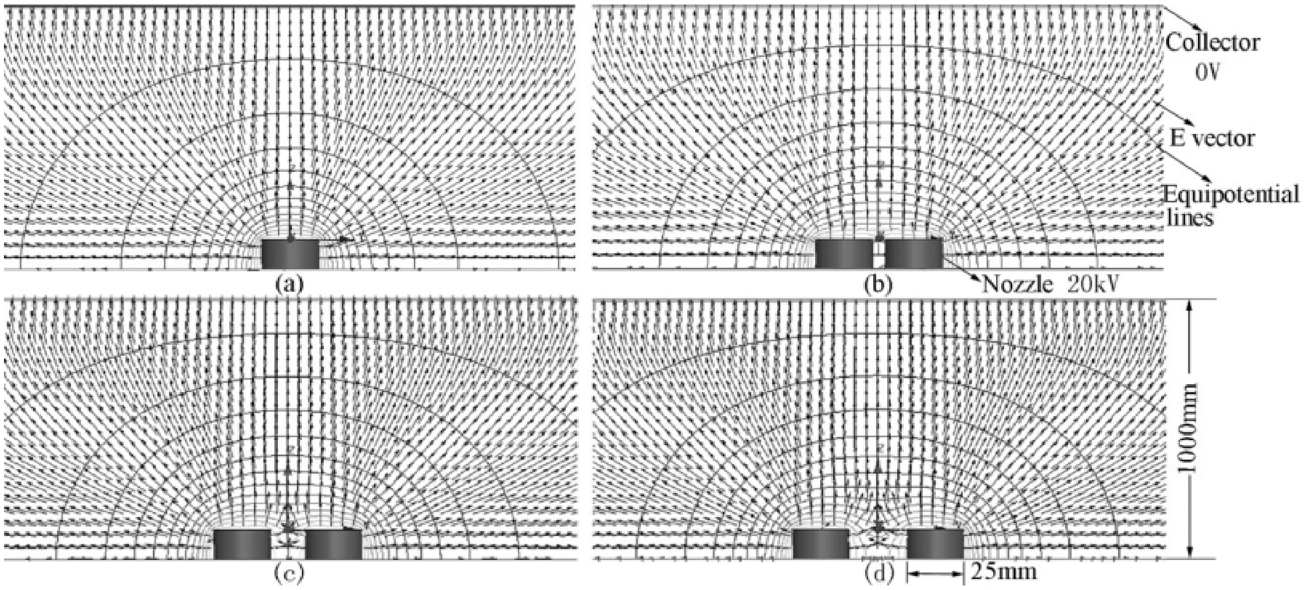

Figure 2 Equipotential lines and E vector calculated for single and double nozzles electrospinning. (a) single nozzle, (b) double nozzle, distance between nozzles 30 mm, (c) double nozzle, distance between nozzles 40 mm, (d) double nozzle, distance between nozzles 50 mm.

means the electric field strength is weaker and direction of electric field is almost perpendicular to collector there. Figure 2(c) shows electric field of double nozzles electrospinning with the distance of two nozzles is 40 mm. Equipotential lines near the right edge on top of left nozzle in Figure 2(c) are closer than that near the same position in Figure 2(b), and the electric field lines incline toward to the other nozzle slightly then turn to be perpendicular to the collector. Figure 2(d) shows electric field of double nozzles electrospinning with the distance of two nozzles is 50 mm. Equipotential lines near the right edge on top of left nozzle in Figure 2(d) are closer than that near the same position in Figure 2(c), and the electric field lines incline toward to the other nozzle then turn to be perpendicular to the collector. When the distance of two nozzles is 30 mm, interference of electric field is strong, electric field lines seldom inclined toward to the other nozzle. When the distance of two nozzles is increased to 40 mm, interference of electric field turns weak. When the distance of two nozzles is increased to 50 mm, interference of electric field on electrospinning can be neglected.

Jets' path of single and double nozzles electrospinning was also observed. Many jets emit from the nozzle, and jets emit aslant from edge on top of nozzle when single nozzle was used for electrospinning. Electric field strength is strong near edge on the top of nozzle, and surface charge density there is high. Electric force there is easy to overcome surface tension to form jets. The electric field lines there are declining, so the jets are declining. When double nozzles were used for electrospinning and distance between nozzles was 30 mm, no jets emit at the part near the other nozzle on the top of nozzle. Jets can emit from middle part and the part away from the other nozzle on the top of nozzle. Emitted jets from middle part on top of nozzle incline slightly faraway from the other nozzle, path of the jets there is short, elongation smaller. Emitted jets from the part away from the other nozzle are similar to that of single nozzle electrospinning at the same position. When the distance between two nozzles is 30 mm, one third of the area on top of nozzle has no jet. When the distance between two nozzles is 40 mm, only one fifth of the area on top of nozzle has no jet. When the distance between two nozzles is 50 mm, all the area on top of nozzle has jets, and the emitted jets of one nozzle are almost the same as that of single nozzle electrospinning. Electric field interference decreases when the distance of two nozzles increase. When the distance between two nozzles is 50 mm, influence of electric field on jets can be neglected.

