International Journal of Electrospun Nanofibers and Applications, Vol. 3, No. 2 (July-December, 2017)
ISSN : 0973-628X

The Conductivity Enhancement of Electrospun PVP Nanofibers with an Inorganic Salt Additive

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Abstract: *The properties of electrospun PVP nanofibers are affected by an inorganic salt additive, KCl. The conductivity and nano-effect are studied in this paper. The PVP nanofibers containing 0.6 wt.% KCl exhibits a surprisingly small diameter. A very simple theoretical prediction is given to explain the relationship between the average diameter of the nanofibers and the conductance of the electrospun solution.*

Keywords: *Electrospinning; Conductivity; Nanofibers, nano-effect, spider*

1. INTRODUCTION

Electrospinning has been rapidly developing in the last decade as a simple and versatile approach to producing nanofibers from various synthetic and natural polymers [1,2]. Many new devices have been designed, such as vibration-electrospinning [3,4], magento-electrospinning [5,6] and bubble-electrospinning [7,8,9].

Nanofibers with diameters of less 100 nm always behave extremely well in many aspects due to nano-effects[10], for example remarkable strength, high surface energy and surface reactivity, excellent thermal and electric conductivity [1,2]. As an illustrative example, we consider a dragline assembly with diameter of 3×10^{-6} meter which consists of many nano fibers with diameter of about 20nm. We can estimate the number of nanofibers in the assembly, which reads [11,12]

$$n = \left(\frac{3 \times 10^{-6}}{20 \times 10^{-9}} \right)^2 \approx 2 \times 10^4$$

There are tens of thousands of nanofibers in a single dragline assembly [13, 14].

Similar to the Hall-Petch relationship, the nanofiber strength depends upon fiber diameter in nano-scale (from few nanometers to tens of nanometers) [10]:

$$\tau = \tau_0 + \frac{k_\tau}{d^{1/2}}$$

where k_τ is the fitting parameters (material constants), τ_0 is the strength of the bulk material respectively, d is the fiber diameter.

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Comparing the strength of a single fiber with diameter of 3×10^{-6} meter, τ_{SF}, with that of a dragline assembly consisting of 2×10^{4} nanofibers with diameter of 20×10^{-9} meter, τ_{DA}, we estimate

$$\frac{\tau_{DA}-\tau_0}{\tau_{SF}-\tau_0}=2.4\times10^{6}$$

Extraordinarily high strength of a dragline assembly is predicted compared with a single fiber with same section area and same material.

The finding shows it is a challenge to developing technologies capable of preparing for nanofibers within 100 nm. To this end, non-ionic surfactants was used in our previous study to improve electrospinability [15]. In this study KCl is added into the electrospun solution to enhance conductivity, as a result, the electrostatic force acting on the conductive jet and jet velocity are remarkably increased. According to the conservation of mass during the electrospinning procedure [16, 17]

$$\rho r^2 \rho u = Q \tag{1}$$

where u is the velocity of the jet, Q is the flow rate, ρ is the density and r is the radius of the nanofiber.

The radius of nanofiber deceases with increase of jet velocity ($r \propto u^{-1/2}$). So conductivity can best adjust the spinning procedure, and our aim of this paper is to prepare for nanofibers within about 100 nm by adjusting the concentration of KCl.

2. EXPERIMENT

2.1 Materials

Polyvinylpyrrolidone (PVP) with the serial number of K-30, KCl and absolute alcohol were purchased from Shanghai Chemical Reagent Co. Ltd., China. Deionized water was supplied by college of chemistry of Donghua University. The mixture of deionized water and absolute alcohol with the weight ratio 1:2 was used as a solvent. All materials were used without any further purification.

2.2 Instrumentation

The electrospinning setup consisted of a syringe, a needle, a grounded collected plate, a flowmeter and a variable DC high-voltage power generator (0-100kv, f180-L). The scheme of the electrospinning process was showed in Fig. 1.

Fiber diameters and the morphology of the nanofibers obtained were analyzed using a scanning electron microscope. The Conductivity Meter (DDS-310) was used to test the conductance of the solution.

