Preparation of electrospun nanofiber membrane for air filtration and process optimization based on BP neural network

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Abstract
The filtration layer in a medical protective mask can effectively prevent aerosol particles that might carry viruses from air. A nanofiber/microfiber composite membrane (NMCM) was successfully fabricated by electrospinning polyvinylidene fluoride (PVDF) nanofibers collected on the electrified and melt-blown polypropylene (PP) nonwovens, aiming to improve the filtration efficiency and reduce the resistance of respiration of mask. A four-factor and three-level orthogonal experiment was designed to study the effect of electrospinning parameters such as spinning solution concentration, voltage, tip-collect distance (TCD), and flow rate of solution on the filtration efficiency, resistance of respiration as well as quality factor of NMC developed to predict the resistance of respiration. Experimental results demonstrated that the filtration efficiency of NMCM ≥ 95% in comparison to that of electrified and melt-blown PP nonwovens 79.38%, which increases by 19.68%. Additionally, the average resistance of respiration is 94.78 Pa, which meets the protection requirements. Multivariate analysis of variance indicated that the resistance of respiration of the NMCM has significantly dependent on the concentration, voltage, TCD, and flow rate of the spinning solution and the quality factor of the NMCM has dependent on the resistance of respiration. The air permeability ranges from 166.23 to 314.35 mm s⁻¹, which is inversely proportional to the filtration resistance. As far as the filtration resistance is concerned, the optimal spinning parameters were obtained as follows. The concentration of spinning solution is 15%, the voltage is 27 kV, the TCD is 22 cm, and the flow rate is 2.5 ml h⁻¹. The relative error of the BP neural network varies from 0.49505% to 1.49217%, i.e. the error value varies from 0.17 to 1.33 Pa. The predicted resistance of respiration corresponding to the optimal process is 68.1374 Pa.

1. Introduction
SARS, MERS, and COVID-19 are infectious respiratory diseases that are transmitted through aerosol and are harmful to life and health. An effective way to prevent virus transmission is to wear masks with high filtration efficiency and low resistance of respiration [1]. However, there are international concerns about the shortage of critical personal and protective equipment (PPE) supply chains for single use [2]. Besides, the use of disposable masks in epidemic prevention has caused environmental pollution and virus transmission [3], and brought challenges for the decomposition of abandoned masks. Therefore, it is necessary to improve the service lives of masks and to develop reusable masks in the development of high-efficiency and low resistance of respiration fiber membranes.

At present, electrified and melt-blown polypropylene (PP) nonwovens are mainly used as the filtration materials for masks [4]. However, the filter efficiency decreases rapidly with increase of usage times and the service life is short. In case of mask the filtration of particulate matter mainly includes media filtration and cake filtration. By the combined interactions of deposition, interception, Brownian motion, gravity sedimentation
and electrostatic action, the media filtration can effectively capture particles on the fibers’ surface [5]. The electrostatic charge plays the important role in capturing virus-carrying aerosols with a diameter from 100 nm to 300 nm [6]. However, the steam produced by breathing leads to electrostatic attenuation on the surface of the fibers, which result in remarkable decrease of filtration efficiency. As far as cake filtration is concerned, it initially captured particles as the collection point, the particles accumulate to form a dendritic structure. Adjacent dendrites are gradually connected together, forming a ‘filter cake’ at the upstream end of the filter to mechanically capture the particles [7]. The electrostatic effect rapidly decreases due to the ‘shielding effect’ of the deposition of particles on the charge of the fibers during particle accumulation. The filtration effect gradually varies from deep filtration to surface filtration. The resistance of respiration gradually increases with the accumulation of the filter cake, which results in decreases of respiratory comfort [8]. Therefore, it is necessary to develop high-efficiency and low-resistance filtration materials for masks so as to prevent the transmission of viruses and protect human health. The nanofibers membrane has high surface area can not only improve the interception and Brownian motion in media filtration, but also reduce the accumulation of particles resulting from particles acting as collection points [9]. Porous and fluffy fiber membranes composed of nanofibers and microfibers can enhance the ‘slip effect’ of air flow, reduce resistance of respiration and improve respiratory comfort [10].