Figure 3 shows fiber webs of single and double nozzle electrospinning after spinning for 2 min. It can be seen from Figure 3(a) that fiber web spun from one nozzle is a round. Jets almost emit from edge on top of nozzle, and the emitted jets are inclining, so most fibers deposit at the edge of fiber web. When the distance of two nozzles is 30 mm, closer part of fiber webs spun from two nozzles has fewer fibers. Fiber web spun from each nozzle is about two thirds of a round. When the distance of two nozzles is 40 mm, closer part of fiber webs spun from two nozzles have some fibers. Fiber web spun from each nozzle is about four fifths of a round. When the distance of two nozzles is 50 mm, closer

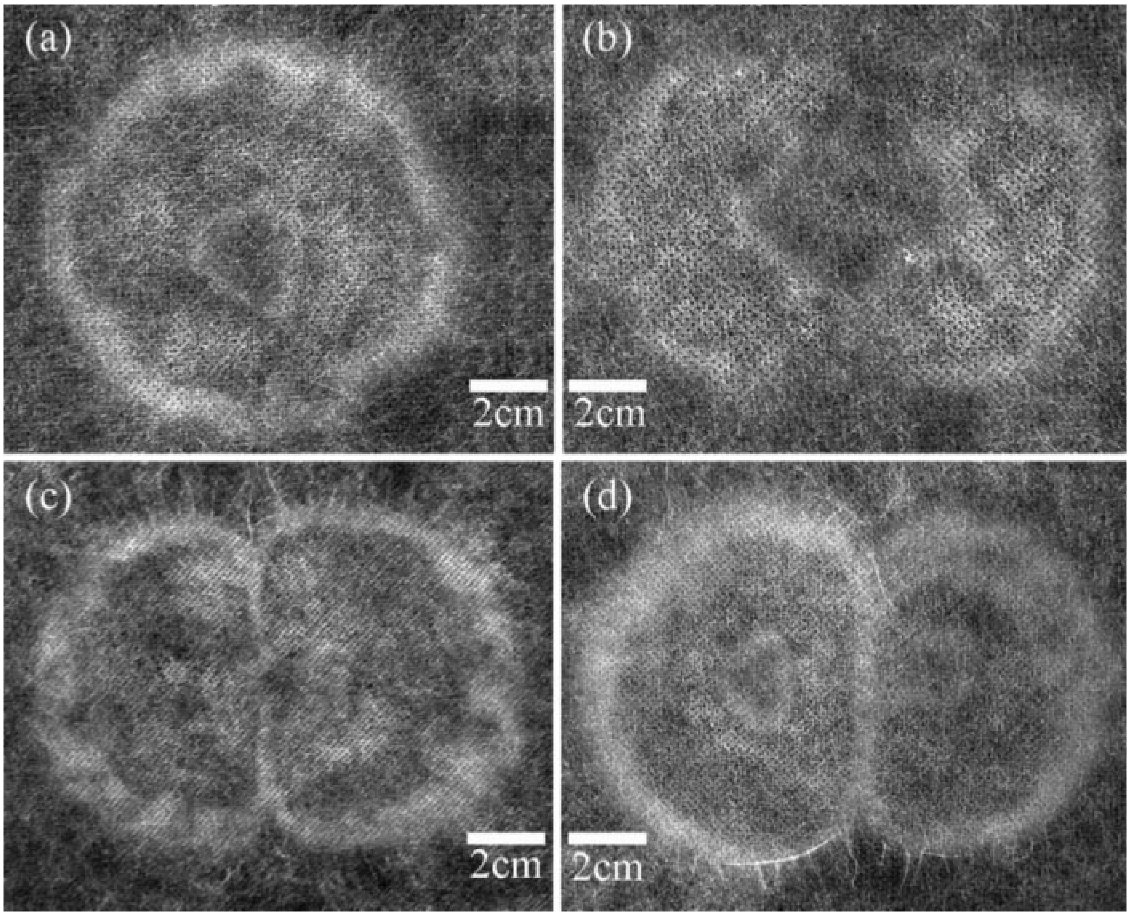

Figure 3 Fiber web Photographs of single and double nozzles electrospinning. (a) single nozzle, (b) double nozzles, distance between nozzles 30 mm, (c) double nozzles, distance between nozzles 40 mm, (d) double nozzles, distance between nozzles 50 mm.

