Study on the Optimization of Double Parameters of the Air Flow Resistance and the Permeability of Electrospun Nanofiber Nonwovens

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Abstract

In this paper, neural network is used as the tool to study the factors affecting the air flow resistance and the permeability of electrospun nanofiber nonwovens and analyze the major factors affecting the air flow resistance and the permeability such as concentration, distance, voltage and solution filling speed. First, design a five-level orthogonal table for all factors in accordance with the orthogonal experiment theory, select the corresponding parameter values, use polyvinyl alcohol (PVA) to prepare 50 samples on DXES-01 automatic electrostatic spinning machine, train them with neural network model and obtain the precise fitting function. The optimization function is constructed by the idea of two-objective optimization, and its three relative optimal values are calculated, 8.135611, 8.134624, 8.115814. Compared with the experimental results, the average relative error is 12.89 and 8.34. The experimental results show that the error is also ideal.
Keywords: BP neural network; computerized simulation; electrospun nanofiber nonwovens; air flow resistance; permeability; prediction

1 Introduction

Electrospun nanofiber nonwovens have a wide range of applications in medical, industrial and other fields. However, how to produce the needed products is still the bottleneck of their development. The impact of nanofiber on permeability is studied in the paper [1], and the impact of nanofiber thickness and filling rate on permeability is studied in the paper [2]. However, the relationship between these properties and the production processes, or the relationship between these properties and the fiber diameter/porosity is directly related to the production and application of electrospun nanofiber nonwovens. In recent years, the neural network technology has been used to explore the properties of electrospun nanofiber nonwovens in many researches [3-6]. however, for the researches on the application of neural networks (including the applications in other areas), their research has been focused on generating a corresponding individual value through the matlab run, rather than getting the corresponding numerical relationship. This is a defect of the application of neural network at present. Since 2009, our research team has carried out in-depth study on MATLAB and explores and restores the original function relationships in the MATLAB run, which can make our research much more scientific.

Consumers' requirements for clothing are not only satisfied with the warmth, but also have higher comfort and beauty. The rigid, flexible and the permeability index of electrospun nanofiber nonwovens are directly related to its comfort, therefore, We choose air flow resistance and permeability to study.

In this paper, according to the manufacturing parameters of electrospun nanofiber nonwovens, we have selected 50 groups of parameter combinations by using the orthogonal experimental design idea [11-12], and we have made 50 samples according to these parameters, and its air flow resistance and permeability were measured. The relationship between the four parameters and the two target parameters is obtained by neural network. Furthermore, the optimal parameters of air flow resistance and permeability are obtained by using the idea of two-parameter optimization.

2. Experiments

2.1 Drugs

The equipments used in this experiment are polyvinyl alcohol (PVA) (with a molecular weight of 27,000 to 32,000) produced by Taiwan Chang Chun Petrochemical Co., Ltd. (alcoholysis degree: 86 ~ 89 mol%, degree of polymerization: 500).

2.2 Instruments

The equipments used in this experiment are DXES-01 fully automatic electrostatic spinning machine (produced by Shanghai Dongxiang Nano Technology Co., Ltd.); TSI8130 automated filter tester (produced by TSI Instrument(Beijing)Co.,Ltd); TM-1000 desktop scanning electron microscope (produced by Naka Division, Hitachi High-Technologies Corporation).

2.3 Sample Preparation

In order to study the factors affecting the air flow resistance and the permeability of electrospun nanofiber nonwovens, there are five technical parameters according to previous experience in the manufacturing of electrospun nanofiber nonwovens, which include: the spinning time be set to 90 minutes, the solution concentration be set to 14%, 15%, 16%, 17%, 18%; the spinning distance (cm) be set to 11, 13, 15, 17, 19; the input voltage (kV) can be set to 10, 15, 20, 25, 26; the solution filling rate (ml/h) be set to 0.5, 0.7, 1, 1.2, 1.5. Therefore, to gain more general experiment data and avoid repeated experiments, the mathematics method of orthogonal experiment design idear is applied and the orthogonal table is designed （Table1）, according to the practical problems, the orthogonal table is modified slightly, the test times are increased appropriately, and 50 groups of samples are obtained.

The air flow resistance and the permeability passing rate of each sample are measured by TSI8130 automatic filtering tester (See Table 1).

