A NEW CIRCULAR SPINNERET SYSTEM FOR ELECTROSPINNING
Numerical Approach and Electric Field Optimization

by

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Original scientific paper
https://doi.org/10.2298/TSCI1904229Z

Electrospinning is believed to be the most effective technique to produce microfibers or nanofibers at large scale, which can be applied in various high-tech areas, including energy harvester, tissue engineering, and wearable sensors. To enhance nanofiber throughput during a multi-needle electrospinning process, it is an effective way to keep the electric field uniform by optimizing electrospinning spinnerets. For this purpose, a novel circular spinneret system is designed and optimized numerically by a 3-D finite element model, the optimal collector shape is also obtained.

Key words: *electric filed simulation, a circular spinneret, uniform electric field, electrospinning*

Introduction

With the development of micro- and nanoprocess technology, nanofibers have been popular in the research field, such as scaffolds for tissue engineering, flexible display, microfluidic chip, and batteries *etc.* [1-6]. Electrospinning is a simple and economical way to fabricate nanofibers. The use of electric field force as an acting force is the main difference between electrospinning and the traditional ones.

In conventional electrospinning set-ups, needles are commonly used as electrospinning heads to fabricate nanofibers, as they can easily produce uniform, multi-structured, composite/multi-material and controllable nanofibers in comparison to needleless electrospinning [7, 8]. It is worth mentioning that bubble electrospinning is a useful method in needleless electrospinning [9-12]. Recent interest has been focused on high throughput of nanofibers by electrospinning. However, single-needle electrospinning is of low yield which is less than 0.1 g/h (gramme per hour), and cannot meet the demands of industrialization [13]. To address this issue, a large amount of multiple-jet electrospinning methods have been proposed and continuously developed including multi-needle electrospinning and free-surface electrospinning [14, 15]. Although the later has higher fiber production rate than the former, it has disadvantages of low controllability of jets, much difficulty in fabricating multi-component fibers

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and requirement of high voltage. Relatively, multi-needles electrospinning is excellent in what the disadvantages of free-surface electrospinning has. However, interaction between jets due to the non-uniform electric field distribution can cause jet repulsion and deviation during electrospinning process, which limits the development of multi-needle electrospinning.

In order to enhance nanofiber throughput of multi-needles electrospinning, a lot of electrospinning set-ups were designed. Theron *et al.* [16] described a multi-jet theoretical model and showed several multi-needles arrangements, demonstrating that a decrease in the inter needle distance led to greater repulsion between the jets, and the Columbian interactions affected the stability of the process and uniformity of the nanofibers. Tomaszewski and Szadkovski [17] compared different multi-jet electrospinning spinnerets with different shapes, and concluded that the concentric electrospinning head was the best type with respect to both the efficiency and quality of the process by the statistical analysis of experiments' data. In 2006, Kim *et al.* [18] used a cylindrical electrode to stabilize the spinning jets and consequently concentrate the collection zone to one-third of the area. Liu *et al.* [19] and Tian *et al.* [20] also used this method to obtain uniform electric field during multi-needle electrospinning process. Additionally, uniform electric field is the key point for multi-needle electrospinning production. Liu and Guo [21] used the finite element analysis software ANSYS to optimize the electric field uniformity in multi-needle electrospinning process, and showed that the maximal field intensity occurred at the needle's tip and on the needles edge, and the field intensity increased dramatically when a plastic (Polytetrafluoroethylene) case was placed around each needle. Besides, the needle length, the applied voltage and the needle spacing might affect the uniformity of the electric field intensity. Kim *et al.* [22] designed a cylinder-type multi-needle electrospinning system for mass production of nanofibers in 2015. In this study, a new circular spinneret multi-needle electrospinning system is put forward.

The electric field distribution of electrostatic spinning spinneret influences the formation and movement of jets [23]. During the spinning process, the electric field distribution will cause an obvious phenomenon which is *the end effect*, and it is difficult to control the electric field [22, 24-26]. In this paper, the finite element method is used to simulate the electric field of the electrospinning spinneret. It can show the distribution of the electric field is simple and intuitive. Furthermore, the effect of the shape of fiber-collector on electric field is analyzed. The purpose of this paper is to reduce or eliminate the unbalanced phenomenon in the electric field of electrospinning, to enlarge the electric field strength, and to increase the efficiency of production, in an order to reduce production cost and increase production profit.

