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ARTICLE

Needleless Electrospinning: Reciprocation *vs.* Rotation

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ABSTRACT

Needleless electrospinning is a versatile method to produce nanofibers. In particular, the rotary version of this technique has enjoyed widespread use because there is no need to clean the spinneret. The rotation speed is limited by the potential deviation of the jet due to the centrifugal force. Other limitations are due to the fast volatilization of the solvent from the opened spinning system. In order to overcome these drawbacks, here a novel reciprocating system based on a moving spinning-plate is proposed. The spinning process is implemented in a half-closed system with the spinning-plate immersed in the solution tank. When the immersed spinning-plate moves up from the solution tank, multiple jets are ejected from the droplets on the tips of the spinning-plate under the effect of an electric field force. The morphology of the obtained nanofibers has been analyzed by scanning electron microscopy. The results indicated that the obtained fibers are uniform in structures and small in diameters. Both issues of needle clogging and intense solvent evaporation can be mitigated using this alternate approach.

KEYWORDS

Needleless electrospinning; reciprocation; spinning-plate; nanofibers

1 Introduction

A great number of fabrication methods have already been studied to produce nanofibers among which electrospinning is simple but effective technique. Nanofiber membranes from various materials such as polymers, composites, and ceramics can be generated through the electrospinning method [1–4]. Due to their outstanding properties such as high porosity, high specific surface area and controllable fiber diameters, nanofiber membranes show enormous potential for various applications such as tissue engineering, drug delivery, catalysis, sensors, energy conversion and storage, reinforcement, water treatment, and environmental protection [5–11].

The low output of the conventional electrospinning with a single-needle hinders its industrial applications. Needleless electrospinning [12] and bubble electrospinning [13–16] were investigated to address such a problem. The former technique generally adopts a rotary spinneret such as cylinders, coils, and needle-disks in which the jets are ejected from the surface of the spinneret [17]; and the latter uses the polymer bubbles for mass-production of nanofibers.

2 Rotary Needleless Electrospinning

The comparison of different rotary needleless electrospinning techniques is shown in Fig. 1. Rotary needleless electrospinning is an alternative strategy for the mass-production of nanofibers. In general, the rotary needleless electrospinning is conducted in an open system with a solution tank and a rotary spinning device. These setups have different kinds of industrial spinnerets: cylinder spinneret [18], rotary wire spinneret [19], spiral coil [20], rotary needle spinneret [21], ball [22], needle-disk [12]. However, the cylinder type is still one of the most productive.

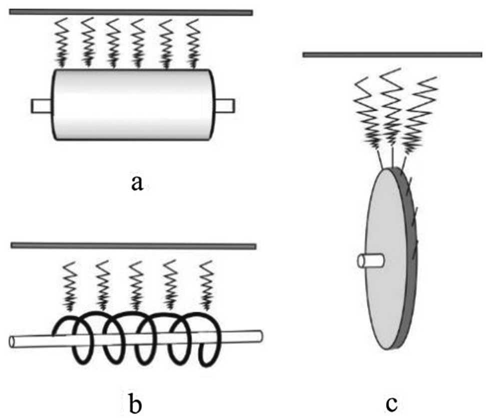

Figure 1: Rotary needleless electrospinning equipment. (a) A rotary cylinder spinneret [18], (b) A spiral coils spinneret [19], (c) A Needle-disk electrospinning setup [12]

In such a setup, the spinning spinnerets are all connected with a high voltage power supply and driven by a motor. Mostly, the needleless rotary spinnerets are partially immersed in the polymer solution. The polymer solution is loaded on the surface of a rotary spinning spinneret and the obtained nanofibers are collected on a collector above the rotary spinneret. Multiple Taylor cones are simultaneously self-formed in the out flowing solution by rotation action and electric field force. Then nanofibers are electrospun upwards and deposited on the collector.

