Design and research of supplying power for spinning emitter in needleless electrospinning with non-metallic rotating shaft

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Abstract. Electrospinning is a widely used technique for nanofiber preparation at large scale that is mainly divided into two categories, namely, multi-needle and needleless categories. Among them, needleless electrospinning technologies are being in-depth researched and developed, because there is no needle blockage, electrostatic interference between the needles, and the yield is high. At present, the needless electrospinning devices with rotating shaft are applied widely. In order to supply power for the spinneret emitter conveniently, the metal shaft is used mostly and add electricity for it by brush. However, it not only weakens the utilization of electric energy, but also affects the intensity and the distribution of the electric field, and then affects the quality of the electrospinning. In this paper, a design of supplying power for spinneret emitter with a non-metallic rotating shaft was proposed, and the diameter formula of non-metallic rotating shaft under different electrospinning conditions was deduced. The intensity and distribution of the electric field of this design scheme is researched based on a fractal electrospinning head by the finite element analysis software COMSOL Multiphysics 5.0. At last, the electrospinning experiments were carried out by the electrospinning devices with non-metallic rotating shafts to prove the optimization effects.

1. Introduction
Electrospinning is an effective technique to produce nanofiber using electric field force to stretch the spinning jets from the polymer solution [1]. Currently the electrospinning technique which enables mass production of nanofibers has been classified as two categories, i.e., multi-needle type (with capillary needles) [2, 3] and needleless type [4–13]. Multi-needle electrospinning, in spite of the advantage of higher productivity than single needle, its disadvantage such as spinning channel clogging and difficulty in cleaning, especially the "End effect" has severely hindered its industrialization due to its generation of non-uniformity in electric field intensity [14]. Needleless electrospinning technique is a spinning method using high voltage electric field to form jets on the free liquid surface. There are not the problems
such as needle blockage and mutual interference between needles, which can greatly improve the yield of electrospinning. Therefore, a lot of needleless electrospinning devices has been researched and manufactured in recent years, such as roller and wire commercialized by Elmarco with the brand name Nanospider [5, 6], as well as rotating disk [7], spiral coil [8], magnetic suspension [12], and so on, have been used to produce nanofibers at large scale. Among them, the needleless electrospinning devices with rotating spinning emitters are used widely.

The rotating shaft almost is metallic material in these needleless electrospinning devices. It is a common method to use the brush to supply power for the metal rotating shaft, and then to make charges for the spinning emitters. However, the induced electric field of the metal rotating shaft affects the one of the spinning emitters, and then affects the spinning effect. Meanwhile, it will cause waste of energy. Therefore, it is of great significance to use non-metallic rotating shaft for the needleless electrospinning devices. However, it is a problem that how to supply power for the spinning emitters with non-metallic rotating shaft and minimize the influence of the electric field on the spinning emitters.

Aiming at the above problems, a method supplying power for the the spinning emitters in needleless electrospinning with non-metallic rotating shaft was proposed, and the diameter formula of the non-metallic rotating shaft under different spinning conditions was deduced. Then a kind of electrospinning head based on the fractal theory with non-metallic rotating shaft was designed, and its electric field distribution and power utilization ratio were researched by the finite element analysis software COMSOL Multiphysics 5.0, at last, the optimization effects were proved by the electrospinning experimentals.

2. Design non-metallic rotating shaft

A kind of non-metallic rotating shaft in needleless electrospinning devices need to be designed to minimize the influence of the electric field on the spinning emitters, reduce energy consumption, and prevent wire winding.

2.1. Structure design of non-metallic rotating shaft

As shown in Figure 1, the non-metallic rotating shaft is composed of central shaft, supported sleeve, end covers, jump ring, bearings, powered ring, housings, metal wire I, and metal wire II. The supported sleeve and the end covers on both sides are collectively called "roller". In order to minimize the influence of the electric field, reduce the weight, and be easily manufactured, the material of the central shaft and the roller can choose the plastic with high corrosion resistance, high strength, and high insulation. There are N holes on the supported sleeve, and the metal wire I passes through and links with the spinning emitter. If the spinning emitter is discontinuous single type (such as rotating disk), N is the number of the discontinuous single type. If the spinning emitter is continuous type (such as spiral coil), N equals one, and the hole should be close to the right end cover. There are two holes in the central shaft and on both sides of the right end cover, respectively named hole a and hole b, and they intersects with central hole. The jump ring contacts with shoulder c. The right bearing contacts with the jump ring. The powered ring is a metal thin slice and located in the bearing bore of the right housing and contacts with the right bearing.

