EFFECT OF TEMPERATURE ON THE STRUCTURE AND FILTRATION PERFORMANCE OF POLYPROPYLENE MELT-BLOWN NONWOVENS

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Abstract:

By applying the simultaneous corona-temperature treatment, the effect of electret temperature on the structure and filtration properties of melt-blown nonwovens was investigated. Fiber diameter, pore size, thickness, areal weight, porosity, crystallinity, filtration efficiency, and pressure drop were evaluated. The results demonstrated that some changes occurred in the structure of electret fabrics after treatment under different temperatures. In the range of 20°C~105°C, the filtration efficiency of melt-blown nonwovens has a relationship with the change in crystallinity, and the pressure drop increased because of the change in areal weight and porosity. This work may provide a reference for further improving filtration efficiency of melt-blown nonwovens.

Keywords:

Polypropylene, electret temperature, melt-blown fabrics, structure, filtration performance

1. Introduction

Emerging environmental problems, especially fine particle pollution (<2.5 μm, promulgated by the US Environmental Protection Agency) can cause great harm to human health such as to respiratory tract and extra pulmonary organs [1-4]. Currently, air filtration is one of the most direct and effective methods for resolving particulate pollutants, and the key is air filtration materials. There are many varieties of nonwoven filter materials, and the diversity of the production process makes it applicable to different fields [5]. Melt-blown nonwoven materials are widely used in air filtration because of their fine fibers, large surface area, high porosity, and good filtration characteristics [6-8].

At present, the research on how to improve the filtration performance of melt-blown nonwovens mainly focuses on two aspects. One is improved from the structure of nonwoven fabric [4, 9]. Deng et al. [3] successfully fabricated multi-scale micro/nanofibers membrane by one-step melt-blown technique. Soltani and Macosko [9] used the islands-in-the-sea approach to prepare nanofiber melt-blown nonwovens. However, these methods have some shortcomings such as having large filtration resistance and increasing energy consumption. The other is combined with electret technology. Electret technology is an electric field poling method that via a corona charging system with adjustable electric field provides charge to fabrics. Electret filters not only include the traditional dust trapping way (interception effect, inertance effect, diffusion effect, gravity effect) but also can absorb dust particles by electrostatic force (electrostatic effect) [10-12]. It has been broadly demonstrated that electret filter material with electrostatic charges added on fibers will improve particle collection efficiency without increasing the filtration resistance [13-15]. There are plenty of research for corona charging. Shu et al. [16] studied the electret technology of air filtration material and found that charging voltage, followed by charging speed and distance, are the main factors to affect the filtration efficiency. Brochocka et al. [17] used polypropylene (PP) admixed with additives with varying electrostatic potentials, and the results proved that electrostatic forces of nonwovens are strengthened. Chang et al. [18] developed a two-layer charged composite filter and found that it had a high figure of merit and a better holding capacity for PM_{2.5} (particle size < 2.5 μm). However, few studies have been done on combining corona charging with temperature. Zhang et al. [19] investigated the electromechanical performance of cellular PP electrets charged at a high temperature (≥100°C). Ji et al. [20] studied the charge storage and its stability of corona-charged PP nonwoven fabric treated with a high temperature (≥90°C), and the results showed that charge storage and its stability were improved. However, little attention was paid to the effect of electret temperature on structure and filtration performance of PP melt-blown nonwovens. According to Zhong-Bao J’s research, we assumed that charged at a high temperature (≥70°C), PP melt-blown nonwovens may increase their filtration efficiency.

Herein, in this report, we applied the method of simultaneous corona-temperature treatment, that is to say, applying external temperature treatment while polarizing. The simultaneous corona-temperature treatment first activates the dipole in the dielectric material at a high temperature (≥70°C). Under the action of the electric field force, the dipoles are aligned along the direction of the electric field, and the electric field
is maintained until the dielectric material is cooled to a certain low temperature, so that the originally activated dipole inside dielectric material is frozen, and in addition, a complicated charging phenomenon may occur between the electrode and the dielectric material under the action of an applied electric field. The electret thus formed contains a space charge and a dipole charge [21].