2.3 Electrospinning Process

All concentration measurements were done in weight by weight (w/w). The mixture of deionized water and absolute alcohol with the weight ratio 1:2 was used as solvent. PVP with the concentration of 38% was solved in the above solvent. KCl was added into the

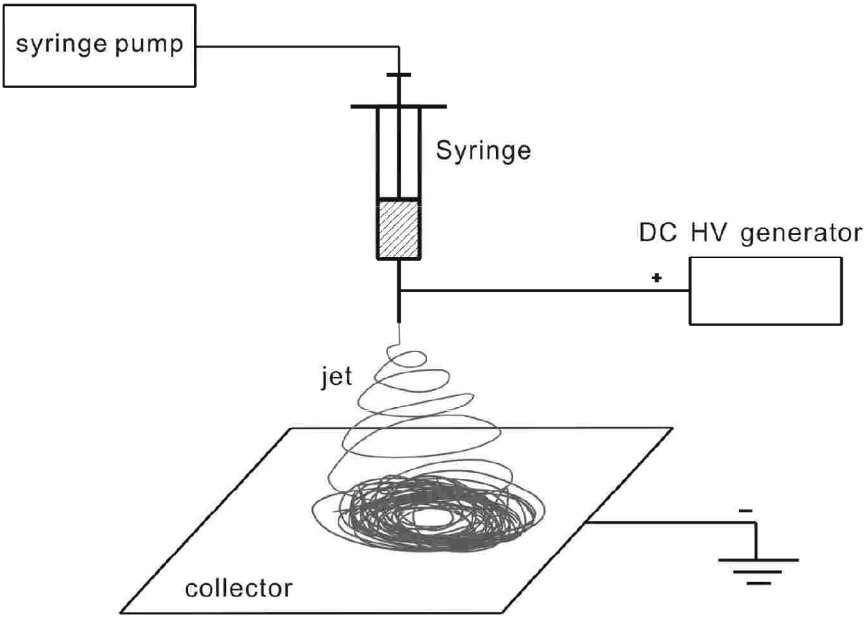


Figure 1: Electrospinning Setup

obtained solution at the ratio of 0.2, 0.4, 0.6, 0.8, 1.0wt%, respectively. The prepared solution was magnetically stirred at 30 centigrade degrees. The tip-to-collection distance was 15cm. The applied voltage connected to the needle was 20kv. All electrospinning processes were carried out under room temperature in a vertical spinning configuration.

3. RESULTS AND DISCUSSION

The morphology of the electrospun fibers, PVP fibers, was investigated by a scanning electron microscope (SEM, JSM-5610). The fiber mat was collected on a SEM disk and coated with gold before photographing. SEM micrographs are illustrated in Fig. 2. Conductance was remarkably increased when KCl was added into solution, see Fig. 3. Fig. 4 showed that the average diameter of the fibers decreased with the increase of KCl concentration until $wt.\%=0.6\%$.

The scaling relationship between the surface charge (σ) of the jet and the conductance of the solution (G) can be generally expressed in the form [11,15]

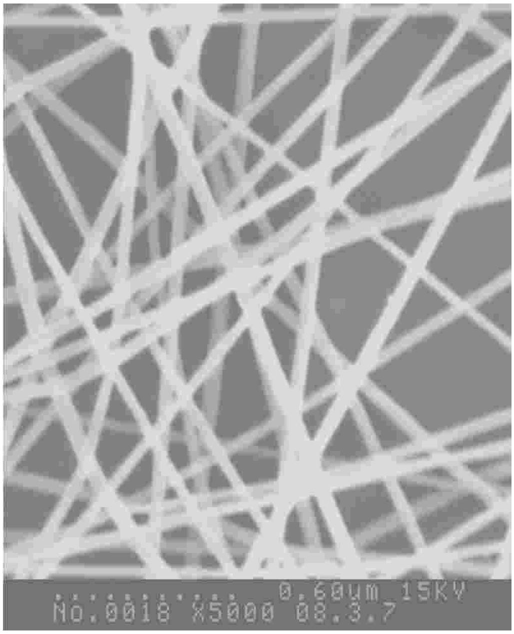
$$\sigma \propto G^m, \tag{2}$$

where m is a scaling exponent.