Electric field analysis of the new circular spinneret

A 3-D model was used in our study, the Poisson equation can be written in the form:

$$-\nabla^2 \varepsilon_r \varepsilon_0 \phi = \rho \tag{1}$$

where ε_r is the relative dielectric constant in the vacuum, ε_0 – the relative dielectric constant in the dielectric, ϕ – the electric potential, ρ – the space charge density. In this study, $\rho = 0$.

The electric field strength, E, and electric displacement, D, can be obtained by the following equations:

$$E = -\nabla \phi \tag{2}$$

$$D = \varepsilon_r \varepsilon_0 E \tag{3}$$

The boundary conditions are:

$$-\vec{n}D = \rho_s \tag{4}$$

$$\vec{n}(D_1 - D_2) = 0 \tag{5}$$

where $\vec{n}$ is the normal vector on the interface, ρ_s – the surface charge density. The $\rho_s = 0$ implies no free charge at the interface between the two dielectrics, D_1 – the electric displacement of copper, and D_2 – the electric displacement of air.

Simulation results and analysis

In our simulation model, the copper needles and the fiber collector were exposed in air, and a high voltage of 20000 V was applied to the needles, and the fiber collector was earthed. We assume zero voltage on air boundaries at infinity. The other basic parameters of the electrospinning process model were listed in tab. 1.

Table 1. Basic model parameters

Diameter of needles [mm]	Length of needles [mm]	Distance between two needles [mm]	Distance between collector and needles [mm]	Size of fiber-collector [mm^3]	Size of air domain [mm^3]
0.5	15	15	100	200 × 200 × 2	250 × 250 × 125

A double-row spinneret system was illustrated in fig.1. The double-row structure is conventionally used in the multi-needle electrospinning [22, 25, 27]. Figure 2 showed the distribution of electric field intensity in the surface of needle tips, the electric field intensity of the needle tips was calculated and drawn in fig. 3.

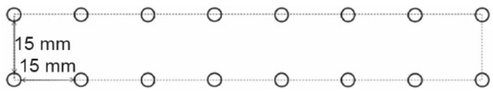

Figure 1. Arrangement of the double-row spinneret system

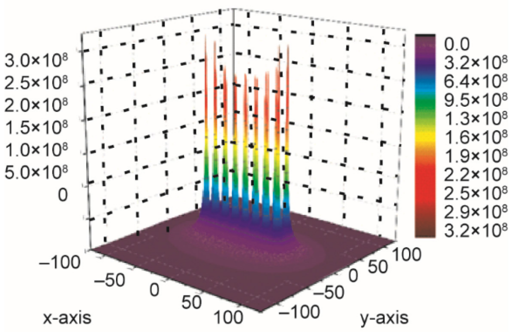

Figure 2. Electric field intensity colormap of the double-row spinneret (*for color image see journal web site*)

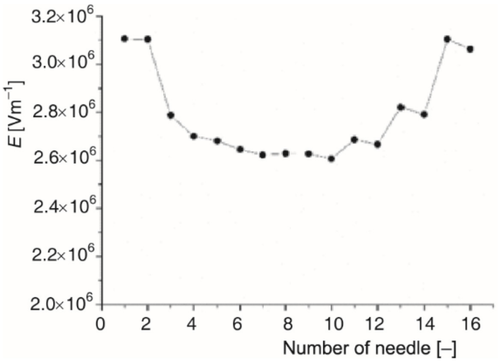

Figure 3. Electric field intensity line-graph of the double-row spinneret

Another spinneret system along a circumference was also studied in this paper as illustrated in fig. 4. The circular spinneret consists of 16 needles and a device which connects the needles and the solution pump. Figue 5 showed the distribution of electric field intensity in the surface of circular spinneret tips, and the electric field intensity of the spinneret tips was calculated and drawn in fig. 6.