The fabrication of polymer nanofibers includes spinning, template synthesis, phase separation, self-assembly, and electrospinning [11]. Electrospinning is an effective way for preparing nanofibers. High-voltage static electricity is added to the polymer solution/melt. After the Taylor cone was drawn, the nanofibers were collected on the collecting device [12]. Electrospun nanofibers have many advantages, such as a large specific area, high porosity, good air permeability, and moisture permeability, which meets the requirements of new biological protection materials [13]. Cui et al [14] used polyvinyl alcohol (PVA)-sodium lignosulfonate (LS) as the raw materials to prepare the flexible and transparent composite nano fiber membranes through electrospinning and thermal crosslinking method. The filtration efficiency for fine particulate matter (PM 2.5) was 99.44%. Cheng et al [15] used PA66 as the raw material to prepare an electrospun nanofiber window screen that could capture more than 99% of particles in the air. Lin et al [16] used PVDF as raw material to manufacture a fluffy fiber membrane with a pressure drop of 123Pa. Wang et al [17] prepared a rechargeable polyamide-based n-haloamine nanofiber membrane for an efficient antibacterial mask. The nanofiber membrane has antibacterial effect after chlorinated reaction. Therefore, electrospun nanofiber membranes have great market potentials in filter area.

The performance of nanofiber membrane is mainly affected by the solution properties, spinning parameters, and environmental conditions [18]. The solution properties include the concentration, viscosity, surface tension, conductivity, molecular weight, and solvent type. In addition, the spinning parameters mainly includes
the voltage, flow rate, tip--collect distance (TCD), and needle diameter [19]. Moreover, the environmental factors include the temperature and humidity [20]. For example, Peng et al [21] investigated the influence of spinning parameters on fiber properties and optimized the microstructural morphologies and diameter distributions of the PLGA and PVA nanofibers by adjusting the electrospinning parameters, such as solution concentrations, applied voltages, flow rates, and TCD. Okutan et al [22] studied the influence of concentration, voltage, and flow rate on the morphology of gelatin nanofiber, but did not contain the influence of the receiving distance. Gee et al [23] explored the amount of membrane beta phase of PVDF by varying electrospinning parameters. Russo et al [24] fabricated the nanofiber membrane with polyvinylidene fluoride (PVDF) [25] and dimethyl sulfoxide (DMSO)/acetone and analyze the influence of spinning solution concentration, voltage, and receiving distance on the fiber morphology, however, the spinning flow had not been considered.

The behavior of electrospun nanofiber membrane is affected by many factors. Multivariate analysis of variance (MANOVA) can be used to analyze the significance of the interaction between the influencing factors, as well as the significance of the overall difference between the internal levels of factors [26]. At the same time, MANOVA can reduce the joint probability of rejecting the true zero hypothesis in one-way analysis of variance (ANOVA) [27]. Due to the nonlinear relationship between multiple factors and filtration efficiency, resistance of respiration and quality factors, a back-propagation (BP) neural network can be used to establish a functional mapping of multiple inputs and outputs. BP neural networks adopt the gradient descent method [28]. Multi-dimensional function mapping is approximated through self-training for recognition and prediction, which has good fault tolerance [29]. Li et al [30] proposed a BP neural network model and predicted the concentration of biological aerosols.

In this paper, an PVDF nanofiber membrane was electrospun and collected on electrified and melt-blown PP nonwovens to obtain a nanofiber/microfiber composite membrane (NMCM), which was used as the core filtration material in medical protective mask. The preparation process of NMCM and it’s application is shown in figure 1. The spinning parameters such as the solution concentration, voltage, receiving distance, and flow rate were selected as independent variables. A orthogonal experiment with four-factor and three-level was designed to analyze the influences of the electrospinning parameters on the filtration efficiency, resistance of respiration, and quality factor. The significance of the spinning factors for the filtration efficiency, resistance, and quality factor was obtained by a multi-factor analysis of variance and the optimization process was discussed. A BP neural network was developed to simulate and predict the resistance of respiration corresponding to the optimal process.