Table.1 Experiment Results of Air Flow Resistance and Permeability

No.	Distance (cm)	Voltage (kV)	Speed (ml/h)	Concentration (wt%)	Air Flow Resistance (pa)	Permeability (%)	No.	Distance (cm)	Voltage (kV)	Speed (ml/h)	Concentration (wt%)	Air Flow Resistance (pa)	Permeability (%)
1	11	10	0.5	14	41.32	14.3	26	8	28	1.2	18	69.3	86.32

2	11	15	0.7	15	725.67	0.0053	27	8	20	1	18	58.9	81.9
3	11	20	1	16	113.78	12.14	28	8	17	0.7	18	125.5	98.39
4	11	25	1.2	17	867.16	0.005	29	8	15	0.5	18	85.1	95.2
5	11	26	1.5	18	905.63	0.003	30	8	13	1.5	18	115.3	97.75
6	13	10	0.7	16	5.52	71.68	31	10	28	1	18	15.5	35.44
7	13	15	1	17	100.4	1.00	32	10	20	0.7	18	18.8	42.4
8	13	20	1.2	18	329.85	0.42	33	10	17	0.5	18	17.3	41.98
9	13	25	1.5	14	24.02	57.32	34	10	15	1.5	18	66.4	83.58
10	13	26	0.5	15	191.13	3.89	35	10	13	1.2	18	58.6	82.52
11	15	10	1	18	3.88	77.4	36	13	28	0.7	18	18.1	42.48
12	15	15	1.2	14	36.83	19.57	37	13	20	0.5	18	21.8	50.7
13	15	20	1.5	15	217.93	9.06	38	13	17	1.5	18	77.1	87.58
14	15	25	0.5	16	258.35	0.0041	39	13	15	1.2	18	62	82.24
15	15	26	0.7	17	398.46	0.0058	40	13	13	1	18	36.2	66.06
16	17	10	1.2	15	2.24	85.32	41	15	28	0.5	18	26.9	62.04
17	17	15	1.5	16	29.24	15.74	42	15	20	1.5	18	135.3	98.15
18	17	20	0.5	17	296.98	7.0	43	15	17	1.2	18	61.3	84.26
19	17	25	0.7	18	207.52	0.036	44	15	15	1	18	36.3	68.88
20	17	26	1	14	204.86	0.706	45	15	13	0.7	18	17.7	45.72
21	19	10	1.5	17	3.16	85.5	46	18	28	1.5	18	184.9	99.2
22	19	15	0.5	18	15.92	36.32	47	18	20	1.2	18	80.5	90.58
23	19	20	0.7	14	49.4	29.52	48	18	17	1	18	41.9	69.6
24	19	25	1	15	149.6	0.51	49	18	15	0.7	18	21.2	48.84
25	19	26	1.2	16	255	0.05	50	18	13	0.5	18	8	22.74

3. BP neural network model and applications

BP neural network [3-6,8,10,14,16,17] is a kind of multilayer forward neural network with unidirectional propagation, which is capable to learn and store plenty of mapping relations of input/output model without describing the mathematical equations of this mapping relation in advance[7,8]. Its learning rule is to use steepest descent algorithm and adjust constantly by back propagation. In the case of BP network, there is a mportant theorem, which means that any continuous function in closed interval can be approximated by using a BP network of single hidden layer, the weight and the threshold of the network make the square sum of errors of the network smallest. Consequently, a three-layer BP network can complete any mappings from any n-dimension to any m-dimension

In using BP neural networks, for the selection of the number of neurons on the hidden layer, based on the empirical formula of previous studies $n = \sqrt{n_i + n_0} + a$, where n refers to the number of hidden layer neurons, n_i refer to the number of input nodes, n_0 refers to the number of output nodes. according to the principle-“as few hidden-layer neurons as possible, as rapid convergence as possible, as low approximation errors as possible”, the number of hidden-layer neurons is set as fifteen after simulation training; the transfer function is set as the transfer function combination of ‘transig’ and the ‘transig’ then the optimal approximation errors is the best, and select trainlm'as the training function.

Matlab2012b[9] is used to train and simulate the network, and the results of the network training are shown in fig.1.

