Electric Field Structure Analysis and Experimentation of Needle-plate Type Electrospinning Machine

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Abstract

Electrospinning technique is currently one of the most important methods for preparing nanofiber. It is important and essential to analyze the distribution of electric field in electrospinning machine. The electric field’s distribution in the typical electrospinning device was calculated and analyzed based on finite element calculation theory of electric field. The electric field is optimized by the optimization of the structure parameters, and a set of optimal sequence is got. Based on the experimental system of the electrospinning machine, contrast experiment is performed in before and after the optimization of electric field. The experimentation results show that the distribution of fiber diameter of polyimide non-woven fabric is equal and has an certain directivity after adding assistant electric field. The simulation analysis provides an effective reference for the optimization design of electric field’s distribution in the electro-spinning device.

Keywords: We would like to encourage you to list your keywords in this section

1. Introduction

The polymer solutions or melts with charge flow and deform at strong static electric field, and solvent is evaporated or the melt is cooled and solidified, then fibroid substance is obtained. In high electric field, fluid is ejected from Taylor core and formed jet flow. Jet flow with electricity speed up and its diameter becomes tiny in the electric field [1-3]. This is the reason that electrospinning can obtain the nanofibre. Figure 1 is schematic diagram of electrospinning device [4]. In essence, electrostatic force is unique driving force in electrospinning. So, whether the distribution of electric field is reasonable will direct affect the fineness and morphology of electrospinning fibre. The fluidic instability phenomenon exist in undesired electric field distribution, especially in sudden drop of field intensity, this will lead to uncertainty of jet flow in the receiver. Unordered diffusion in the process of electrospinning exist with external disturbance (especially in lower concentration and viscosity of solution) [5]. This not only pollute experimental environment, but also waste experimental material and reduce the efficiency of electrospinning. The fluidic instability phenomenon can be weakened by controlling the shape and the strength of macroscopic electric field based on the analysis of Reneker’s electrostatic spinning process [6-7]. Consequently, it is important and essential to analyze the distribution of electric field in electrospinning machine.
2. Finite Element Calculation Theory of Electric Field

2.1. The potential function $\phi$

Suppose the potential function $\phi$ of each small unit $e$ is the linear function of $r$ and $z$, so the electric filed is regarded as a homogeneous one approximately in each small unit domain. Thus every point’s potential of each unit meet the following potential interpolation function.

$$\phi = \alpha_i + \alpha_j r + \alpha_k z$$  \hspace{1cm} (1)

Aiming to one single unit, suppose its three node number respectively is $i$, $j$, and $m$ (counterclockwise arranging), the function of the start point $i$ should meet Equation (1).

$$\begin{cases}
\phi_i = \alpha_i + \alpha_j r_i + \alpha_k z_i \\
\phi_j = \alpha_i + \alpha_j r_j + \alpha_k z_j \\
\phi_m = \alpha_i + \alpha_j r_m + \alpha_k z_m 
\end{cases} \hspace{1cm} (2)$$

$$\alpha_i = \frac{1}{2S_e} \left( \alpha_j \phi_j + \alpha_k \phi_k + \alpha_m \phi_m \right)$$

$$\alpha_j = \frac{1}{2S_e} \left( b_j \phi_i + b_j \phi_j + b_m \phi_m \right)$$

$$\alpha_m = \frac{1}{2S_e} \left( c_j \phi_i + c_j \phi_j + c_m \phi_m \right) \hspace{1cm} (3)$$

$S_e$ is the area of unit $e$:

$$S_e = \frac{1}{2} \begin{vmatrix} r_i & z_i \\ r_j & z_j \\ r_m & z_m \end{vmatrix} = \frac{1}{2} \left( b_j c_i - b_i c_j \right) \hspace{1cm} (4)$$

So the interpolation function of unit $e$ is as follows.

$$\phi(x, y) = \frac{1}{2S_e} \left[ (a_j + b_j r + c_j z) \phi_i + (a_j + b_j r + c_j z) \phi_j + (a_m + b_m r + c_m z) \phi_m \right] \hspace{1cm} (5)$$
2.2. The energy function of unit e

The energy function of unit e is as follows.

\[ W_e = \int \frac{\partial \varphi}{\partial r} \left[ \left( \frac{\partial \varphi}{\partial r} + \frac{\partial \varphi}{\partial z} \right) \cdot 2\pi d_r d_z \right] \]  

(6)

According to the Equation (3), we know that \( \frac{\partial \varphi}{\partial r} = \alpha_2 \), \( \frac{\partial \varphi}{\partial z} = \alpha_3 \), that is, \( \frac{\partial \varphi}{\partial r} \) and \( \frac{\partial \varphi}{\partial z} \) of each point in unit e are both definite value, and it is not influenced by coordinate \((r, z)\), so \( W_e \) can be simplified.

\[ W_e = \frac{\varepsilon}{2} \cdot 2\pi \left[ \frac{\sum b_i \varphi_s}{4S_e^2} (\sum_{i,j,m} b_i \varphi_s)^2 + \frac{\sum c_i \varphi_s}{4S_e^2} (\sum_{i,j,m} c_i \varphi_s)^2 \right] \int r d_r d_z \]

(7)

\[ \int r d_r d_z = \frac{r_i + r_j + r_m}{3} S_e = r_e S_e \]

(8)

Where, \( r_e \) is the distance from the center of triangle unit e to the axis z.