| Table 1. Information of factors and it’s Levels. |
|-----------------------------------------------|
| Factor                                        |
| Variable                                     |
| Level                                         |
| Concentration(%)                             | X1 | 13 | 14 | 15 |
| Voltage(kV)                                   | X2 | 27 | 28 | 29 |
| TCD(cm)                                       | X3 | 16 | 19 | 22 |
| Flow rate(mL/h)                               | X4 | 1.5| 2  | 2.5|

2. Experiment

2.1. Materials
Polyvinylidene fluoride (PVDF, Mw = 670,000–700,000, solef6020/1001) was provided by Wuxi United Hengzhou Chemical Co., Ltd. The solvent N, N-Dimethylformamide (DMF), AR was provided by Shanghai McLean Biochemical Technology Co., Ltd. Electrified and melt-blown polypropylene (PP) nonwoven with areal density of 30 g m⁻² was provided by Shandong Junfu Nonwoven Fabric Co., Ltd.

2.2. Experimental scheme
The effects of spinning parameters on the filtration performance of fiber membrane are the spinning solution concentration, voltage, TCD, and injection rate [31]. In the orthogonal experiment, the factors and levels are shown in table 1. As far as the filtration efficiency and resistance of the nanofiber membrane are concerned, the orthogonal experiment with four-factors and three-levels (L9) was designed. The orthogonal experiment is displayed in table 2. The NMCMs were fabricated through different spinning processes. The SPSS and MATLAB were used for statistical analysis.
2.3. Fabrication of the NMCMs

2.3.1. Preparation of spinning solution
Spinning solutions with mass fractions of 13%, 14%, and 15% PVDF were selected. The PVDF powder was added into the DMF solvent and stirred in 80 °C water for 4 h with an intelligent magnetic stirrer (ZNCL-G, Henan Aibote Technology Development Co., Ltd) until the powder was completely dissolved. Then, the solution stood at room temperature for 1 h until the bubbles completely disappeared.

2.3.2. Spinning process
The spinning solution was injected into a 20 ml syringe. Based on table 2, the spinning process was executed by adjusting the high-voltage DC voltage, the TCD, and the flow rate.

2.3.3. Fabrication
The electrospinning device with multiple needles is shown in figure 2. Three needles (No. 22) were fixed on a sliding table, moving horizontally with a speed of 100 mm min⁻¹. The fibers were collected on a drum rotating with a speed of 50 r min⁻¹. The roller was wrapped with an aluminum foil and melt-blown PP nonwovens, respectively. Aluminum foil was used to collect the PVDF nano fiber membrane with area density of 2 g/m². The electrified melt-blown PP nonwoven fabric with area density of 32 g m⁻² was used to prepare the NMCM. Then, the PVDF nano fiber membrane and NMCM were dried at 40 °C for 6 h in electric drying equipment (GZX-9146 MBE, Medical equipment factory of Shanghai Boxun Industrial Co., Ltd).

2.4. Characterization

2.4.1. Scanning Electron Microscopy (SEM)
The morphologies of PVDF nano fiber membrane and NMCM were observed with a field-emission scanning electron microscope. In order to improve the conductivity of the sample, gold was sprayed on the sample in advance. The diameters of the PVDF nanofibers and the electrified and melt-blown PP fibers were measured. The data were used to calculate the mean value and coefficient of variation.