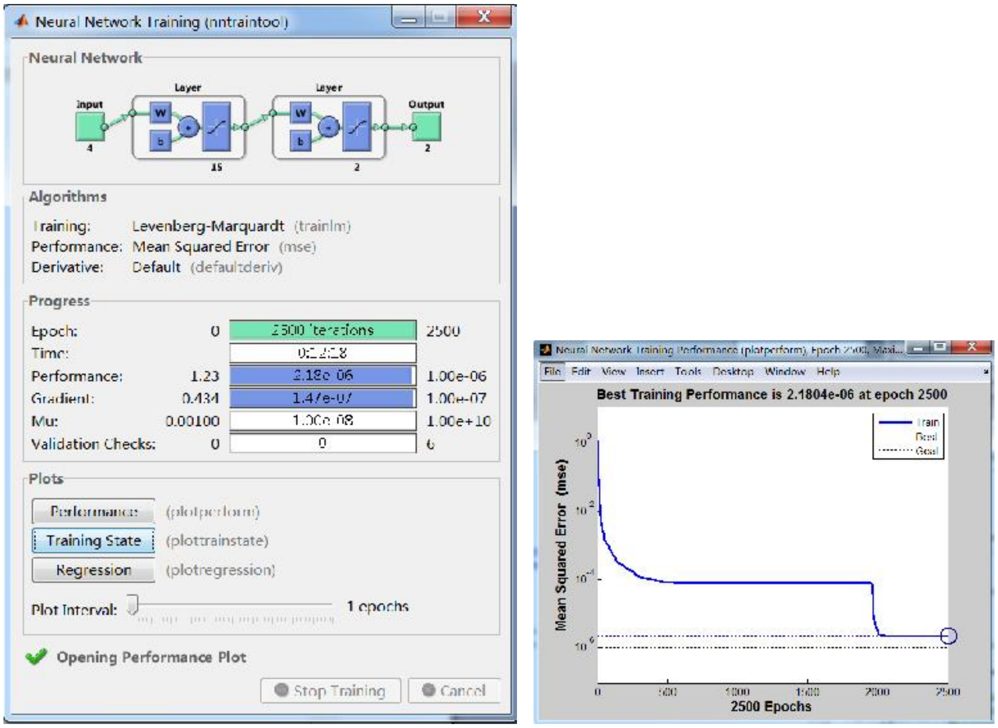
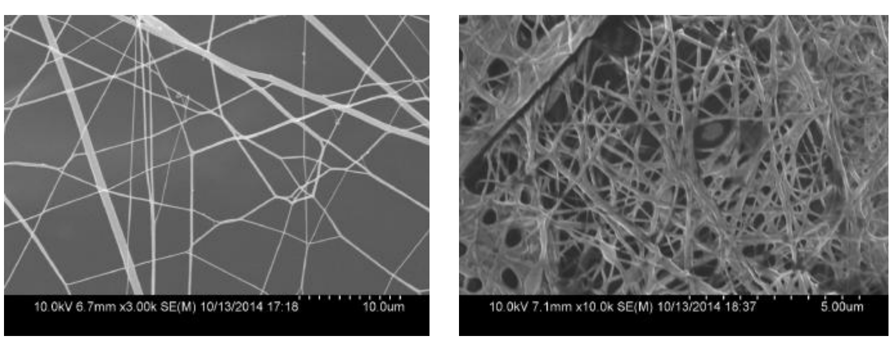


Fig.1 Results of Network Training

According to the results of network training in Fig.1, it can be seen that BP neural network model produces relatively ideal fitting results for the original data. In order to find more optimal parameters from current experiment data, the function relationship between each parameter and air flow resistance, filtering efficiency is obtained. However, when neural network is applied, No.48 Group is left out, the experiment results of which are:

Air flow resistance of 68.7065 and filtering efficiency of 90.8136, which contain remarkable errors compared with the actual experiment data, the air flow resistance of 80.5, and the filtering efficiency of 90.58. It illustrates that the fitting results are not very ideal.

