The Auxiliary Electrode Can Improve the Electric Field Distribution of the Roller Electrostatic Spinning

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Abstract: Although needle-free roller electrostatic spinning technology has the advantages of higher output than traditional needle electrostatic spinning, it has the problem of uneven distribution of electric field and poor quality of filaments. The emphasis of this study is to solve the non-uniform distribution of the electric field of roller electrostatic spinning so that it can produce high-quality nanofibers. The electric field analysis shows that the electric field distribution is most uniform when (1) ring electrode is connected to 5kv and parallel electrode is connected to 11kV, and (2) auxiliary electrode is connected to -700V. The finite element analysis of the electric field shows that the auxiliary electrode increases the electric field intensity in the spinneret area. The auxiliary electrode in needleless roller electrostatic spinning technology can be used to develop high efficiency and low energy consumption nano-fiber production system.

1. Introduction
Electrospinning is a simple and effective technology for the preparation of polymer nanofibers. Electrospinning nanofibers have great potential applications in the fields of filtration, biomedicine, chemical engineering, sensor [3-5], energy conversion and storage [6-11]. In traditional electrospinning, auxiliary field is sometimes used to improve the spinning ability, increase the output of nanofibers (also known as productivity in literature [12,13]), or regulate the deposition of fibers. In order to improve productivity, Kim [14] et al. used five-needle electrospinning, added metal rings, and improved electric field distribution. However, the interference between multiple needles results in uneven distribution of electric field. Needle-free electrospinning technology was proposed. For example, Czech University [15] proposed the production of nanofibers by rotating electrodes, Zheng [16] and others designed metal disk nozzles, and Wuhan Textile University [17] designed the electrospinning of ring nozzles.

In these studies, the uneven distribution of electric field greatly affects the quality of filament. Therefore, we add auxiliary electrodes to needle-less roller electrospinning to improve the electric field distribution on the basis of improving productivity. The application of auxiliary electrodes not only improves the production efficiency of electrospinning, but also restrains the instability of jet bending and improves the electric field polarization of collecting plate.

2. Theoretical analysis

2.1 Electric Field Boundary Conditions
In the air region of electrospinning, boundary conditions need to be set for different media of air and flywheel, receiving plate and parallel plate. For example, in the boundary of air and receiving plate, as shown in Figure 2, using Maxwell's second equation, when \( \frac{\partial}{\partial t} E = 0 \) \( \nabla \times E = 0 \rightarrow E = -\nabla \phi \) (1)

\[ \int_C E \cdot dl = 0 \]

(2)

Therefore, it is concluded that the voltage drop difference between any two points in the electrostatic field is a fixed value, which has nothing to do with the path of electric field line integration.

From formula (1), we can draw a conclusion.

\( \nabla \cdot J = \nabla \cdot (\gamma E) = \gamma \nabla \cdot E + E \nabla \cdot \gamma = 0 \)

(3)

The materials used in this paper are considered to be homogeneous media, i.e. \( \nabla \gamma = 0 \), which is obtained by substituting (3)

\( \nabla^2 \phi = 0 \)

(4)

That is, the Laplace equation also adapts to the potential function of the electrospinning electric field. From the above derivation, we can conclude that the problem of the Laplace equation can be attributed to the boundary problem of the electrospinning field.

2.2 Electric Field Analysis

In the electrospinning process, the applied voltage and collection distance all affect the electric field intensity distribution. The critical voltage is attributed to the surface tension and viscosity of the solution. Taylor proposes a formula for predicting critical applied voltage \( V_c \), which is given by the following formula [18]:

\[ V_c^2 = 4 \ln \left( \frac{2d}{R} \right) (1.3\pi R \gamma)(0.09) \]

(5)

Among them, D is the distance between nozzle and collector (cm), R is the outer radius of nozzle (cm), and \( \gamma \) is the surface tension of liquid (dyne/cm).

In this paper, the liquid tank and the receiving plate, as well as the additional auxiliary parallel electrodes, can be regarded as capacitors, as shown in Figure 3. Free charge occurs on the surface of the
conductor, which generates electric field E. The electric field line begins at the positive pole of the power supply and ends at the negative pole. Because the tangential component of the electric field on the conductor surface is always zero, the electric field is always perpendicular to the conductor surface. The electric field component at any point on the surface of a conductor is

$$E_n = \hat{n} \cdot E = \frac{\rho_s}{\varepsilon}$$  \hspace{1cm} (6)

Where \(\rho_s\) is the surface charge density at a point on the surface of the conductor, \(\hat{n}\) is the outer normal unit vector of the same point, and \(\varepsilon\) is the dielectric constant of air. The voltage and electric field E can be combined by the above formula, i.e

$$V = - \int_{P_1}^{P_2} E \cdot d$$  \hspace{1cm} (7)

Among them, the points P1 and P2 are any two points on the conductor 1 and the conductor 2, respectively.

3. Model establishment

Using the electrostatic model in COMSOL Multiphysics software, the electrostatic field in the electrospinning process under different conditions was analyzed by finite element analysis. The calculation model is based on this equation [19]

$$E = -\nabla V$$  \hspace{1cm} (8)

Where E is the electric field strength and the visible potential. The actual geometry and size of the electrospinning device are completed by three-dimensional SOLIDWORKS software. The conditions are: (1) the radius of the roller is 20.0 cm and the height is 1.0 cm; (2) the distance between the roller and the receiving plate is 15.0 cm; (3) the auxiliary electrode is a ring electrode, a parallel electrode and a single plate electrode; (4) the voltage of the auxiliary electrode is variable; (5) the bottom of the liquid tank is grounded, and the top of the receiving plate is connected with a high voltage, as shown in Figure 3. In order to create grids in the workspace, the cell size is set to the maximum of 30 mm and the minimum of 5.4 mm. The mesh sizes of the receiving plate and the roller are set to a maximum of 10.5 mm and a minimum of 0.45 mm, respectively. The software is used for grid generation and calculation, and the electric field intensity distribution map is drawn.