Table 2. Scheme of the four-factor and three-level (L9) (3⁴) orthogonal experiment.

| No. | X₁  | X₂  | X₃  | X₄  | Concentration (%) | Voltage (kV) | TCD (cm) | Flow Rate (mL/h) |
|-----|-----|-----|-----|-----|-------------------|--------------|----------|-----------------|
| 1   | 1   | 1   | 1   | 1   | 13                | 27           | 16       | 1.5             |
| 2   | 1   | 2   | 2   | 2   | 13                | 28           | 19       | 2               |
| 3   | 1   | 3   | 3   | 3   | 13                | 29           | 22       | 2.5             |
| 4   | 2   | 1   | 2   | 3   | 14                | 27           | 19       | 2.5             |
| 5   | 2   | 2   | 3   | 1   | 14                | 28           | 22       | 1.5             |
| 6   | 2   | 3   | 1   | 2   | 14                | 29           | 16       | 2               |
| 7   | 3   | 1   | 3   | 2   | 15                | 27           | 22       | 2               |
| 8   | 3   | 2   | 1   | 3   | 15                | 28           | 16       | 2.5             |
| 9   | 3   | 3   | 2   | 1   | 15                | 29           | 19       | 1.5             |

Figure 2. Electrospinning device.

Table 2. Scheme of the four-factor and three-level (L9) (3⁴) orthogonal experiment.
2.4.2. Filtration efficiency and resistance of respiration

The filtration efficiency and resistance of the NMCM for particulate matter filtration were tested with an automatic filter material tester (SLGLY-2626). According to the standard of GB 19083-2010, the filtration efficiency of non-oily particles should exceed 95%, and the resistance of respiration should be less than 343.2 Pa when the gas flow rate is 85 l/min. For the filter material tester, the gas flow rate is stable at 85 ± 2 l/min. A 2% NaCl solution was prepared, and the parameters of aerosol particle were adjusted to bring the count median diameter (CMD) within the range of 0.075 ± 0.020 μm. The geometric standard deviation of CMD is less than 1.86 (equivalent to the mass median aerodynamic diameter (MMAD) of 0.24 ± 0.06 μm).

2.4.3. Quality factor

The quality factor is a comprehensive index for evaluating the efficiency and resistance of a filtration. Formula (1) shows that the resistance of respiration decreases with the increases of the filtration efficiency as the quality factor is constant. High-quality filtration materials should have higher filtration efficiency and lower resistance of respiration. Therefore, the higher quality factor, always companies with the better comprehensive filtration behavior of the material.

\[
QF = - \frac{\ln(1 - \eta)}{\Delta P}
\]  

where QF is the quality factor, \(\eta\) is the filtration efficiency, and \(\Delta P\) is the differential pressure of respiration.

2.4.4. Air permeability

The air permeability of NMCM was measured by using the YG (b) 461E automatic fabric permeability tester according to the standard GB/T 5453-1997. The test area density is 20 cm², and the pressure difference is 200Pa.

3. Results and discussion

3.1. Microstructure analysis

Figure 3 indicates the morphology and diameter distribution of the PVDF nanofiber membrane. The diameter of the fibers were measured by using image pro plus. Figures 3(a)–(e) indicate that the fiber diameters varied from 200 to 800 nm and mainly distributed at 500 nm. In figures 3(f)–(h), the fiber diameters are distributed
from 400 to 1500 nm, which demonstrating that the uniformity of fiber membrane is pretty worse. However, the diameters of fiber in figures 3(c) and (i) are mainly distributed from 300 to 500 nm, and the variation coefficient of fiber diameter is at a relatively lower level.

As shown in figure 3, the average fiber diameter and mean square error of nine experiments were significantly affected by spinning parameters. No.3 has the lowest average fiber diameter of 426 nm and No. 9 has the lowest coefficient of variation of 13.15%. In addition, No.8 has the largest fiber diameter of 926nm and the highest coefficient of variation of 35.93%. The much difference and uniformity of fiber diameters was attributed to the unstable drafting of Taylor cone during spinning [32].

Results also shows that the influencing factors were ranked in descending order for fiber diameter, i.e. Concentration > Flow rate > TCD > Voltage.

3.2. Filtration efficiency
The filtration efficiency of single layer 30 g m$^{-2}$ electrified and melt-blown PP nonwovens has only 79.38%. In order to achieve 95% filtration efficiency, double layers of 30 and 20 g m$^{-2}$ electrified and melt-blown PP nonwovens have been used for protective mask. The filtration efficiencies of the nine numbers of NMCMs based on table 2 are shown in table 3. The filtration efficiencies of the NMCMs increases by 19.68% in comparison to that of the electrified and melt-blown PP nonwovens with area density of 30 g m$^{-2}$.