The electric force (F_E) acting on the charged surface isometrically scales with the surface charge:

$$F_E \propto \sigma. \tag{3}$$

Consider the initial stage of the ejection of the charged jet, according to Newton's second law, we have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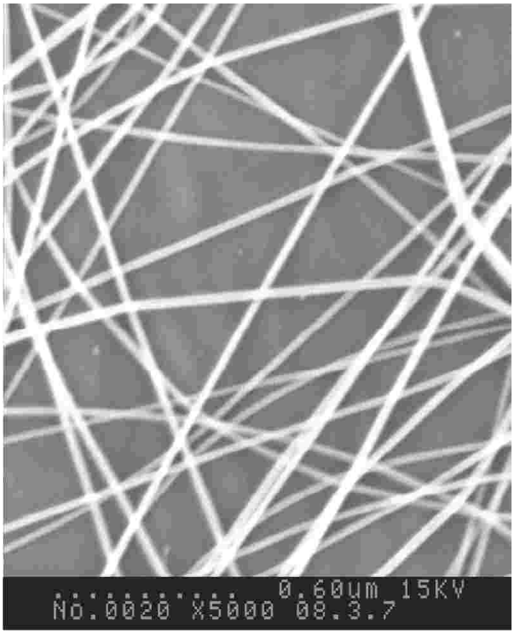
(a)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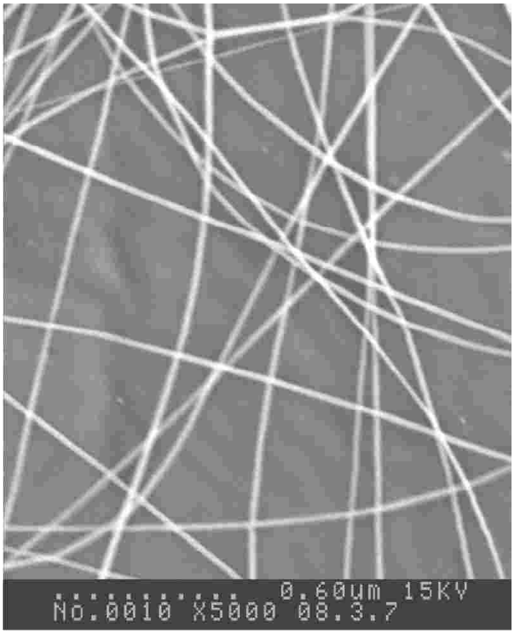
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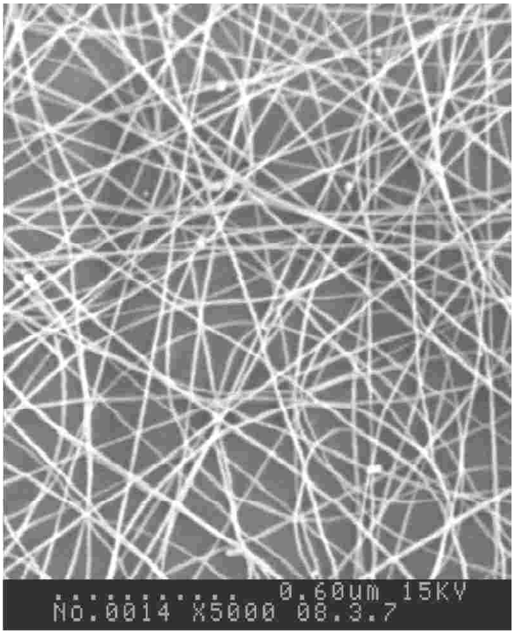
(c)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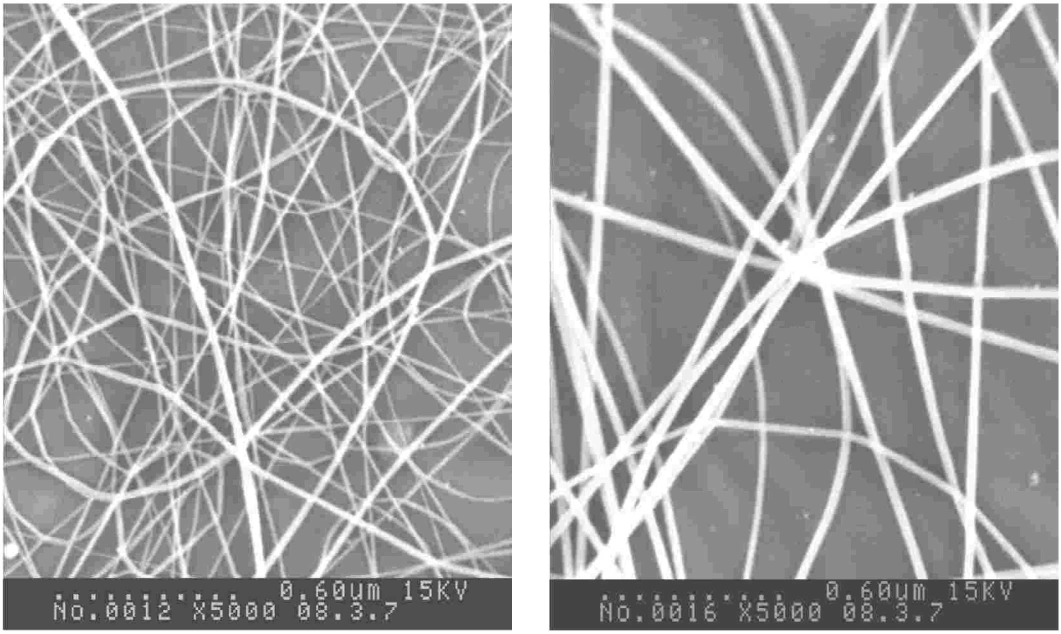
(d)



