A Review on the Research Status of Massive Production of Nanofibers via Electrospinning Technology

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Abstract: Nanofibers can be widely used to prepare a variety of materials, such as filter materials, biosensors, protective coating for military suits, three-dimensional tissue scaffolds, composite reinforcement, drug carrier, wound dressing and electronic devices due to their high specific surface area, and small pores generated among nanofibers in the end products. Electrospinning is an efficient method for massively manufacturing nanofibers, nano-thin film materials. In this paper, the basic mechanism of massive electrospinning technology, including multi-needle electrospinning and needle-less electrospinning are discussed. The interference among needles/nozzles has been a barrier to realize massive production of nanofibers via multi-needle electrospinning technology. The influence from different arrangement/configurations of the needles, the characteristics and applications of the eletrospun products are also analyzed. In needle-less electrospinning process, the key problem is how to generate surface disturbance in the polymer solution or polymer melt. The principles and characteristics of the generation of magnetic field disturbance, bubble disturbance, spinning solution disturbance on the surface of the rotating spinning electrode, spinning solution disturbance on the surface of rotating disk electrode and massive production of electrospun fibers via porous tubular spinning head are summarized and compared.

Keywords: nanofibers; electrospinning; production; needleless

1. Introduction

With the development advancing of nanotechnology, electrospinning technology has become an efficient and practical preparation method of nano fibers, increasingly extensive attention is focused on the research of nanomaterials research [1]. Electrospinning device mainly consists of three parts sections: high voltage power supply, the needle(s) (metal capillary) and the collection/receiving screen. High voltage power is typically supplied by DC power; needle(s) can be placed arranged vertically or horizontally, which connected with the injection pump for quantitatively controlling of the liquid spinning solution quantitatively. Receiving screen can be in the form of metal plates, nets, rollers or be specially designed according to specific circumstances. In the electrospinning process with needle, the strong electric field is can polarized the polymer solution,. , forming the so-called Taylor Cone on the tip of the needle. At this time, the polymer solution is formation of Taylor Cone due to the comprehensive action of three same sex forces mutually exclusive including i.e., Coulomb force, surface tension and charge visco-elastic force. When the Coulomb repulsion force on the Taylor Cone is further increased and finally and the charge is greater overcomes the its surface tension and visco-elastic force, the cone gains more length, becoming more slender and spinning solution jets are formed and move towards the receiving screen located at the lower electric field end; the polymer solution overcomes its own surface tension and viscous force and can be formation of spraying meanwhile, a thin stream the solution jets go through the course of bending instability; then , with solvents volatilizing fast, polymer curing , and then producted nanofibers was are collected in on the receiver screen [2] as a result..

2. Large Scale Production Technique for Electrospinning Nanofibers

Nowadays bulk production of the electrospun nanofibers has become hot spot in the worldwide nanotechnology research field, and the most important electrospinning techniques for massive production of nanofibers are addressed below.

2.1. Multi-needle Array Electrospinning

Combination of multi-needle array electronic spinning is natural extension of the traditional single needle electrospinning. The needles can be arranged with equal distance along a straight line, round, oval, etc [3].

In his electrospinning research, Tomaszewski [4] adopted linear, elliptical and circular arrangement of the spinning needles separately, and then measured the spinning efficiency in terms of the average yield per needle. It was found that the linear arrangement of the needles returned the least yield, the oval needle arrangement generated fairly good yield, and the circular needle arrangement produced nanofibrous product with the most efficiency and best quality out of the three needle arrangement methods.

Theron et al [5] used nine spray heads instead of single jet head in his research, with nine needles arranged in 3 × 3 arrays and 9 × 1 arrays respectively. Different from the single needle device, the spinning jets in multi-needle electrospinning are not only controlled by the electric field force, but also affected by the Coulomb repelling force from the neighboring jets. In addition to the center of the needle, the other jet needles are bent to the off-center position, while the needle is also easy to congestion. It was also found that the side spinning needles tended to spray jets bending towards outside of the needles compared to the needle in the middle.

G. Kim et al [6] added metallic rings to the multi-needle array as auxiliary electrode, weakening the interaction of the charges between the needles and avoiding the interference of the external environment on the spinning head. The result showed that this method could stabilize the jet spray range and increase the productivity of nanofibers, but the problem of needle blockage still existed.

Ding [7] made use of the multi-needle Electrospinning with some needles spraying polyvinyl alcohol solution, other needles spraying cellulose acetate solution to produce mixed nanofiberous webs. The method provided a guideline for the production of functional nano-fiberous web.

2.2. Needleless Electrospinning of Multiple Nanofibers

The key of effectively scaling-up the production of electrospinning is how to generate numerous Taylor cones from the liquid free surface of polymer solution (i.e., how to generate free surface disturbance). In needleless electrospinning, there can be a variety of controlling methods to generate instability from the solution free surface via producing disturbance waves, such as the application of magnetic technology, ultrasound technology, and mechanical methods. Typically three methods of perturbation can be used to produce Taylor cones, which are: (1) magnetic field disturbance electrospinning technology; (2) inflatable bubbles disturbance solution electrospinning technology; (3) rotating the surface of the electrode produced disturbance electrospinning technology [8].