The problems in the experiment data in No.6 and No.16 can be easily found from a careful observation of the experiment data images:



6# 16#

Fig.2 Images of Samples in No.6 and No.16

There are almost no fibers in 6#, and adhesion phenomenon in 16# is observed. After two samples are eliminated, the training is obtain again by the neural network to obtain:

The function of the air flow resistance:

$f(x1, x2, x3, x4) =$ 1805.0/(exp(9.966/(exp(0.528*conj(x1) + 0.9244*conj(x2) - 8.939*conj(x3) - 2.607*conj(x4) + 32.21) + 1.0) - 3.671/(exp(1.904*conj(x1) - 0.6068*conj(x2) + 0.6279*conj(x3) - 1.613*conj(x4) + 17.64) + 1.0) - 168/(exp(0.1327*conj(x2) - 0.4393*conj(x1) - 2.064*conj(x3) + 0.9377*conj(x4) - 15.02) + 1.0) + 12.52/(exp(0.8041*conj(x1) - 0.3115*conj(x2) - 389*conj(x3) + 0.087*conj(x4) + 1.95) + 1.0) - 0.3327/(exp(1.759*conj(x4) - 0.0952*conj(x2) - 7.745*conj(x3) - 0.9961*conj(x1) - 1.562) + 1.0) + 1.781/(exp(0.4842*conj(x2) - 0.3834*conj(x1) + 2.365*conj(x3) - 0.1813*conj(x4) - 8.544) + 1.0) - 13.16/(exp(0.8407*conj(x1) - 0.1484*conj(x2) - 5.939*conj(x3) + 1.746*conj(x4) - 25.35) + 1.0) - 6.381/(exp(0.08201*conj(x1) - 0.3056*conj(x2) - 12.92*conj(x3) - 0.5097*conj(x4) + 27.51) + 1.0) + 13.88/(exp(12.68*conj(x3) - 1.112*conj(x2) - 0.7495*conj(x1) + 3.573*conj(x4) - 47.52) + 1.0) - 12.04/(exp(0.9184*conj(x1) - 0.6261*conj(x2) - 9.852*conj(x3) - 1.365*conj(x4) + 41.44) + 1.0) - 1.398/(exp(0.8493*conj(x1) - 0.2004*conj(x2) + 7.889*conj(x3) - 1.057*conj(x4) - 1.205) + 1.0) - 995/(exp(0.01837*conj(x1) + 0.1955*conj(x2) + 16.76*conj(x3) + 1.987*conj(x4) - 57.71) + 1.0) + 548/(exp(0.263*conj(x1) + 1.609*conj(x2) - 25.35*conj(x3) + 0.5874*conj(x4) - 156) + 1.0) + 3.527/(exp(0.1053*conj(x1) - 0.9945*conj(x2) - 7.808*conj(x3) + 0.8478*conj(x4) + 16.53) + 1.0) - 0.4803/(exp(0.559*conj(x1) + 0.2448*conj(x2) + 0.6398*conj(x3) + 0.1134*conj(x4) - 26.28) + 1.0) + 5.008) + 1.0) - 899.3

The function of permeability Function:

$g(x1, x2, x3, x4) =$ 198.4/(exp(351/(exp(1.904*conj(x1) - 0.6068*conj(x2) + 0.6279*conj(x3) - 1.613*conj(x4) + 17.64) + 1.0) - 2.143/(exp(0.528*conj(x1) + 0.9244*conj(x2) - 8.939*conj(x3) - 2.607*conj(x4) + 32.21) + 1.0) + 21.55/(exp(0.1327*conj(x2) - 0.4393*conj(x1) - 2.064*conj(x3) + 0.9377*conj(x4) - 15.02) + 1.0) - 17.49/(exp(0.8041*conj(x1) - 0.3115*conj(x2) - 389*conj(x3) + 0.087*conj(x4) + 1.95) + 1.0) + 10.55/(exp(1.759*conj(x4) - 0.0952*conj(x2) - 7.745*conj(x3) - 0.9961*conj(x1) - 1.562) + 1.0) - 37.94/(exp(0.4842*conj(x2) - 0.3834*conj(x1) + 2.365*conj(x3) - 0.1813*conj(x4) - 8.544) + 1.0) + 2.379/(exp(0.8407*conj(x1) - 0.1484*conj(x2) - 5.939*conj(x3) + 1.746*conj(x4) - 25.35) + 1.0) + 27.35/(exp(0.08201*conj(x1) - 0.3056*conj(x2) - 12.92*conj(x3) - 0.5097*conj(x4) + 27.51) + 1.0) - 1.672/(exp(12.68*conj(x3) - 1.112*conj(x2) - 0.7495*conj(x1) + 3.573*conj(x4) - 47.52) + 1.0) + 0.4917/(exp(0.9184*conj(x1) - 0.6261*conj(x2) - 9.852*conj(x3) - 1.365*conj(x4) + 41.44) + 1.0) + 13.1/(exp(0.8493*conj(x1) - 0.2004*conj(x2) + 7.889*conj(x3) - 1.057*conj(x4) - 1.205) + 1.0) + 22.92/(exp(0.01837*conj(x1) + 0.1955*conj(x2) + 16.76*conj(x3) + 1.987*conj(x4) - 57.71) + 1.0) - 0.8407/(exp(0.263*conj(x1) + 1.609*conj(x2) - 25.35*conj(x3) + 0.5874*conj(x4) - 156) + 1.0) - 18.41/(exp(0.1053*conj(x1) - 0.9945*conj(x2) - 7.808*conj(x3) + 0.8478*conj(x4) + 16.53) + 1.0) - 5.901/(exp(0.559*conj(x1) + 0.2448*conj(x2) + 0.6398*conj(x3) + 0.1134*conj(x4) - 26.28) + 1.0) - 11.91) + 1.0) - 99.19