The material has a specific melting point, and it requires a certain amount of energy to accelerate its chemical structure change and increase the quantity of formed dipole within the electrets. Considering the integrity of the fabric, we choose a temperature range of 70–110°C. Therefore, we chose corona charging fabric as the control group; the other groups were treated with the simultaneous corona temperature. Here the effect of electret temperature (the temperature applied during the electret process is called electret temperature) on structure and filtration performance was investigated. At this time, corona charging fabric was charged under indoor condition without external temperature, and for the convenience of discussion, we would mark the electret temperature of corona charging fabric as room temperature. The only difference between all samples was the difference in the electret temperature.

2. Materials and methods

2.1. Materials

The raw material used was modified PP with a melt index of 1500 g/min. On the same bases of the melt-blown process and electret process and changing electret temperature, ten kinds of sample were fabricated. The melt-blown PP electret fabrics were produced using the melt-blown installation in Zhejiang Zhaohui Filter Technology Co. Ltd. We chose corona charging fabric (room temperature) as the control group; the other groups were treated with the simultaneous corona temperature. Here the effect of electret temperature (the temperature applied during the electret process is called electret temperature) on structure and filtration performance was investigated. At this time, corona charging fabric was charged under indoor condition without external temperature, and for the convenience of discussion, we would mark the electret temperature of corona charging fabric as room temperature. The only difference between all samples was the difference in the electret temperature.

2.2. Methods

The electret samples were formed via a corona charging system with the adjustable electric field to provide charge to PP fabrics [22]. When corona poling was performed at room temperature, the corona system was not heated. For the convenience of discussion, we recorded the room temperature as 20°C. Schematic diagram of the corona charging system is shown in Figure 1.

The surface morphology of samples was observed using a scanning electron microscope (JSM-5610LV, Japan). The fiber diameters were calculated using the software Image J by measuring 100 fibers using the scanning electron microscope (SEM) images.

The pore structure of samples was investigated using a capillary flow porometer (CFP-1100-AI, Porous Materials Inc., USA) based on the bubble point test.

\[ \rho_a = \frac{m}{A} \]  
(1)

where \( \rho_a \) is the areal density (g/m\(^2\)) and \( m \) is the mass (g) measured by an electronic scale (ML503/02, USA). Ten measurements were taken.

The porosity of the fabric can be calculated by the mass-density method. The mass of the sample is divided by the density of the raw material to obtain the true volume of the fiber. The specific calculation formula is as follows [23]:

\[ V_p = \frac{M}{\rho} \]  
(2)

\[ V_d = l \times s \times d \]  
(3)

\[ C = \left(1 - \frac{V_p}{V_d}\right) \times 100\% \]  
(4)

In equation (2), \( M \) is the average mass of the sample (g), \( \rho \) is the density of raw material (g/cm\(^3\)), and \( V_p \) is the absolute volume (true volume) of the fiber in the fabric (cm\(^3\)). In equation (3), \( l \) is the sample length (cm), \( S \) is the sample width (cm), \( d \) is the thickness (cm) of the sample measured at a specified pressure, and \( V_d \) is the bulk volume of fabric at nominal thickness (cm\(^3\)). In equation (4), \( C \) is the porosity of the fabric.

Crystallization performance of the fabric was measured using X-ray diffractometer (ARL XTRA, Switzerland) with the scanning angle 5°–55° and the scanning speed 2°/min, and the crystallinity was calculated using the software Jade.
The filtration efficiency and the pressure drop of the fabric were evaluated using a custom-design automatic filter tester. The measured fabric area was 100 cm$^2$. The aerogel was sodium chloride with a particle size of 0.3 μm, and the measured filtration rate was 5.33 cm/s (flow rate was 32 L/min). Three measurements were taken for each sample.