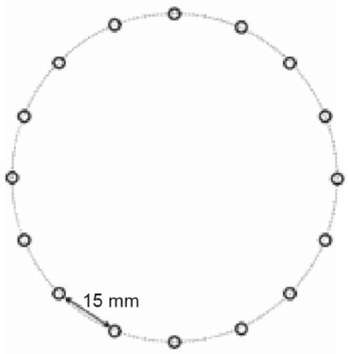

Figure 4. Arrangement of the circular spinneret

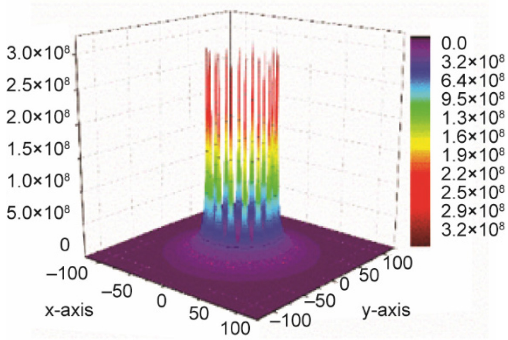

Figure 5. Electric field intensity colormap of the circular spinneret (*for color image see journal web site*)

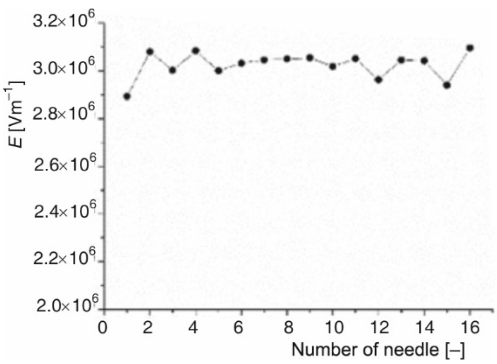

Figure 6. Electric field intensity line-graph of the circular spinneret

A comparison of figs. 6 and 3 shows that the electric field of the circular spinneret is more uniform which can reduce the end effect effectively.

In order to optimize the shape of the fiber-collector, we consider a square one, the geometrical parameters were listed in tab. 2, and other parameters were same as given in tab. 1.

The electric field intensity of each needle tip was calculated numerically, and the coefficient of variation, a standardized measure of dispersion of frequency distribution from the data of electric field intensity, was calculated respectively and showed in tab. 3. The cuboid collector was the most effective among three shapes of the collector to produce a uniform electric field.

Table 2. The size of various fiber-collectors

The shape of fiber-collector	Square	Cuboid	Circle
Size of fiber-collector [mm^3]	200 × 200 × 2	200 × 100 × 2	$\pi \times 100^2 \times 2$

Table 3. The coefficient of variation of various collectors

The shape of collector	Square	Cuboid	Circle
Coefficient of variation	0.0175	0.0169	0.0211

Experiment

Materials and methods

Polyvinyl alcohol (PVA, 1799) was purchased from Aladdin. The distilled water was purchased from Watsons. All the raw materials were used as received without further purification. The 10 g PVA powder was dissolved in 90 g distilled water and heated at 90 °C for

3 hours under stirring to form a transparent viscous solution. The viscous solution was loaded into a pump equipped with the circular spinneret made of stainless steel.

The electrospinning equipment was purchased from Foshan Lepton Precision Measurement and Control Technology Co., Ltd (QZNT-MF02). The circular spinneret made of stainless steel was installed on *x*-axis linear motion platform. Nanofiber collector made of aluminum with the shape of cuboid moves on *y*-axis with conveyor. The pump, which supplies solution to spinneret, was controlled by a servo motor, and the flow rate was 0.2 mL per minute. The distance between electrospinning spinneret and collector was 130 mm, and a high voltage power (0-50 kV, 0.1 kV) was connected to the electrospinning spinneret. The environment temperature was controlled at 25 °C and the environment relative humidity at 50%. The circular spinneret was supplied with 20 kV of voltage. The circular spinneret electrospinning device is shown in fig. 7.