Table 3. Filtration performance and air permeability of particulate matter of NMCM.

| Properties               | 30 g m$^{-2}$ PP | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
|--------------------------|-----------------|---|---|---|---|---|---|---|---|---|
| Filtration efficiency (%)| 79.38           | 97.15 | 96.32 | 95.70 | 95.50 | 95.41 | 96.69 | 95.07 | 95.43 | 95.40 |
| Resistance of respiration (Pa) | 63.00 | 119.33 | 123.33 | 103.00 | 86.67 | 89.33 | 160.00 | 92.00 | 100.00 | 101.00 |
| Quality Factors          | 0.0251          | 0.0299 | 0.0268 | 0.0306 | 0.0335 | 0.0352 | 0.0216 | 0.0327 | 0.0310 | 0.0309 |
| Air permeability (mm s$^{-1}$) | 376.39 | 221.46 | 212.97 | 251.83 | 314.35 | 283.87 | 166.23 | 291.4 | 304.56 | 303.96 |

Figure 4. Effects of spinning parameters on filtration resistance and quality factor.
Assuming that the interaction between all spinning parameters is ignored, the influences and interactions of all variables are zero at the same time. The influences of the concentration of the spinning solution, voltage, TCD, and flow rate on the filtration efficiency of the NMCMs were neglected.

The SPSS software was used for a multivariate analysis of variance (MANOVA). A minimum of three tests were executed for each sample of the NMCMs prepared with the nine processes. The significant level is 0.05, i.e. the confidence interval is 95%. The results of the inter-subject effect test of multivariate variance show that $P_{\text{Concentration}} = 0.084 < 0.05$, $P_{\text{Voltage}} = 0.759 > 0.05$, $P_{\text{TCD}} = 0.075 > 0.05$, and $P_{\text{Flow Rate}} = 0.192 > 0.05$. Therefore, the original assumption, i.e. the concentration, voltage, TCD, and flow rate have indistinctive influences on the filtration efficiency of the NMCMs is varied. This means that the filtration efficiency of an NMCM steadily increase to over 95%, which is not affected by the spinning parameters.

### 3.3. Resistance of the respiration

On the basis of table 2, the resistances of respiration of the different NMCMs were obtained, as shown in table 3. The resistance of respiration ranges from 86.67 to 160 Pa, which is lower than 343.2 Pa required for protection. Since the area density has a negative relationship to the resistance of respiration [33], the increase of NMCMs in comparison to that of the electrified and melt-blown PP nonwovens with area density of 30 g m$^{-2}$ is attributed to the increase of area density of the fiber membrane. In addition, the nanofibers are closely arranged in membrane, which has smaller pore dimension, and thus the enhanced of resistance of respiration is attributed to the tight structure of the NMCMs.

#### 3.3.1. Multivariate analysis of variance

The similar way for resistance of respiration was used to analyze the filtration efficiency of fiber membrane. The results show that $P_{\text{Concentration}} = 0.000 < 0.05$, $P_{\text{Voltage}} = 0.000 < 0.05$, $P_{\text{TCD}} = 0.000 < 0.05$, and $P_{\text{Flow Rate}} = 0.000 < 0.05$. The results also indicates that the resistance of respiration is extremely influenced by some parameters such as the concentration, voltage, TCD, and flow rate.

#### 3.3.2. Influence of spinning process

Figure 4 shows the influence of spinning parameters on the filtration resistance and quality factor. The fiber diameter increases with increase of the concentration. Loose fiber arrangement causes a decrease in filtration resistance [34]. Since the drawing force from the electric field on the fiber is greater than the repulsive force from the non-conductive receiving device, the number of fibers collected on the receiving device and the resistance of respiration will be increased with the increase of voltage [35].