3. Results and discussions

3.1. Fiber diameter of samples

Fiber diameter is one of the basic structural parameters of fiber-based air filter materials, and it will directly affect the pore size, porosity, and pore structure of the materials, which will affect the filtration efficiency and air resistance of the materials [24]. The SEM image and the fiber diameter distribution of the fabric charged at 20°C are respectively shown in Figures 2 and 3; we can find that the fiber is fine and the fiber diameter in the range of 1–2 μm accounts for 75%.

Figure 2. SEM of fabric charged at 20°C.

Figure 3. Fiber diameter distribution of fabric charged at 20°C.

It can be seen from Figure 2 that the fibers in the melt-blown nonwoven fabric charged at 20°C are disorderly arranged to form a three-dimensional network structure. When the external temperature is applied (Figure 4), the surface morphology of fabrics has a relatively serious phenomenon of melting and agglomeration, and the pore of the three-dimensional structure is blocked, which in some extent destroys the surface structure of fabrics.

The average diameters are shown in Table 1. No visible change in the fiber diameter is found with the increase in the electret temperature. This was because the refinement of the fiber mainly occurs near the nozzle of the die during the production of the melt-blown nonwoven fabric.

3.2. Pore size and distribution of samples

Park et al. [25] studied the effect of different pore sizes and pore size distribution on fiber filtration performance. The results showed that air filtration materials with smaller pore size and uniform pore size distribution have better filtration efficiency. As shown in Figure 5, more than 95% of the pore size was mainly concentrated between 3 μm and 14 μm when the fabric was charged at 20°C.

Figure 6 displays that temperature treatment broadens the range of the pore size distribution of the fabric from 3–14 μm to 3–17 μm. We can see that all samples have a finer fiber diameter (Table 1). Generally, finer fibers would form a finer pore size and more uniform pore size distribution; however, during the process of charging at a high temperature (≥70°C), the formed melt-blown nonwoven fabric was heated again and the finer fibers were more easily melted; there were many molten beads attached to the fiber (Figure 7), resulting in the pore size becoming slightly larger.

The mean pore diameters further confirmed the conclusion. All samples charged in the range of 70–110°C have a larger mean pore diameter than those charged at 20°C.

3.3. The thickness and areal weight of samples

As shown in Table 3, as the electret temperature increased, the thickness first increased and then decreased, but the variation was not large, between 0.2 and 0.24 mm.

As shown in Figure 8, the smallest areal weight of samples charged at 20°C was 18.31 g/m$^2$; the areal weight of samples charged in the range of 70–95°C stayed at approximately 27 g/m$^2$. The areal weight continued to increase when the temperature continued to rise. When the electret temperature was low (at 70°C), the fiber shrunk by heat, the width of the fabric became narrow, and the thickness and the areal weight increased. As the temperature continued to rise (≥70°C), the shrinking fibers continued to melt and became fluid adhering to the fiber web, which became flat after cooling (Figure 4), so the thickness decreased while the areal weight continued to rise.

3.4. The porosity of samples

The porosity of the fiber assembly refers to the ratio of the pore diameter inside the fiber filter material to the fiber body structure. The porosity of the fabric decreased with the increase in the electret temperature (Figure 9). The porosity at 20°C was the highest, reaching 89.94%; the porosity was relatively stable and stayed at approximately 87% when the electret temperature was in the range of 70–95°C. When the temperature continued to rise, the porosity dropped significantly. For the melt-blown filter material, under the premise of a certain pore size, the
Figure 4. SEM images of fabric charged in the range of 70–110°C.