Thus,

\[ W_e = \frac{1}{2} \cdot 2\pi \varepsilon r_e \left[ \left( \sum b_i \varphi_s \right)^2 + \left( \sum c_i \varphi_s \right)^2 \right] \]

(9)

2.3. Calculation of electric field strength

Computational equation of electric field intensity is as follows.

\[ \vec{E} = -\nabla \varphi = - \frac{d\varphi}{dr} \cdot e_r - \frac{d\varphi}{dz} \cdot e_z = E_{r_e} e_r + E_{z_e} e_z \]

(10)

Where, \( E_{r_e} = -\frac{\partial \varphi}{\partial r} = -\frac{1}{2S_e} \left( \sum_{i,j,m} b_i \varphi_s \right) \), \( E_{z_e} = -\frac{\partial \varphi}{\partial z} = -\frac{1}{2S_e} \left( \sum_{i,j,m} c_i \varphi_s \right) \).

Its absolute value is,

\[ E = \sqrt{E_{r_e}^2 + E_{z_e}^2} = \sqrt{\left( \frac{\partial \varphi}{\partial r} \right)^2 + \left( \frac{\partial \varphi}{\partial z} \right)^2} \]

(11)

3. Electric Field Structure Simulation of Needle-plate Type Electrospinning Machine

3.1. Set up and simplification of electric field

In order to get better collecting result of spinning, the electric-field distribution between the spinning jet and the negative plate is the main influencing factor. Therefore, the working model of the whole electric field can be divided into 2 parts: one is the metal spinning jet, the other is negative plate. The spinning jet added high voltage static electricity is the factor that produces electric field, and the generated electrostatic field has a spatial symmetry, so we can deal with it as 2D field. We analyze the model by simplify it into two dimension electric field model.

Because the aperture of metal spinning jet is very tiny (usually 0.4mm), in order to simplify the structure of spinning jet, we separately set up the finite-element model of the
model Figure 2(a) and model Figure 2(b), and analyze and compare the difference of simulation results. The difference between model Figure 2(a) and model Figure 2(b) is that model Figure 2(a) has pore and model Figure 2(b) is replaced in entity. The analysis result shows that there are identical voltages distribution maps of the two types of structures, as is shown in Figure 2. It indicates that the spinning jet can be completely replaced by model Figure 2(b). And the result from structural simplify can be controlled within allowable error.

(a) Voltages distribution before simplification  (b) Voltages distribution after simplification

**Figure 2. Voltages distribution maps of spinning jet**

**Figure 3. The simplified FEA mesh generation model of needle-plate type**

**Table 1. Parameters setting of the model**

<table>
<thead>
<tr>
<th>Model</th>
<th>Spray gun</th>
<th>&quot;-&quot; plate</th>
<th>Air medium</th>
<th>Shielding net</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dielectric constant</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>5</td>
</tr>
<tr>
<td>Voltage load</td>
<td>8000V</td>
<td>-5000V</td>
<td>----</td>
<td>0V</td>
</tr>
</tbody>
</table>

**3.2. FEA of electric field**

Using traditional H-method to FEA of electrostatic field [8, 9], we thus proposed some assumptions: 1) the dielectric constant of medium is constant and doesn’t depend on electric field; 2) influences of electric charge of electrification spinning fiber was ignored; 3) effects of control elements on electric-field distribution would be neglected; 4) we supposed the volume density of field electric charge ρ=0. Through selecting various kinds of unit and
Comparing analysis results with actual data, we chose 8 nodal points two dimension unit (PLANE121). Table 1 shows the material property, unit type and setting of electric tension loading.

3.3. Simulated result of electrostatic field

Figure 4 and Figure 7 show the distribution of electric-field vector which got after analyzing. In high voltage electrostatic spinning electric field analysis, mainly should be considered the distribution situation of electrostatic spinning working electric field strength. Simulated result indicated that the distribution of electric field strength had the following characteristics: 1) Figure 4 shows that the electric-field vector crosswise of electrostatic spinning working electric field was axial symmetric distribution. Cloud image of potential isoline is as shown in Figure 5. 2) Figure 6 shows that we could analyze that: Same as the physical truth, the maximum of field strength appeared on the position of spinning pipe orifice and its direction pointed upward vertical to the negative plate. The maximum of field strength was $E = 2.64 \times 10^6$ V / m. 3) The allocation plan of spinneret shown in Figure 7, we find out that: the nearer the electric-field strength was to the negative plate, the faster the electric-field strength declined. The field strength sudden dropped to a lower value especially in a small distance near the spinneret pipe orifice. The other parameters remain the same, when the width of shielding net changes, we can obtain the relation between maximum electric field and shielding net width, which is as shown in Figure 8. The other parameters remain the same, when the impressed voltage $U$ changes, we can obtain the relation between maximum electric field and the impressed voltage $U$, which is as shown in Figure 9.