The resistance of respiration decreases with the increase of receiving distance. As shown in figure 4 (c), the stretching effect of the electric field on the jet weakens and the fibers easily escape with the increase of TCD [36, 37]. Fibers with finer diameter are loosely collected, which resulting in a reduction of the resistance of respiration. The resistance of respiration firstly increases, and then gradually decreases with the increase of the flow rate. The electric field force plays an important role in overcoming the repulsive force of the collection device while it has a little flow rate, which resulting in a large number of fibers being collected on the device [38].

The receiving device plays an important role to the repulsive force of the jet with a larger flow rate of solution, which overcoming the traction force of the electric field and causing the fiber to escape and the decrease in resistance of respiration.

### 3.4. Quality factor

The quality factor is a dimensionless index for comparison of the filtration efficiency and resistance of respiration. According to Formula 1, the quality factor was calculated by using the filtration efficiency and resistance of respiration of NMCMs. Except for No. 6, the quality factor of NMCMs ranges from 0.268 to 0.352, which is higher than that of the electrified and melt-blown PP nonwovens with area density of 30 g m$^{-2}$. It shows that the comprehensive performance of the NMCMs had been significantly improved.

The quality factor was analyzed by a multivariate analysis of variance as for different spinning parameters. The results of the inter-subject effect test of multivariate variance reveal that $P_{\text{Concentration}} = 0.155 > 0.05$, $P_{\text{Voltage}} = 0.006 < 0.05$, $P_{\text{TCD}} = 0.001 < 0.05$, and $P_{\text{Flow Rate}} = 0.001 < 0.05$. It can be concluded that the concentration of the spinning solution had indistinctive effects on quality factor, however, the voltage, TCD, and flow rate has extremely significant influences on quality factor. It is obviously obtained that the quality factor increases with the decrease of the resistance of respiration. It is verified that the filtration efficiency has been significantly improved with NMCMs. Therefore, the quality factor of NMCM mainly depends on the resistance of respiration.
3.5. Air permeability

The air permeability of NMCMs fabricated by different processes varies from 166.23 to 314.35 mm s$^{-1}$, which is slightly less than that of electrified and melt-blown PP nonwovens. This is ascribed to the deposition of nanofibers and the increased fiber film thickness. However, the air permeability of Nos. 4, 8 and 9 have higher than 300 mm s$^{-1}$. Multivariate analysis of variance showed that $P_{\text{Concentration}} = 0.000 < 0.05$, $P_{\text{Voltage}} = 0.000 < 0.05$, $P_{\text{TCD}} = 0.000 < 0.05$, and $P_{\text{Flow Rate}} = 0.000 < 0.05$, which indicates that the air permeability of NMCMs is extremely influenced by the concentration of solution, voltage, TCD, and flow rate. Therefore, it is necessary to optimize the process to improve the respiratory comfort.

The air permeability and filtration resistance of NMCMs are shown in figure 5. The filtration resistance and the air permeability were considered as independent and dependent variable, respectively, the filtration resistance of NMCMs varies from lower value to higher ones. The relationship between air permeability and filtration resistance was obtained, as follows.

$$y = ax^b$$  \hspace{1cm} (2)

Where, $a$ and $b$ are constants, and equal to 28716.53 and $-1.01$, respectively.

The result shows that $R$ is 98.40. As shown in figure 5, the air permeability decreases with the increase of filtration resistance. Therefore, the air permeability could be optimized by selecting the suitable filtration resistance.

3.6. Optimization and prediction of spinning process

3.6.1. Optimization of spinning process on the basis of filtration resistance

The variation of filtration resistance is similar to that of filtration efficiency, but is inverse to that of quality factor and air permeability. Therefore, it is necessary to optimize the spinning process so as to reduce the filtration resistance. The order of influencing factors is TCD > flow rate > voltage > concentration according to multivariate analysis of variance. The levels of concentration, voltage, TCD and flow rate were selected as the independent variables to analyze their influence on filtration resistance based on different experiments.

The optimum spinning process was obtained as follows. The concentration is 15%, the voltage is 27 kV, the TCD is 22 cm, the flow rate is 2.5 ml h$^{-1}$. This is a new combination of each factor.
Figure 7. Fitting effects of the training, verification, and testing.

