Effect of Electret Process Parameters on Filtration Performance of Polypropylene Melt-Blown Nonwoven Fabric

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Abstract: With the spread of the novel coronavirus, masks become daily necessities, and their protective effect mainly depends on the core materials, so improving the performance of the core material polypropylene melt-blown nonwoven fabric has become the current research hotspot. The filtration performance of PP melt-blown nonwoven fabric mainly depends on the electret process parameters. The electret treatment of PP melt-blown nonwoven fabric is carried out by using high voltage corona discharge. The research on the influence of the electret process parameters, such as charging time, charging voltage and charging distance, on the filtration performance of PP melt-blown nonwoven fabric will have guiding significance for the practical production. In this paper, after a lot of research and experimental work, find out the influence of process parameters on the filtration performance of nonwoven fabrics. It is found that the best condition for the sample is the charge time of 12 min, the charge voltage of 15 kV and the charge distance of 4 cm. The filter efficiency is 90.2%, which is more than 1.5 times higher than that before the sample. The air permeability of melt-blown nonwovens after electret treatment did not decrease.

1. Introduction
The novel coronavirus has been spreading rapidly and extensively since the end of 2019, which has caused serious threats to people's lives around the world, therefore public safety and health issues have drawn wide attention. Novel coronavirus pneumonia, severe acute respiratory syndrome (SARS) and avian flu are all respiratory infectious diseases. Wearing masks has become an effective approach to protect the infection of respiratory infectious diseases. Polypropylene spraying nonwoven fabric is the core material for making masks. Ordinary nonwoven fabrics can not effectively remove small particles in the air, and can not achieve the ideal protective effect. By treating the electropole of polypropylene melt-blown nonwoven fabric, the filtration and adsorption capacity of polypropylene melt-blown nonwoven fabric can be greatly improved, and it has excellent protection ability by electing PP melt-blown nonwoven fabric. Therefore, it is of great practical significance to study the influence of electret process parameters on the filtration performance of polypropylene melt-blown nonwoven fabric.

Electrets are dielectric materials that could store charge for a long time [1,2] The standing-polarization treatment of polypropylene filter material could enhance the electrostatic adsorption capacity and the filtration of smaller particles, which can improve the filtration efficiency without increasing the filtration resistance. In recent years, there have been more studies on electret treatment of filter materials [3-6]. Wang Feipeng[7] enhanced the filtering effect of transformer oil purification and extended the service life of filter materials through fluorination and electret treatment of polypropylene filter materials. Huang Zheng[8] first prepared polyamide acid nanofiber membrane by electrostatic spinning technology[9], and then obtained polyyimide nanofiber membrane through
thermal imination. Then, Polyimide nanofiber membrane was obtained by thermal imination[10], and electret air filter materials were obtained by electret treatment. The results show that the polyimide nanofiber membrane treated with corona discharge electret and doped with nanoparticles has excellent air filtering performance and low filtration resistance. Liu Fan[11] prepared SiO$_2$ /PU nanofibers by electrostatic spinning by mixing electret nanometer SiO$_2$ into polyurethane (PU) spinning solution. The test results showed that with the increase of the mass fraction of electret nanometer SiO$_2$, the filtration efficiency and filtration resistance of the fiber membrane increased first and then decreased. When the SiO$_2$ mass fraction is 5%, the filtration performance of the material has been optimized, the filtration efficiency is 94.256%, and the filtration resistance is 29.71 Pa. Qian Yao[12] selected polytetrafluoroethylene fiber with strong polarity to conduct friction electret to form needle-punched nonwoven filter materials. The results show that the filter material treated by electret has high filtration efficiency and low filtration resistance. The literature review shows that many investigations have been focused on this issue, however, there are many electret process parameters, which may involve with filtration performance, and how these parameters coupled with each other affect the filtration performance is still unclear.

In this paper, high voltage corona discharge [13,14] is used to conduct electret treatment of polypropylene melt-blown nonwoven fabric. The effects of charging time, charging voltage and charging distance on the filtration performance of nonwoven fabrics were studied. Therefore, this work may provide valuable information for the production of polypropylene nonwoven filter materials.

2. Experiment

2.1 Sample Preparation

The experimental samples are polypropylene spraying nonwoven fabric produced by Shandong Huaye nonwoven company. The mass per unit area is 30g/m$^2$. After cutting the nonwoven fabric to a certain specification, the sample should be treated with electrostatic removal, because nonwoven fabric in the process of production will generate static electricity. The JX308 ion air gun produced by Shenzhen Jixin Technology Co., LTD is employed to remove the static electricity.

2.2 Electret Treatment of Corona discharge of Experimental Sample

The nonwoven fabric samples were treated with corona discharge electret. The electret device is needle - plate electrode type, designed and built by the authors. Tianjin Dongwen high Voltage power supply Co., LTD was used to produce polarized high voltage power supply with output voltage of DC 0-100000V. When the sample of nonwoven fabric is placed on the supporting plate and the tip voltage is applied and increased. When the voltage reaches a certain level, the tip corona discharge is generated, which releases electrons or ions and makes the sample of nonwoven fabric charged. The nonwoven fabric samples were treated under different parameters, including charging time, charging voltage and charging distance.