The key problem of supplying power to the spinning emitter with non-metallic rotating shaft is the link method of the metal wires. The specific link method is as follows: one end of the metal wire I is connected with the spinning emitter, and the other end is penetrated in the hole a, and penetrated out from the hole b, then connected with the jump ring; one end of the wire II is connected with the powered ring, and the other end is penetrated through the hole in the right housing, then the right bearing is mounted into the bearing bore and presses the powered ring. In this way, the positive electrode of the direct high voltage power supply is connected with the wire II, and the spinning emitter also is charged through the powered ring, right bearing, jump ring and wire I.
Figure 1. Structure of the non-metallic rotating shaft: (a) The assembly drawing; (b) The local exploded drawing. 1. Central shaft, 2. Supported sleeve, 3. End cover, 4. Jump ring, 5. Bearing, 6. Powered ring, 7. Housing, 8. Metal wire I, 9. Metal wire II.

2.2. Parameters calculation of the non-metallic rotating shaft

The key parameters of the non-metallic rotating shaft mainly include the dimensions of the roller (such as outside diameter \(D\), wall thickness \(a\) and the length \(L\)) and the minimum diameter \(d\) of the central shaft. Among them, \(D\) and \(L\) mainly depend on the shape, layout and inside diameter of the spinning emitter, and they can be used as known quantities. The wall thickness \(a\) can be determined according to the strength of the material of the supported sleeve. Then the total mass \(M\) of the roller and the spinning emitter is equivalent to the known quantity.

The force analysis of the non-metallic rotating shaft is shown in Figure 2. The minimum diameter \(d\) of the central shaft is calculated according to strength checking based on allowable bending stress. The main steps are as follows.

Figure 2. Force analysis diagram of the non-metallic rotating shaft.
(1) Calculate the viscous resistance $f$ acting on the spinning emitter

$$
\tau_f = K \left( \frac{dv}{dr} \right)^n = K \gamma^n \quad (n<1)
$$

where $K$ and $n$ are the consistency index and non-Newtonian index of the spinning polymer solution respectively, and they are constant. The viscous resistance $f$ can be calculated by Equation (1).

$$
f = A \cdot \tau_f,
$$

Among it, $A$ is the contacting area between the spinning emitter and the spinning polymer solution.

(2) Calculate the torque $T$ acting on the non-metallic rotating shaft

Measure the distance $R_f$ between the highest point of the spinning emitter and the central axis. And then

$$
T = f \cdot R_f = A \tau_f \cdot R_f.
$$

(3) Calculate the bending moment $M$ acting on the non-metallic rotating shaft

$$
M = (Mg / 2) \cdot (L / 2 + 40)
$$

(4) Calculate the equivalent bending moment $M_e$ of the risk section

$$
M_e = \left[ M^2 + (\alpha T)^2 \right]^{1/2}
$$

As the speed of the electrospinning process is generally low, so the reduction coefficient $\alpha$ is selected as 0.3. And then

$$
M_e = \left[ M^2 + (\alpha T)^2 \right]^{1/2} = \left[ (Mg / 2)^2 \cdot (L / 2 + 40)^2 + (0.3 f R_f)^2 \right]^{1/2}
$$

(2)

(5) Calculate the minimum diameter $d$ of the non-metallic rotating shaft

According to the ending-torsion strength checking method [16], there is Equation (3).

$$
d \geq 21.68 \times \left( \frac{M_e}{0.1 \cdot \sigma_{-1}} \right)^{1/3}
$$

(3)

where $\sigma_{-1}$ is the allowable bending stress of the non-metallic rotating shaft, and can be retrieved from reference [16].

3. Example

The electrospinning head (illustrated in Figure 3) is designed by our research group based on the fractal theory [17]. We take it as an example to determine the specific dimensions of the non-metallic rotating shaft according to the above contents.