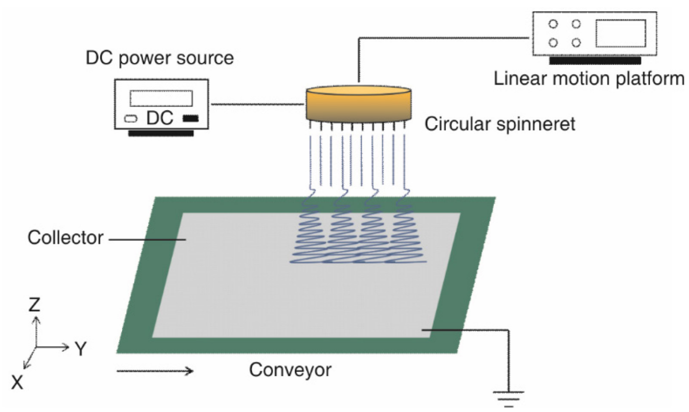

Figure 7. The circular spinneret electrospinning device and schematics

Results and analysis

The circular spinneret shown in fig. 7 was used to study the influence of geometry of spinneret on the fiber diameter. In this group of experiment, the spinning voltage was 20 kV, the distance between the spinneret and collector was 13 cm. Figure 8 shows the SEM image of the fiber diameter distribution. It can be seen that the nanofibers obtained from the circular

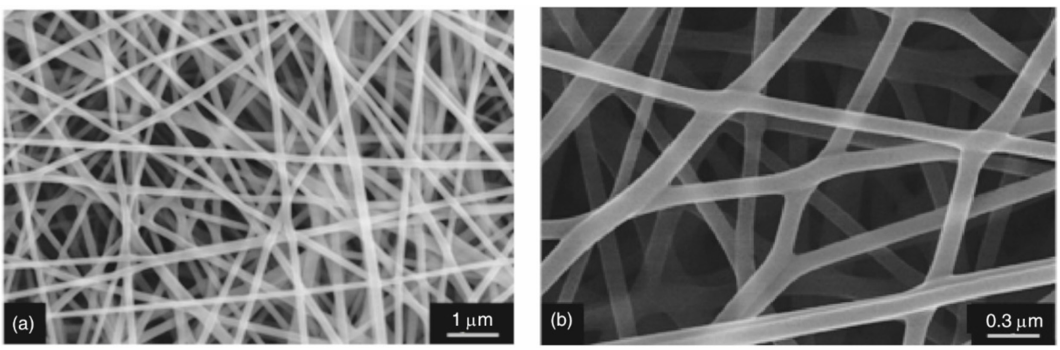

Figure 8. The SEM image of nanofibers

spinneret is fine and uniform. From the SEM image of nanofibers, the fibers obtained from different layers has a slightly larger average fiber diameter which shows the fibers is much uniform. This is likely because of the more uniform distribution of the electric field created by the circular spinneret.

Conclusions

In this work, a novel circular spinneret was proposed and simulated by finite element method. The following conclusions are drawn.

- Compared with the traditional double-row spinneret, the electric field of the circular spinneret is more uniform which is proved experimentally and numerically.
- The collector with cuboid shape creates a more uniform electric field distribution.

Acknowledgment

This work was financially supported by Science and Technology Project of Guangdong Province (2017B090911012), University Innovation and Entrepreneurship Education Major Project of Guangzhou City (Item Number: 201709P05), Project of Science and Technology of Foshan City (2015IT100152), Key Project of Science and Technology of Guangdong Province, China (No. 2015B010124001), Applied Science and Technology Development Foundation of Guangdong (2015B090921007), Guangdong Provincial Natural Science Foundation （No. 2015A030312008, National Natural Science Foundation of China (No. 51305084), Guangdong High-level Personnel of Special Support Program (Outstanding young scholar in science and technology innovation) (No. 2014TQ01X212), Training program for outstanding young teachers in higher education institutions of Guangdong Pr ovince (No. YQ2015056), Guangzhou Science and Technology Plan (Grant No. 201803010065), Science and Technology Planning Project of Guangzhou City of China (Grant No. 201604016084), Guangdong Provincial Natural Science Foundation (No. 2016A030308016) and R&D Key Projects from Guangdong Province (No. 2015B010133005). All corresponding authors are equal.

Nomenclature

D – dielectric flux density, [Cm^{-2}]
E – electric field stength, [Vm^{-1}]
V – electric potential energy, [J]

Greek symbols

ε_0 – relative dielectric constant in dielectric
ε_r – relative dielectric constant in vacuum
ρ – space charge density, [Cm^{-3}]
ρ_s – surface charge density, [Cm^{-2}]

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Paper submitted: January 9, 2018
Paper revised: July 23, 2018
Paper accepted: July 28, 2018