Fig 3 (a) no auxiliary electrode is added;(b) ring and parallel electrodes are added;(c) an auxiliary electrode is added above the collection plate

4. Experiment and results

4.1 The electric field simulation

There are many disadvantages in traditional needle electrostatic spinning, such as low yield, easy to plug the needle, etc. Roller type electrostatic spinning can easily solve the disadvantages of traditional electrostatic spinning technology, but the access voltage is much higher, resulting in energy waste. FIG. 3 (a) shows the physical model without auxiliary electrode. When the voltage between the liquid tank
and the receiving plate is connected to 15KV, COMSOL is used to calculate the electric field distribution of the section at the highest point of the roller (see FIG. 4a). It is concluded that the maximum electric field generated at the highest point of the roller reaches $5.49 \times 10^4$ V/m, ensuring that the electric field tension received by the droplet at this point is in balance with the sum of its surface tension and gravity, and spraying occurs to form nanofibers. Figure 2 (b) shows the distribution of electric field lines in the x-y section of the electrostatic spinning device when it is working, and (c) shows the current lines on the side of the device. Using this new type of roller for electrostatic spinning can improve the production of nanofibers and improve the possibility of obtaining high-quality nanofibers. It is worth emphasizing that the material with a relatively high dielectric constant is used, so that the roller not only does not destroy the distribution of the whole electric field, but also realizes the maximum electric field of the droplet at the highest point of the roller. This ensures that the spray occurs only when the droplet reaches the highest point.

Fig 4 (a) electric field distribution at the highest point of the roller; (b) make a section of the x-y plane along the highest point of the roller to find the electric field trend; (c) make a section of the z-x plane along the highest point of the roller and find the distribution of the current line

### 4.2 Addition of Auxiliary Electrodes

In order to improve the electric field of electrospinning, auxiliary electrodes were added. One is to add annular electrodes and two pairs of parallel electrodes (Fig. 3b); the other is to add auxiliary electrodes 2.0 cm above the receiving board (Fig. 3c).

Fig. 5 (a) shows the electric field intensity on the line without auxiliary electrodes, and Fig. 5 (b) shows the electric field distribution when annular and parallel electrodes are added. The maximum electric field is at the sprinkler, and the electric field decreases with the distance from the head increasing. When the distance from the nozzle is 95 mm, the electric field intensity decreases to the minimum. Then, with the distance increasing, the electric field of the receiving plate is almost equal to the electric field at the nozzle. It is concluded that the addition of auxiliary electrodes reduces the electric field intensity of the receiving plate and increases the minimum electric field on the axis, indicating that the electric field distribution is more uniform.

Fig 5 The relationship between electric field intensity and sprinkler head distance

But when we introduce auxiliary electrodes, we find that there is polarization in the collector plate. Fig. 6 (a) is the distribution of electric field without auxiliary electrodes. When we introduce auxiliary electrodes, we find that the uniformity of electric field distribution is destroyed (see Fig. 6b). We change the voltage of annular electrodes, as shown in Fig. 7 (a). We found that the electric field distribution of the annular electrode is uniform (collector plate electric field and spinneret electric field) when the voltage is 5 kV when the annular electrode varies in the range of 1 kv-10 kv. When parallel electrodes are connected to 11 kV voltage, the electric field distribution of the collector plate is uniform and reaches $7.51 \times 10^5$ V/m (see Fig. 6c).
Fig 6 Collect the electric field distribution of the plate

In the above experiments, it can be known that the addition of ring and parallel electrodes will not result in the formation of Taylor cone because of the lack of electric field force due to the addition of auxiliary electrodes. Next, we analyzed whether the second scheme can eliminate or improve the edge effect of the collector board. When the auxiliary electrode is connected to -1000V to 300V voltage, the electric field intensity of the central line of the collector plate is calculated (see Fig. 7b). The effect of the auxiliary electrode voltage on this side is shown. With the increase of the voltage, the electric field at the edge of the collector plate decreases. In addition, it is found that the variation of the electric field at the edge of the collector plate is also changing. When the auxiliary electrode voltage is -700V, the electric field at the edge of the collector plate is relatively smooth. Therefore, the electric field distribution of the collector can be improved to the greatest extent by adding -700V voltage to the auxiliary electrode.

Fig 7 (a) the relationship between the voltage of the ring electrode and the intensity of the electric field; (b) the relationship between the auxiliary electrode voltage and the electric field of the collector plate

5. Conclusion

In summary, we numerically investigated the effect of two reference auxiliary electrodes on the electric field distribution of needleless roller electrospinning. After calculation, the ring electrode is connected to 5kv, and the parallel electrode is connected to 11kv to achieve the most uniform electric field distribution in the entire working field (including the receiving plate, the spinning field, and the roller). However, it is also possible to add only the single-plate electrode on the top of the collecting plate and access -700v. The latter is more energy efficient. We have found that the introduction of the auxiliary electrode can increase the electric field strength in the spinneret field and improve the uneven distribution of the electric field. It can provide reference for the development of roller electrospinning and even needle-free electrospinning.

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