2.3 Analysis and test Methods of Experimental Samples

2.3.1 Scanning electron microscopy (SEM). The scanning electron microscope (SEM) produced by American FEI Company was used to characterize the surface morphology of nonwoven fabric samples before and after standing pole treatment. The samples were fixed with conductive adhesive and sputtered with gold nanoparticles. The test environmental temperature is at 20 ℃, relative humidity is 65%, the high voltage is 15 KV, and the image magnification rate is 5000.

2.3.2 Performance test of filter material. The 8130 automatic filter material detector produced by TSI was used to test the filtration efficiency of nonwoven fabric samples after electret treatment. The sodium aerosol is used as test carrier. The test was conducted at a temperature of 20 ℃ and relative humidity of 65%. The filtration performance of samples is tested in accordance with GB 19083-2010.
and other relevant standards. The penetration rate of particulate matter can be obtained by automatic filter material tester. The actual filtration efficiency of nonwoven fabric samples is:

\[ \text{Filtration efficiency} = \frac{1}{\text{Penetration rate}} \]

2.3.3 Air permeability test. The YG461DA digital fabric breathability meter produced by Wenzhou Fangyuan Instrument Co., LTD was used to test the breathability of nonwoven fabric samples before and after electret treatment.

3. Results and Discussion

3.1 Single Factor Experiment

The influences of charging time, charging voltage and charging distance on the filtration performance of melt-spraying nonwoven fabric were studied subsequently by maintaining the other parameters at a fixed value.

3.1.1 Charging time. The experiments are conducted under different charging time (4, 8, 12, 16 and 20 min), while the other parameters are fixed at a constant value, i.e., the air humidity is 30%, the charging voltage is 10 KV and the charging distance is 5 cm. The influence of charging time on the filtration efficiency of polypropylene melt-blown nonwoven fabric is explored and the results are plotted in figure 1.

It is shown that the filtration efficiency increases with the increase of treatment time when the treatment time is less than 8 min, however as the treatment time is increased further the filtration efficiency becomes less sensitive to the treatment time. To explain this, we should mention the impurities and defects on the surface of the sample which may generate charge traps at the initial stage of electret treatment. Under the action of an applied electric field, positive and negative ions are more prone to be trapped when they separate towards the poles \(^{[15,16]}\). External charges may also be injected into the charge trap. With the increase of treatment time, the more charges captured on the surface of the sample, the more particles can be absorbed, so the filtration efficiency increases. However, the charge trap on the surface of the sample is limited. When the trap is full, the charge can not be increased too much, as a consequence the filtration efficiency becomes less sensitive to the treatment time.

3.1.2 Charging voltage. The influence of charging voltage on the filtration efficiency of polypropylene melting spraying nonwoven fabric was studied under the air humidity of 30%, charging time of 4 min and charging distance of 5 cm. The filtration efficiency are plotted as a function of voltage in Figure 2.

![Figure 1](image1.png)  
**Figure 1.** Relation between charging time and sample filtration efficiency

![Figure 2](image2.png)  
**Figure 2.** Relation between charging voltage and sample filtration efficiency
It is found that the filtration efficiency could be largely improved by increasing the voltage from 0 to 5 kV. When the charging voltage is greater than 10 kV, the filtration efficiency becomes less sensitive to voltage and does not increase too much with the increasing of voltage.

With the increase of charging voltage, the ions and electrons could obtain more kinetic energy under strong external electric field, so that they can not only be captured by the charge trap on the surface of the fiber, but also can be combined into the potential trap inside the fiber. As more charge is captured stably inside the fiber, more small solid particles could be absorbed and consequently the filtration efficiency increases. When the charging voltage is larger than 10 kV, most of the internal potential trap inside the fiber is occupied, and the ions and electrons can only enter slowly, as a result the filtration efficiency does not increase too much under this voltage range.

3.1.3 Charging distance. To explore effect of charging distance on filtration efficiency, the charging distance is varied from 2 to 6 cm, while the air humidity, charging time and charging voltage are kept at 30%, 4 min and 10 kV respectively. The filtration efficiency versus distance are illustrated in Figure 3.

![Figure 3. Relation between charging distance and sample filtration efficiency](image)

Figure 3 shows that the filtration efficiency decreases slightly with the increase of the charging distance, this is because as charging distance increase from 2 cm to 6 cm, most of the traps on the surface are basically occupied by ions and electrons released from the electric shock needle and hence the number of potential traps on the surface tend to be saturated. Therefore, the captured charge on the surface of the sample did not change too much with the charging distance, and the adsorbed particles did not decrease too much, that’s why the filtration efficiency decreases slightly with the increase of the charging distance.