The parameters of the fractal slice are as follows: the inside diameter is 69mm, the thickness is 2mm, and the distance $R_f$ between the highest point of the fractal slice and the central axis is 110mm, there are five fractal slices at least, and the distance between them is 40mm. So then the outside diameter of the roller $D$ is also 69mm, and its length $L$ is 272mm. The wall thickness is chosen as 10mm. The weight $M$ of the electrospinning head (including the roller and the fractal slices) is 6kg.

As shown in Figure 4, the dotted line indicates the liquid level. $A_1$ is the maximum connected area between the fractal slice and polymer solution. According to the specific sizes of the fractal slice in reference [17], $A_1$ is calculated and it is 550.98mm$^2$. So the total connected area $A$ of the spinning emitters with five fractal slices is $A = 2 \times 5 \times A_1 = 10 \times 550.98 = 5509.8$mm$^2 \approx 0.0055$m$^2$.

When calculating the diameter of the non-metallic rotating shaft, the polymer solution with higher concentration and suitable for electrospinning should be chosen. For example, we prepared polyvinyl alcohol solution with a concentration of 25%. The measured consistency index $K$ is 63.59, and the measured non-Newtonian index is 0.9645 by Malvin rotation rheometer.
Based on the experience of electrospinning experiment, the suitable speed is 300 r/min, so the angular velocity \( \omega = 2 \pi \times 300/60 = 31.4 \text{ rad/s} \). According to Equation (1), the viscous resistance \( f \) was calculated.

\[
f = A \cdot \tau_f = AK \left( \frac{dv}{dr} \right)^n = AK \left( \int_{r_1}^{r_2} \sigma dr \right)^n = 0.0055 \times 257.2 \times \left( \int_{r_1}^{r_2} 31.4 dr \right)^{0.7125} = 178.77 \text{ N}
\]

The equivalent bending moment \( M_e \) was obtained by Equation (2), and is approximately equal to 7.85 Nm.

The material of the central shaft is nylon, and its allowable bending stress \( \sigma_{\text{al}} \) is determined 70 MPa by checking conference [16]. And then the minimum diameter of the non-metallic rotating shaft was worked out by Equation (3).

\[
d = 21.68 \times \left( \frac{M_e}{0.1 \cdot \sigma_{\text{al}}} \right)^{1/3} = 21.68 \times \left( \frac{7.85}{0.1 \times 70} \right)^{1/3} \approx 22.5 \text{ mm}
\]

4. Electric field simulation

Taking the electrospinning head with five fractal slices and metal rotating shaft or non-metallic rotating shaft as the research object, the electric field simulation was carried out by the finite element analysis software COMSOL Multiphysics 5.0.

The electrostatic field simulation follows Poisson equation in the finite element analysis software COMSOL Multiphysics 5.0, as follows:

\[- \nabla d \varepsilon_r \varepsilon_0 \nabla V = d \rho \]

where \( \varepsilon_0 \) and \( \varepsilon_r \) are vacuum relative permittivity and dielectric relative permittivity respectively, \( V \) is potential energy, and \( \rho \) is space charge density. In this paper, \( d \rho \) is zero. The value of \( \varepsilon_r \) is different according to different material. The receiving plate and the spinning emitter are metal (steel was chosen in this paper), and their \( \varepsilon_r \) is 1.5. The material of the roller and the non-metallic rotating shaft is nylon, and their \( \varepsilon_r \) are 2.55. In addition, the corresponding electric strength and electric displacement vector can be obtained according to the equations \( E = -\nabla V \) and \( D = \varepsilon_0 \varepsilon_r E \) (\( E \) is the electric strength and \( D \) is the electric flux density).

In the simulation, the four boundaries of the air model are set to zero charge and symmetry condition. In this way, the limited model can be considered as infinitely far. And then the bottom of the receiving plate is grounded. The spinning emitter is supplied the required voltage. And the other boundary conditions are continuous. Table 1 shows the parameters of the models and the simulation.

| Voltage (kV) | Receiving plate (mm) | Receiving distance (mm) |
|-------------|----------------------|------------------------|
| 30          | 600 × 500 × 1        | 300                    |
The material of the spinning emitter (i.e. fractal slices) and the roller is steel and nylon respectively in Figure 5. The material of the rotating shaft in Figure 5(a) and Figure 5(b) is steel and nylon respectively. The color of the two ends of the metallic rotating shaft is bright in the electric field simulation, as shown in Figure 5(a). It shows that a higher electric field is also produced on the metallic rotating shaft. And it affects the electric field of the spinning emitter, but also has the risk of spark-over with the external equipments, and then affects the normal operation of the spinning. Figure 5(c) illustrates the specific values of the electric strength and distribution of the electric field. It shows that the maximum electric strength with the metallic rotating shaft is $1.20 \times 10^6$ V/m, and the average value is $9.48 \times 10^5$ V/m; and the maximum electric strength with the non-metallic rotating shaft is $1.33 \times 10^6$ V/m, and the average value is $1.03 \times 10^6$ V/m (i.e. increased by 8.65% compared to the metallic rotating shaft).