Table 1. The fiber diameters of all samples

| Electret temperature (°C) | 20   | 70   | 75   | 80   | 85   |
|---------------------------|------|------|------|------|------|
| Fiber diameter (mm)       | 1.79±0.71 | 1.75±0.61 | 1.82±0.65 | 1.79±0.61 | 1.82±0.79 |
| Electret temperature (°C) | 90   | 95   | 100  | 105  | 110  |
| Fiber diameter (mm)       | 1.87±0.72 | 1.96±0.95 | 1.62±0.64 | 1.64±0.79 | 2.03±0.98 |

Table 2. The mean pore diameter of samples

| Electret temperature (°C) | 20   | 70   | 75   | 80   | 85   |
|---------------------------|------|------|------|------|------|
| Mean pore diameter (mm)   | 8.437 | 16.047 | 9.16  | 9.901 | 9.982 |
| Electret temperature (°C) | 90   | 95   | 100  | 105  | 110  |
| Mean pore diameter (mm)   | 9.312 | 9.639 | 9.040 | 9.089 | 9.078 |

Table 3. Thickness of samples

| Temperature (°C) | 20   | 70   | 75   | 80   | 85   |
|------------------|------|------|------|------|------|
| Thickness (mm)   | 0.20±0.01 | 0.24±0.01 | 0.23±0.01 | 0.23±0.01 | 0.23±0.01 |
| Temperature (°C) | 90   | 95   | 100  | 105  | 110  |
| Thickness (mm)   | 0.23±0.01 | 0.23±0.01 | 0.22±0.02 | 0.22±0.01 | 0.20±0.01 |
Figure 5. Pore size and distribution of the sample charged at 20°C.

Figure 6. Pore size and distribution of samples charged in the range of 70–110°C.

Figure 7. SEM of the sample charged at 70°C.
3.6. Filtration performance

3.6.1. Pressure drop

As shown in Figure 13, the pressure drop at 20°C was the lowest. With the increase in temperature, the filtration resistance stayed at approximately 38 Pa.

From Figure 14, we can see that the trend of the fiber diameter varying with the electret temperature is opposite to the tendency of filtration resistance changing with the electret temperature, that is to say, the pressure drop increased (decreased) when the fiber diameter decreased (increased), and this phenomenon corresponds with the theory. We know that the areal density and porosity are two primary factors to affect the filtration resistance of melt-blown filter materials. The pressure drop would increase when the areal weight increased and the porosity decreased. From Figures 15 and 16, we can conclude that the increase in pressure drop is due to the increase in areal weight and the decrease in porosity.

3.6.2. Filtration efficiency

In Figure 17, with the increase in temperature, the filtration efficiency fluctuated up and down; the filtration efficiency kept above 96% when the temperature was in the range of 20–105°C and dropped significantly when the temperature continued to rise.

In Figure 18, we can clearly see the change in fiber diameter and filtration efficiency with the electret temperature. The filtration efficiency increased (decreased) when the fiber diameter decreased (increased), which also corresponds with the theory. In general, the filtration efficiency will decrease with the decrease in thickness and surface density. In the range of 20–105°C, Figure 19 presents that the trend of thickness and filtration efficiency almost keeps consistent, except at 80 and 100°C, in which the thickness decreased but the filtration increased. Figure 20 displays that the trend of areal weight and filtration efficiency almost keeps consistent, except at 80°C. Combined with Figure 21, we find that at 20–85°C, the crystallinity increased, and the filtration efficiency fluctuated up
and down. However, as shown in Table 4, we can find that the difference in filtration efficiency between the four samples (70, 75, 80, and 85°C) is very small. We can roughly think that at 20–85°C, the filtration efficiency increased with the increase in crystallinity. At 85–95°C, the areal weight remained relatively stable, the thickness decreased, the crystallinity decreased, and the filtration efficiency decreased. At 95–105°C, the areal weight remained relatively stable and the thickness decreased, but the crystallinity increased and the filtration efficiency increased. On this basis, we can conclude that in the range of 20—105°C, the change in the filtration efficiency has a relationship with the change in the crystal structure caused by the electret temperature.