3.2 Multi factor Orthogonal Experiment

In order to further optimize the process parameters of electret treatment, the orthogonal test were performed to obtain the optimal parameters. Three factors including charging time, charging voltage and charging distance were considered in this work, and three values of each parameter are taken to conduct orthogonal experiment, as shown in Table 1.
Table 1. Electret process parameters

| level | factor | time / min | voltage / kv | distance / cm |
|-------|--------|------------|--------------|---------------|
| 1     |        | 4          | 5            | 2             |
| 2     |        | 8          | 10           | 4             |
| 3     |        | 12         | 15           | 6             |

Table L9 \((3^4)\) was used to design the experiment. The optimum process conditions for electret treatment were obtained by using range analysis method. The parameters of orthogonal experiment and the test results of sample filtration efficiency were listed in Table 2.

Table 2. Orthogonal test design and calculation results

| No | A time / min | B voltage / kv | C distance / cm | Filtration efficiency /% |
|----|--------------|----------------|-----------------|--------------------------|
| 1  | 4            | 5              | 2               | 47.2                     |
| 2  | 4            | 10             | 4               | 81.2                     |
| 3  | 4            | 15             | 6               | 85.3                     |
| 4  | 8            | 5              | 4               | 48.1                     |
| 5  | 8            | 10             | 6               | 86.0                     |
| 6  | 8            | 15             | 2               | 89.9                     |
| 7  | 12           | 5              | 6               | 47.8                     |
| 8  | 12           | 10             | 2               | 84.3                     |
| 9  | 12           | 15             | 4               | 90.2                     |
| K1 | 213.7        | 143.1          | 221.4           |                          |
| K2 | 224.0        | 251.5          | 219.5           |                          |
| K3 | 222.3        | 265.4          | 219.1           |                          |
| k1 | 71.2         | 47.7           | 73.8            |                          |
| k2 | 74.7         | 83.8           | 73.1            |                          |
| k3 | 74.1         | 88.5           | 73.0            |                          |
| R  | 3.5          | 40.8           | 0.7             |                          |

\(a\text{Ki}\) - The sum of test index values of level I of this factor.

\(b\text{ki}\) - the average test index value of level I of this factor.

\(c\text{R}\) - Range, for a factor \(R = k_{\text{max}} - k_{\text{min}}\), the greater the \(R\) value, the greater the influence of this factor on the indexes under investigation.

Through orthogonal experiment, we find that the charging voltage is the most sensitive parameter, which has the most significant influence on sample filtration efficiency, and subsequently followed by charging time and charging distance. Table 2 also shows that sample No. 9 has the highest filtration efficiency. The corresponding factor level is A3B3C2, which indicates that the optimal parameter to obtain filtration efficiency could be summarized as follows, charging time 12 min, charging voltage 15 kV and charging distance 4 cm.
3.3 Effect of Electret Treatment on Surface Morphology

The surface morphologies of polypropylene melt-spraying nonwoven fabric before and after electret treatment are illustrated in Figs. 4 and 5 respectively. It can be seen from Figs. 4 and 5 that the fibers in nonwoven fabrics are arranged in disorder and form a three-dimensional network structure. This structure makes nonwoven fabrics have good filtration and air permeability. The optimized electret process parameters as listed in the previous section were used to treat melt-spraying nonwoven fabrics. Through comparing Figs. 4 and 5, we found that slight eminence appears on the surface after electret treatment, this can be attributed to the large amount of charge particles induced by corona discharge, which may break the molecular chain of polypropylene fiber and accumulate on the surface.

![Figure 4. Surface morphology of sample before electret treatment](image)

![Figure 5. Surface morphology of sample after electret treatment](image)

3.4 Air permeability Test Before and After Electret Treatment

In this work, the optimized electret process parameters were used to treat the samples, and the air permeability before and after treatment are measured under 100 Pa. The results are shown in Table 3.

| Test indicators | Before electret | After electret |
|-----------------|-----------------|----------------|
| Air permeability / L · m²·s⁻¹ | 213.4 | 213.1 |

Air permeability is one of the most important indexes of filtration materials. It can be seen from the table that the air permeability of polypropylene melt-sprayed nonwoven fabric has almost no change before and after electret. This shows that the filtration performance can be improved by electret treatment without changing the air permeability. This is especially important in respiratory protective equipment.

4. Conclusion

The filter performance of PP melt-blown nonwoven fabric is enhanced after corona electret treatment. The filtration efficiency increases with the increase of charging time and charging voltage. It decreases with the increase of charging distance. Among these electret process parameters, the charging voltage has the most significant impact on the filtration performance of nonwoven fabrics.

Furthermore, the electret process parameters are optimized through orthogonal test, the maximum filtration efficiency is achieved when the charging time is 12 min, charging voltage is 15 kV and charging distance is 4 cm. Under these conditions, the electret treatment could achieve better electret effect, and the permeability of PP melt-blown nonwoven fabric after electret treatment does not change.

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