In these types of rotary needleless electrospinning equipments, the solution is loaded on the surface of the spinneret by the rotation action. In order to ensure a stable electrospinning process, the rotation speed is limited to avoid the deviation of the solution from the path by the centrifugal force. The electrospinning process will be disturbed; and nanofibers will not be deposited on the collector. Therefore, high rotation speed shows harmful effects on the electrospinning process and efficiency. In addition, the solvent is easily volatilized from the opened spinning system. It can result in changing spinning solution concentration and seriously affect the spinning quality.

3 Reciprocating Needless Electrospinning

In order to overcome the shortcoming of the rotary needless electrospinning, we hereby proposed reciprocating needless electrospinning with a reciprocation spinning-plate which can avoid the impact of high rotation speed caused by the centrifugal force. The novel reciprocating needless electrospinning setup is shown in Fig. 2. The spinning-plate is connected with a high voltage power supply and moves up and down in the polymer solution. When the spinning-plate moves up from the solution, the solution is loaded on the surfaces of the spinning-plate's tips. The solution on the tips of the spinning-plate is easy to form a Taylor cone with the force of electric field and reciprocation. As a result, continuous jets are ejected from the tips of the spinning-plate and a great number of nanofibers will be constantly deposited on the negative collector.

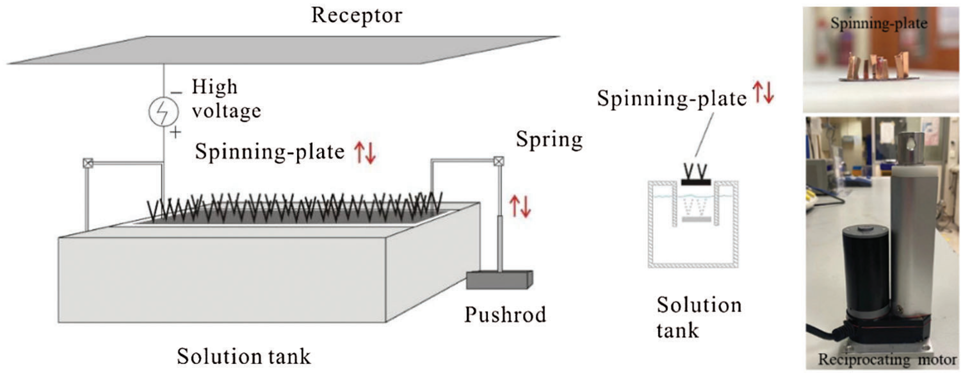

Figure 2: Reciprocating needleless electrospinning setup

Even though the reciprocating speed is very high, the electrospinning stability will not be affected. When the reciprocating speed is low, the solution will load on the surface of the spinning-plate's tips where the jets are constantly produced. When the reciprocating speed is high, the solution on the surfaces of the spinning-plate's tips will move upwards under the action of inertia with the downward movement of the spinning-plate and form droplets. The droplets are far away from the collector which benefits the electrospinning process. The formed droplets are easy to produce Taylor cones with the electric field force. Continuous jets will be ejected from the droplets and deposited on the collector.

This reciprocating needless electrospinning method will not be affected by the moving speed of the spinneret. Whether the speed is high or low, the electrospinning process will proceed steadily. It provides an effective way to promote the stability of charged jets and achieve massive production of nanofibers. Moreover, the closed solution tank can address the solvent volatilization problem and maintain stable spinning conditions and parameters. The production of the nanofibers will be greatly improved by increasing the number of needles on the spinning-plate.

4 Experimental

Polyvinyl alcohol (PVA) used in this experiment was purchased from Shanghai Aladdin Biochemical Technology Co., Ltd. (Shanghai, China) and stored at room temperature. The alcoholysis degree of PVA is 98-99.0 mol%. PVA was directly used as received without any further purification.