### 3.6.3. Quality factor

Filtration efficiency and pressure drop are a pair of contradictions, so evaluating the filtration performance of air filtration materials requires comprehensive consideration of filtration efficiency and filtration resistance. Quality factor (QF) is a balance indicator for evaluating the filtration performance of materials. The specific calculation formula is as follows [28]:

$$QF = -\frac{\ln(1 - \eta)}{\Delta p}$$  \(5\)

In equation (5), \(\eta\) is the filtration efficiency (%) and \(\Delta p\) is the pressure drop (Pa).
The QF varies with the electret temperature as shown in Figure 22. We can see that the QF generally tends to decrease with the increase in the electret temperature in the case of comprehensive consideration of filtration efficiency and filtration resistance. The QF of fabric charged at room temperature is the highest, the corresponding filtration efficiency is 96.17% and the pressure drop is 27.7 Pa. In the samples charged at

It can be known from the above formula that the higher the filtration efficiency of the filter material or the lower the filtration resistance, the larger the QF value; the lower the efficiency or the greater the resistance, the smaller the QF value. In other words, the greater the QF, the better the filtration performance [29-32].
and the mean pore diameter was slightly larger. With the electret temperature raised, the porosity decreased while the areal weight increased, and the thickness first increased then decreased, but the variation was not large. The electret temperature could increase the diffraction peak signal of samples, promote the growth of the alpha crystal, and improve the crystallinity of fabrics.

The results of research on the effect of electret temperature on the filtration performance of melt-blown PP fabrics indicated that the pressure drop raised and kept relatively stable because of the decrease in porosity and the increase in areal weight, and the filtration efficiency increased (decreased) with the increase

70°C–110°C, the QF of the sample treated at 80°C was the largest, the corresponding filtration efficiency was 98.35%, and the filtration resistance was 38.7 Pa. We find that the filtration performance of fabric charged at room temperature was the best in all samples.

4. Conclusions

The results of research on the influence of electret temperature on the structure of melt-blown PP fabrics exhibited that the electret temperature has no significant effect on fiber diameter, but the range of pore size distribution was broadened and the mean pore diameter was slightly larger. With the electret temperature raised, the porosity decreased while the areal weight increased, and the thickness first increased then decreased, but the variation was not large. The electret temperature could increase the diffraction peak signal of samples, promote the growth of the alpha crystal, and improve the crystallinity of fabrics.

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Table 4. Crystallinity and filtration efficiency of samples

| Temperature (°C) | Crystallinity (%) | Efficiency (%) | Temperature (°C) | Crystallinity (%) | Efficiency (%) |
|------------------|-------------------|---------------|------------------|-------------------|---------------|
| 20               | 20.56             | 96.17         | 90               | 43.78             | 96.54         |
| 70               | 28.67             | 98.14         | 95               | 36.67             | 96.34         |
| 75               | 41.12             | 97.43         | 100              | 47.23             | 97.14         |
| 80               | 43.05             | 98.35         | 105              | 48.86             | 97.34         |
| 85               | 45.09             | 97.19         | 110              | 51.48             | 92.96         |
(decrease) in crystallinity when charged in the range of 70–105°C. Based on a combined consideration of air filtration efficiency and pressure drop, the QF of melt-blown nonwoven fabric treated at the room temperature is the highest, and the filtration performance is the best.

Acknowledgment

The work is funded by the Joint Bilateral Industrial R&D of International Scientific and Technological Cooperation (Grant No.: 2017CS4005), the National Natural Science Foundation of China (Grant No.: 51803182), the Fundamental Research Funds of Zhejiang Sci-Tech University, the Ministry of Education, Youth and Sports of the Czech Republic, the European Union – European Structural and Investment Funds in the frames of Operational Programme Research, and Development and Education – project Hybrid Materials for Hierarchical Structures (HyHi, Reg. No. CZ.02.1.01/0.0/0.0/16_019/0000843).

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