2.2.1. Needleless Electrospinning Technology Combined with Magnetic Field

Electrospinning was firstly proposed by Yarin et al [9]. In their research a layered solution system was placed in a permanent magnet or a vertical magnetic field formed by the conductive coil, with the iron magnetic fluid on the lower position, the suspended polymer solution on the the upper location. Gennerally, a normal magnetic field can generate instability on the free surface of the magnetic fluid [10]. Numerous sharp ripples can be generated from the magnetic fluid free surface, and those ripples may turn into upward cone-shaped jets once located in a strong electric field. [11]

The required critical electric field intensity could be decreased to less than 1×10^5V / m via the combination of the magnetic fluid and field in the electrospinning process, while the critical electric field intensity needed to be greater than 1×10^8V / m if Electrospinning without the magnetic fluid and field [11].

In addition, the nanofibers produced by the above quasi-steady method were ranged from 200nm to 800nm in diameter, and the productivity of the electric spinning increased by 12 times, while the degree of pinhole blocking could be reduced. However, this method also has disadvantages, such as the complexity of the device, the problem of two-fluid control, the fiber diameter deviation introduced by impurities contained in the jets including powder, oil, etc [11].

2.2.2. Electrospinning Technology via Inflatable Bubbles Solution

One of the other ways to promote disturbance in liquid surface of the electrical polymer solution is inflating bubbles to the solution, where the bubbles are formed in the inflated solution surface, and the bubble surface is charged in the electric field. Shear stress produced by the surface charge coupling with the external electric field, changes the small air bubbles into cone-shaped bubbles, which are further extended into longer and finer bubbles. Once the electric field intensity exceeds the critical value, filaments would be spun from the highest point of the cone-shaped bubbles. The critical voltage depends on the sizes of bubbles and the internal pressure of the inflated solution. Bubble surface tension is irrelevant with electrical properties of solution, such as the viscosity of the solution. [12]

The diameter of electrospun nanofibers depends on the sizes of the bubbles on the spinning solution surface, which can be controlled by the internal pressure of liquid inflation, the height of the bubbles and the temperature of the air in the trachea. The main advantage of the bubble electrospinning lies in the production of nanofibers as small as 50 nm. In addition, relatively low voltage is used in this method, and the spinning capacity depends on the viscous solution to a minimized degree. Many small bubbles can be generated at a time by using the pipe, and numerous Taylor cones may be formed under the appropriate conditions, therefore this method is more effective than the traditional needle electrospinning.

2.2.3. Electrospinning Technology Using Rotating Roller as Electrode

In 2003, the researchers of Czech Technical University of Liberec observed that the liquid jet can occur on solution surface. They produced nanofibers at large scale by rotating the spinning electrode with its lower end located in polymer solution, and the NanoSpider technology was

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invented as a result, which has been patented worldwide since 2003.

2.2.4. Electrospinning Technology with Rotary Disc Electrode

Zhijuan Xu etc mixed the tetrahydrofuran and dimethylformamide by weight ratio of 60:40 as the solvent, which was blended with the PC (PC mass fraction about 15%), using rotating disc electrode to electrospin fibers. Micron fibers were achieved at the appropriate conditions, few of which are nanofibers. The productivity of electrospun fibers was significantly higher than the common needle spinning. [8a]

The fibers could be splayed on a larger scope, with only part of the produced fibers received on the receiving screen, due to the extensive splaying of the electrospun fibers generated with this method.

2.2.5. Electrospinning Technology with Rotary Disc Electrode

Nigeria Dosunmu et al, in the University of Lagos, , invented a new type of electric discharge device with bulk porous pipeline [13]. 20% w/w Nylon 6 polymer solution was contained in a metal cylindrical tube. The lower end of the tube was connected with a metal electrode with higher voltage. The upper end of the tube is connected to a pressure-generating device. The surface of the pipe contained multi-holes with their diameter ranging from 10 microns to 100 microns. Polymer solution was slowly supplied through the tiny holes. and then polymer droplets formed outside of the tube wall, eventually spinning jets would be generated outside the tube wall, by the combined reaction of the electric force and surface tension.

The electrospun fibers with diameters ranging from 100 to 400nm were resulted from the above method, and the yield could be increased by 250 times compared to the traditional electrospinning technology.

However, this method required an auxiliary device for fluid pressure, making it complicated and the Hole-blocking issue remained with this method.

3. Conclusion

In this paper, various concepts behind obtaining nanofibers at large scale are summarized, including multi-needle electrospinning and needleless electospinning. The arrangement of needles, and the application of additional power field, magnetic field are helpful avenues towards massively manufacturing nanofibers. Electrospinning has become one of the hot spot in the nanomaterials scientific research field, providing a powerful tool for manufacturing novel nano-materials, with significant scientific and practical value.

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