(e) (f)

Figure 2: Scanning Electron Micrographs of Electrospun Fibers at Different KCl Concentrations (wt%): (a) 0, (b) 0.2, (c) 0. 4, (d) 0.6 (e) 0.8 (f)1

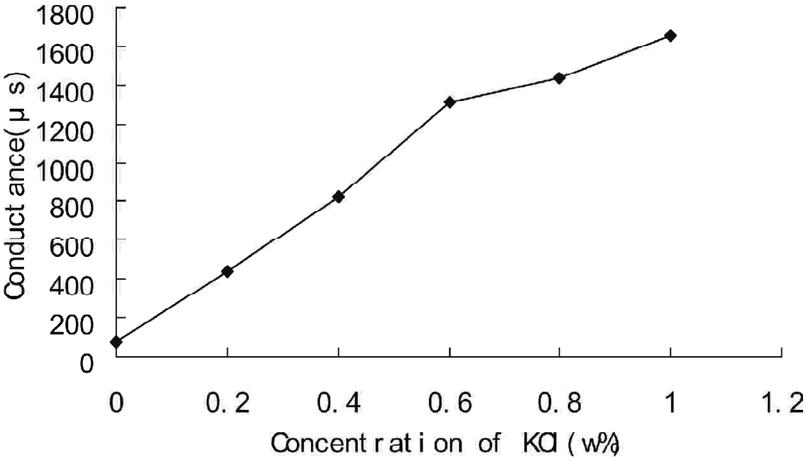


Figure 3: Conductance of 38Wt% PVP Solution with Different KCl Concentrations

$$F_E - F_S = ma, \tag{4}$$

where F_S is the surface tension, a is jet's acceleration.