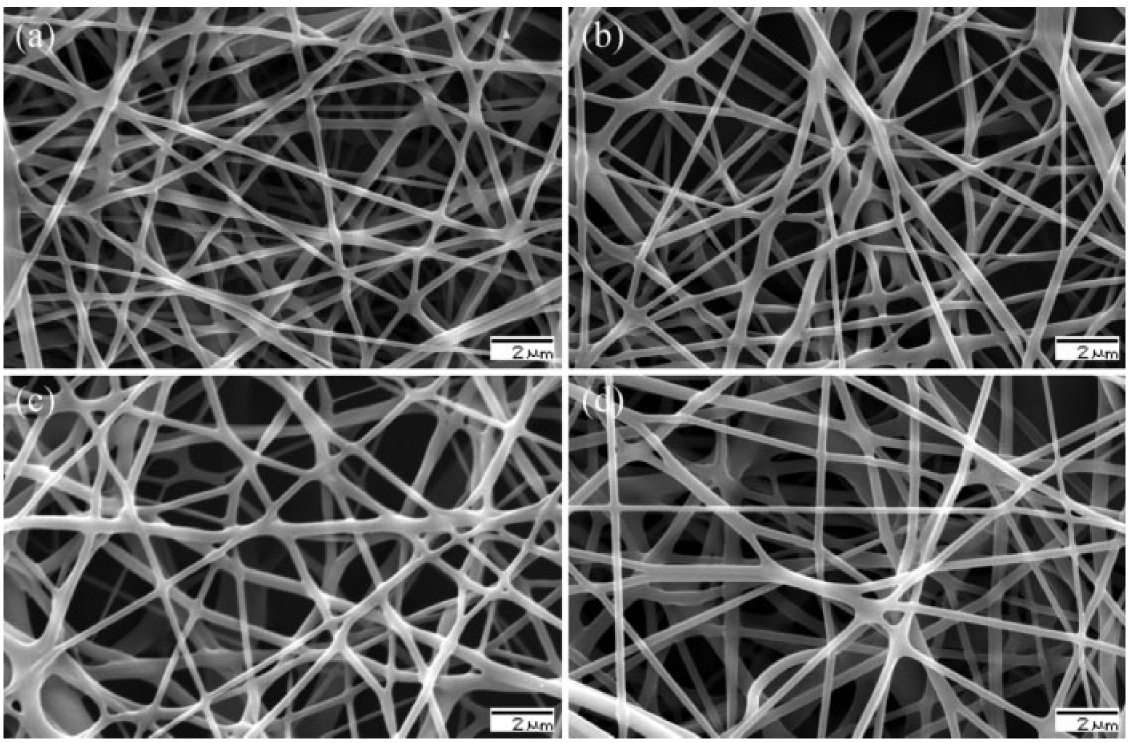

Figure 4 SEM micrographs of single and double nozzles electrospinning. (a) single nozzle, (b) double nozzles, distance between nozzles 30 mm, (c) double nozzles, distance between nozzles 40 mm, (d) double nozzles, distance between nozzles 50 mm.

TABLE I
Fiber Average Diameter and Standard Deviation of Single and Double Nozzle Electrospinning

Sample	a	b	c	d
Average diameter (nm)	231	267	252	246
Standard deviation (nm)	47	83	61	53

part of fiber webs spun from two nozzles have lots of fibers. Fiber web spun from each nozzle is almost a round. When the distance between two nozzles increases, the fiber webs turn white. This indicates that solvent evaporation of electrospun fibers become better. When the distance of two nozzles is 50 mm, fiber web spun from each nozzle is almost the same as that spun from single nozzle.

Figure 4 shows SEM micrographs of samples indicated in Figure 3. Four SEM micrographs at different part of each sample were used and fifty fibers in each SEM micrograph were selected to calculate average diameter and standard deviation, results are shown in Table I. As is shown in Figure 4 and Table I, average fiber diameter and standard deviation decrease slightly along with the increase of distance between two nozzles. When the distance between two nozzles is close, interference of electric field is strong; electric field on top of nozzle is weakened, the elongation of jets is smaller, so spun fibers are thicker. Instability of jets emitted from the side near the other nozzle on top of nozzle is weaker, jet's envelop cone is suppressed, jet path is shorter, jet elongation is smaller, so spun fibers are thicker and solvent evaporation is worse. Interference of electric field at difference part on top of nozzles is different, so standard deviation of spun fibers is larger. Solvent evaporation of some jets in the middle of emitted jets is more difficult, so solvent evaporation of jets emitted from the side near the other nozzle is worse. When the distance between two nozzles is 50 mm, average diameter and standard deviation of spun fibers are larger than those of single nozzle electrospinning, but the difference is smaller. Bead doesn't appear in all the SEM micrographs, which means this kind of nozzle is suitable for electrospinning.

CONCLUSIONS

To improve the product rate of electrospinning, a bottom-up multijet electrospinning nozzle was designed; each nozzle can emit 6–18 jets. Influence of electric field interference on jet path, fiber web, and fiber morphology along with the increase of distance between two nozzles was investigated. Results show that when the distance between two nozzles is close, interference of electric field is strong, jets cannot emit from the part near the other nozzle on top of nozzle, and closer part of fiber webs spun from two nozzles has fewer fibers. Path of jets emitted from middle part on top of nozzle is shorter, elongation of the jets is smaller, spun fibers is thicker and solvent evaporation is worse. When the distance of two nozzles is increased properly, the electrospun fiber web and average diameter of fibers are almost the same as that of single nozzle electrospinning.

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