![Figure 5](image)

**Figure 5.** Simulation of the electric field with different rotating shaft: (a) The electrospinning head with metal (steel) shaft; (b) The electrospinning head with non-metallic (nylon) shaft; (c) The electric field strength of the spinning heads with different rotating shafts.

### 5. Electrospinning experimental

#### 5.1. Spinning solution
The degree of polymerization, hydrolysis, and the relative molecular mass of the polyvinyl alcohol (PVA) (Shanghai Petrochemical Co, Ltd., China) in the experiment was 1700, 99% and 74800 respectively. The distilled water was self-made. An appropriate amount of PVA and distilled water were weighed and mixed according to the concentration 15% of the solution. A magnetic rotor was placed in the solution. Subsequently, the solution was transferred to a thermostatic bath and stirred at 80°C until the solution was clear and transparent [18]. Finally, the experimental polyvinyl alcohol solution with a concentration of 15% was prepared.

5.2. **Spinning devices**
The experiment was performed by the self-made electrospinning device with five fractal slices. Table 2 shows the types and sources of the related instruments.

| Instruments                  | Type               | Source                                  |
|------------------------------|--------------------|-----------------------------------------|
| Spinning device              | Five fractal slices| Self-made                               |
| DC high-voltage power supply | DW-P/N603          | Tianjin Dongwen High Voltage Power Supply, Ltd. |
| Metal halide lamp            | 70W                | Xincheng Lighting, Ltd.                 |
| Motor agitator               | DF-101S            | Gongyi Yuhua Instrument Co., Ltd.       |
| Thermostat water bath        | HH-4               | Kexi Instrument, Ltd.                   |
| Camera                       | Sony DSC-TX9       | Sony                                    |
| Electron microscope          | TM3030             | Techcomp (China) Ltd                    |

5.3. **Experimental parameters**
The depth of the fractal slice in the polymer solution was 15mm. The rotating speed of the spinning head was 300r/min. And the receiving distance was 300mm. A DC power of 25 kV was supplied by the positive voltage to the wire of the non-metallic rotating shaft, while a negative voltage of 5kV was applied to the receiving electrode. The spinning time was 10 min. The spinning process was shown in Figure 6.

5.4. **Experimental results**
The scanning electron microscopy (SEM) image of the nanofiber film prepared by the electrospinning experiment was shown in Figure 7. And then the diameters of one hundred fibers was measured by the software named Image-Pro Plus6.0. Finally, the average diameter and CV value of the fibers were calculated, and they were 324nm and 17.3% respectively.

![Figure 6. Electrospinning experiment with non-metallic rotating shaft.](image1)

![Figure 7. SEM of the prepared fibers.](image2)
6. Conclusions
In this paper, a design scheme of supplying power for spinning emitter with non-metallic rotating shaft in the needleless electrospinning technique was proposed. And the diameter formula of the non-metallic rotating shaft under different spinning conditions was deduced. Then a kind of electrospinning head based on the fractal theory with non-metallic rotating shaft was designed, and as an example, its electric field distribution and power utilization ratio were researched by the finite element analysis software COMSOL Multiphysics 5.0. The study found that the average value of the field strength of the spinning emitter with non-metallic rotating shaft is increased by 8.65% compared with the one with metal rotating shaft. And finally, electrospinning experiment was carried out by the self-made needleless electrospinning device base on the fractal theory, and the average diameter of the prepared electrospun membrane is 324nm, and the CV value is 17.3%. Therefore the energy consumption is reduced by using the non-metallic rotating shaft in the needleless electrospinning devices, at the same time, the spinning quality is accepted. What's more, the linking method of the wires is simple and prevents the winding problem.

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