Figure 8. Error distribution of training, verification, and testing.
3.6.2. Construction of BP neural network for prediction

BP (back-propagation) neural networks were proposed by Rumelhart and McCleland in 1986 [32]. They proposed a one-way-propagation multilayer feedforward network, as shown in figure 6. In this paper, a BP neural network was established with a back-propagation algorithm to predict the resistance of respiration when the spinning parameters were selected as input value and resistance of respiration was selected as the output value. The input and output values were normalized to the range of $[0, 1]$. A regime of 70% training, 15% failure, and 15% testing was chosen to train the neural network. The prediction results were inversely normalized to the simulation prediction value [39, 40].

3.6.3. Accuracy analysis and prediction of the neural network

The regression analysis in figure 7 shows that $R_{Training}$ is 0.9996, $R_{Validation}$ is 0.9984, $R_{Test}$ is 0.9987, and $R_{All}$ is 0.9982, which are close to 1. Figure 8 shows the error distribution, which equals to difference between targets and outputs. The simulation results are presented in table 4. The differences between the simulation value and the actual resistance of respiration varies from 0.17 to 1.33 Pa, and the relative error ranges from 0.49505% to 1.49217%. With respect to results of training, verification, and testing, the fitting and error analysis of the model, as well as the error analysis of the actual values and simulation values, the simulation results of the neural network were accurate. The predicted resistance of respiration was 68.1374 Pa when the optimal parameters had been input into the neural network.

4. Conclusion

In this paper, a 2 g/m$^2$ PVDF nanofiber membrane was manufactured by electrospinning and collected on 30 g m$^{-2}$ electrified and melt-blown PP nonwovens to obtain a PVDF nanofiber/PP microfiber composite membrane (NMCM). A four-factor and three-level orthogonal test was designed to investigate the influence of the spinning process on the properties of the fiber membranes by considering fiber diameter, filtration performance, and quality factor of the fiber membranes as the target values.

(1) The diameter and uniformity of the fiber has been significantly affected by spinning parameters. The concentration of the spinning solution plays the most important role. The fiber diameter increases and the uniformity becomes worse with the increases of concentration.

(2) The filtration efficiency of the NMCM has been increased by 19.68% in comparison to that of melt-blown PP fabric 79.38%. The resistance of respiration of the NMCM ranges from 86.67 to 160 Pa, which is less than 343.2 Pa, according with the requirements of resistance for protection. The filtration resistance was considered as the target value to optimize the process and predict the results. The factors were ranked in descending order, TCD > flow rate > voltage > concentration. The optimal process is obtained including 15% concentration, 27 kV voltage, 22 cm TCD, and 2.5 ml/h flow rate.

(3) The quality factor of the NMCM was seriously affected by the voltage, TCD, and flow rate. The quality factor was mainly affected by the resistance of respiration. The change trend of air permeability was inverse to that of filtration resistance.

(4) The comprehensive fitting coefficient (R) of BP neural network is 0.9984. The relative error varies from 0.50% to 1.49% by comparing simulation results for resistance of respiration with the experimental one. The prediction of the resistance of respiration in response to the optimal process is 68.14 Pa.

Table 4. Relative error analysis of simulation results.

| No. | Actual data Pa | Simulation data Pa | relative error % |
|-----|---------------|--------------------|-----------------|
| 1   | 119.33        | 119.50             | 0.139945        |
| 2   | 123.33        | 124.50             | 0.946219        |
| 3   | 103.00        | 104.00             | 0.970874        |
| 4   | 86.67         | 86.50              | -0.19269        |
| 5   | 89.33         | 88.00              | -1.49217        |
| 6   | 160.00        | 161.00             | 0.625           |
| 7   | 92.00         | 93.00              | 0.086957        |
| 8   | 100.00        | 101.00             | 0.49505         |
| 9   | 101.00        | 101.50             | 0.49505         |
This work is devoted to the development of nano materials for medical protection which provide continuous and stable filtration, improve breathing comfort and prolong mask service life.

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Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

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