We have

$$a \propto F_E \propto \sigma \propto G^m \tag{5}$$

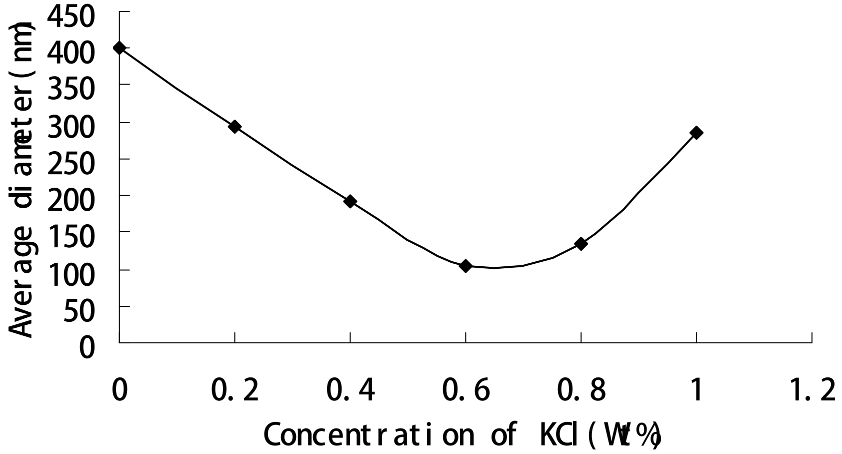


Figure 4: Average Diameter of 38Wt% PVP Nanofibers with Different KCl Concentrations

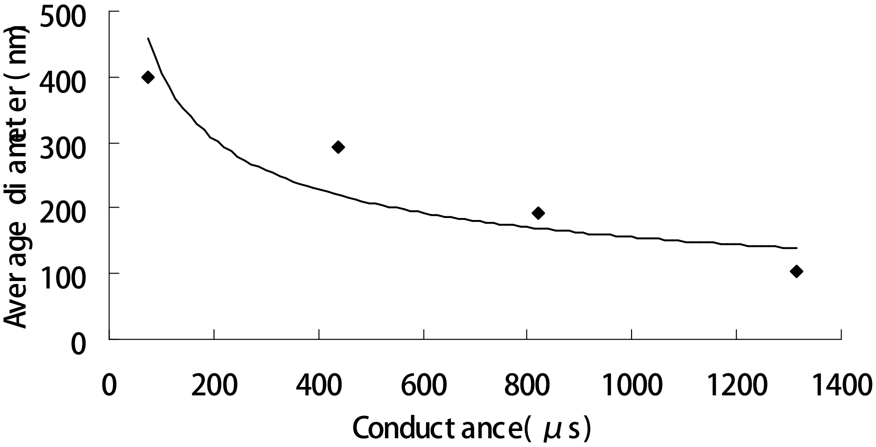


Figure 5: Effect of the Conductance on the Diameter of the Electrospun Nanofibers

According to the conservation of mass , Eq. (1), we have

$$r \propto u^{-\frac{1}{2}} \tag{6}$$

Differentiating Eq.(6) with respect to time, we have

$$\frac{dr}{dt} \propto u^{-\frac{3}{2}} \frac{du}{dt} \propto r^3 a \tag{7}$$

or

$$\frac{d}{dt}\left(r^{-2}\right) \propto a \tag{8}$$

From Eq. (8), we can approximately obtain the following scaling

$$r \propto (a\Delta t)^{-\frac{1}{2}} \text{ or } r \propto a^{-\frac{1}{2}} \tag{9}$$

In view of (5), we have

$$r \propto G^{-\frac{1}{2}m} \text{ or } r \propto G^{-p} \tag{10}$$

where $p = m / 2$.

In our experiment, we obtain approximately (see Fig. 5).

$$r = 2790.4G^{-0.418} \tag{11}$$

4. CONCLUSIONS

The inorganic salt, KCl, can be used to adjust the electrospinning procedure effectively. By suitable choice of KCl concentration, fiber diameter can reach a minimal value. Nanofibers with diameter of less than 100nm always exhibits surprising mechanical, thermal and electronic properties due to the nano-effect as seen in spider fibers. A complex yarn can be produced using the rotor-spun composite yarn spinning process [18], the obtained assembly might behave well, which will be studied later.

ACKNOWLEDGEMENT

The work is supported by National Natural Science Foundation of China under Grant No. 10802021, National Natural Science Foundation of Shanghai under Grant No. 08ZR1400300, the 111 Project under Grant No. B07024 and Program for New Century Excellent Talents in University.

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