![Figure 4. The vector distribution of the electric field strength](image-url)
Figure 5. Cloud image of potential isoline

Figure 6. Vector distribution of nozzle on spinneret pipe

Figure 7. Relation between electric field and collecting distance
4. Optimization of Electric Field Structure of Needle-plate Type Electrospinning Machine

4.1. Optimization of electric field structure

Controlling the shape and the strength of macroscopic electric field could weaken the instability phenomenon of fluidic from the analysis of Reneker’s electrostatic spinning process [10]. A shield net was added to the spinning machine to enclose the electric field in a settled area completely. Comparing with the traditional spinning machine in which the electric field exposed in the whole space, a slight variation of spinning electrostatic field structural parameter would cause a significant change of the shape and the field strength of macroscopic electric field and then influenced the effect of spinning. Therefore the structure optimization problem of electric field generalized as follows: though optimizing the geometrical forms of spinning electrostatic field structure in satisfying actual design condition, this made the lowest value of voltage when spinning caught the necessary value of field strength.

![Figure 8. Relation between maximum electric field and shielding net width](image)

![Figure 9. Relation between maximum electric field and the impressed voltage](image)

When optimizing and designing, we kept the voltage values at the negative plate invariantly while defining the distance between spinneret and the negative plate $L$, the width of shield $W$, the diameter of the negative plate $D$ and the voltage loading $V$ as the optimization design variable. According to the geometrical relationship of parameters and the self-characteristic of spinning experiment, we designed that the variation of the variable $X$ should be content to the follows:

$$X = \{30\text{cm} > L > 10\text{cm}, 100\text{cm} > W > 60\text{cm}, 40\text{cm} > D > 20\text{cm}, 15000\text{v} > V > 6000\text{v}\}$$

The maximum field strength value of electric field was the state variable which was defined not less than proper functioning value. This optimization design didn’t define the
target function. The optimization design was a technology of searching and disposing the design space. Calculating the minimum was not the optimized ultimate goal. Our optimization design objective was to obtain the design array with design conditions, the design array of external voltage loading minimum without defining the target function. We collected 8 nodal points and two dimensions. The maximum of iterations was 30.

4.2. Optimization results

The changing situation of main parameters is as shown in Table 2. Based on the comparison of the results of before and after optimization, we can know that the maximum value of electric field \( E = 2.68 \times 10^6 \text{V/m} \) is satisfied with the electrospinning requirement. In comparison to before optimization, the voltage value is reduced by 10.54%. This decreases the interference of metal motion components in electric field to the distribution of electric field and improves the distribution of electric field. So we can get the excellent morphology of nanofiber from electrospinning.

<table>
<thead>
<tr>
<th></th>
<th>L(cm)</th>
<th>W(cm)</th>
<th>D(cm)</th>
<th>V(v)</th>
<th>E(10^6 V/m)</th>
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<tbody>
<tr>
<td>Before optimization</td>
<td>15</td>
<td>80</td>
<td>30</td>
<td>8000</td>
<td>2.64</td>
</tr>
<tr>
<td>After optimization</td>
<td>11.5</td>
<td>68.3</td>
<td>36.2</td>
<td>7156.8</td>
<td>2.68</td>
</tr>
</tbody>
</table>

Table 2. The comparison of before and after optimization

5. Electrospinning Experiment

5.1. Experimental system of the electrospinning machine

Experimental system of the electrospinning machine is shown in Figure 7. High-voltage power supply, which is made of electrical department of Tsinghua University, can realize the continuous adjustment of the voltage in the range from 0V to 100KV. Shield mesh with uniform gap is weaved by metal wire. In order to reduce the interference of electric field to input signal, shielded cable is used as the connecting line between control platform and injection unit, between computer and control card.

![Figure 10. Experimental system of the electrospinning machine](image)
5.2. Results and analysis of experiment

Figure 11(a) and Figure 11(b) are the SEM image of polyimide non-woven fabric obtained in before and after the electric field structure optimization respectively. We can see obviously that dispersity of fiber diameter in Figure 11(a) is larger than in Figure 11(b), and fiber orientation in Figure 11(a) is not better than in Figure 11(b). Figure 12(a) and Figure 12(b) are the distribution of fiber diameter in before and after the electric field structure optimization respectively. From Figure 12, after the optimization of electric field structure, the distribution of fiber diameter of polyimide non-woven fabric is equal and has a certain directivity.

6. Conclusions

Based on Finite element calculation theory of electric field, the finite element model of electric field is established using ANSYS, and the distribution is calculated. The features of distribution are analyzed. Simulation analysis provides some useful and valid reference for the optimization of electric field. The electric field is optimized by the optimization of the structure parameters, and a set of optimal sequence is got. This sequence is satisfied with work requirements of electrospinning. In comparison to before optimization, the voltage value is reduced by 10.54%. This protects the control components and ensures the stability of the control elements and operator's safety. Based on the experimental system of the electrospinning machine, contrast experiment is performed in before and after the optimization of electric field. Experimental results show that optimization of electric field can improve the electric environment and the distribution of fiber diameter of polyimide non-woven fabric is equal and has a certain directivity.
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References