PVA solution was prepared at room temperature by dissolving the polymer in deionized water with a concentration of 8 wt%. The PVA solution was stirred in a magnetic stirrer (DF-101S, Jintan Xinrui Instrument Factory, Changzhou, China) while heated at 80°C for two hours to ensure complete dissolution.

The electrospinning setup was shown in Fig. 2. The experimental setup consisted of a solution tank, a metal spinning plate, a collector, a high voltage power supply, and a reciprocating pushrod. The PVA solution was electrospun at room temperature at a voltage of 30 kV. The spinning-plate used in this experiment was positively charged. The negative collector was placed 15 cm from the top of the solution tank. The spinning-plate moved up and down from the solution tank during the electrospinning process with the speed of 10 mm/min. With the electric field force, continuous nanofibers were deposited on the collector and collected in the form of a non-woven nanofiber membrane.

5 Result and Discussion

The experiment was carried out at room temperature. During the electrospinning process, the collecting system was connected to negative voltage and the spinning-plate was connected to high voltage. The electrospinning process can be divided into three steps: (i) solution feed: the reciprocating plate causes the needless to take up the polymer solution and form a continuous film on the needless, and then pass through the electric field; (ii) droplet formation: a number of droplets are continuously formed on the liquid film on the tips of the needles; (iii) Taylor cone formation and jet initiation: jets emerge from the surface of the needle tips when the force of the electric field overcomes surface tension. When the spinning-plate moved up from the solution, there were droplets on the tips. With the electrostatic force, the Taylor cones were formed on the droplets. With the electrostatic force was large enough to overcome the surface tension of the Taylor cones. Multiple jets were ejected from the tips and moved towards the negative collector.

The morphology and diameters of PVA nanofibers were determined using a scanning electron microscope (SEM, Hitachi S-4800, Tokyo, Japan). The SEM images of PVA nanofibers are shown in Fig. 3. The electrospun PVA nanofibers exhibited a smooth surface and cylindrical morphology. PVA nanofibers were randomly distributed in nanofiber membranes with uniform structures that adhered to each other. The average diameter of the PVA nanofibers was about 250 nm.

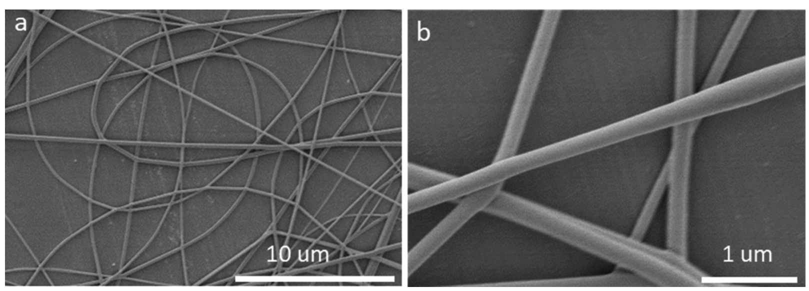

Figure 3: SEM images of PVA nanofibers. (a) SEM image at low multiple. (b) SEM image at high multiple

6 Conclusions

Electrospinning is a simple but effective technique for fabricating micro/nanofibers. A great number of fabrication methods have already been proposed. In this paper, we reported a novel needleless electrospinning method with a reciprocated spinneret. It avoided the effect of the centrifugal force on the spinning process due to high rotation speed. The reciprocating motion showed a positive impact on the electrospinning process. On the other hand, the multiple needles greatly increased the efficiency of nanofibers production; and the closed solution tank could prevent the solution volatilization compared to the open solution tank. The obtained nanofibers showed uniform morphology. The electrospinning efficiency can be controlled by the shape, diameter, number, arrangement, and movement frequency of the needles. It lay a foundation for future research of nanofibers with well-defined characteristics. In the future, we plan to explore the effects of reciprocated speed, spinning-plate characteristics including surface structure, conductivity, and fineness on the morphology and diameter of the nanofibers.

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Conflicts of Interest: The authors declare that they have no conflicts of interest to report regarding the present study.

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