Additionally, using the above function， we calculate the air flow resistance of 48 sample to be 76.6924,, and the permeability to be 90.7130. The relative errors compared with original data are (76.6924-80.5)/80.5=-0.0473=4.73% and (90.7130-90.58)/90.58=0.0015, this result is better. Then, these function are studied, where x1, x2, x3 and x4 respectively represent concentration (%); distance (cm); voltage (kV) and solution filling rate (ml/h).

4. Discussion and Optimization of Experiment Results

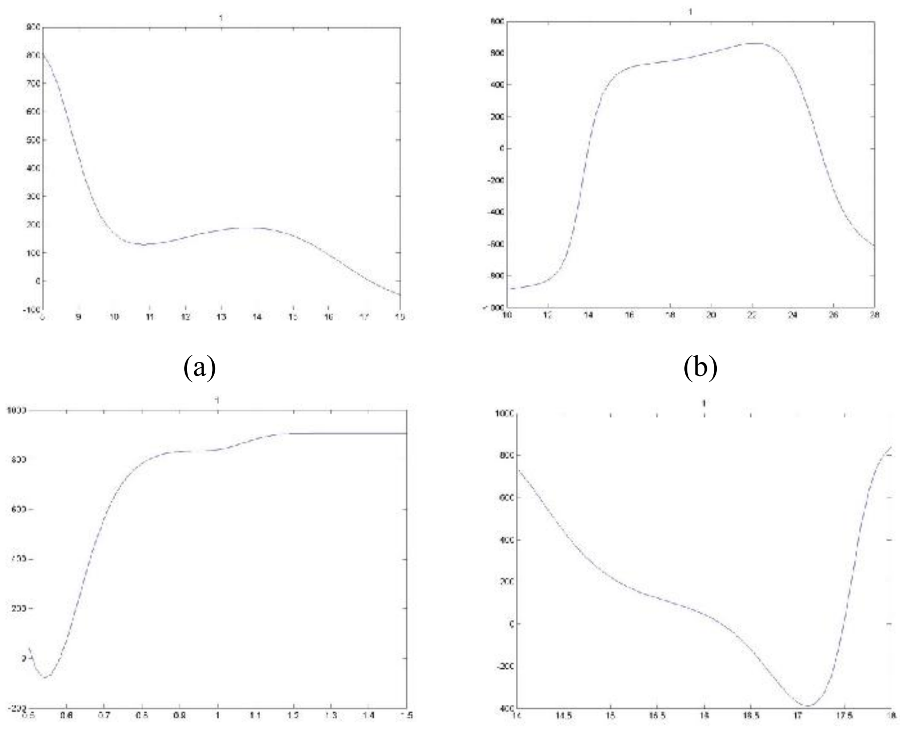
Firstly, we study the air flow resistance changes to the fourth variable while fixing three variables(see the fig. 3) :

Fix the voltage (kV), the solution filling speed (ml/h) and the concentration (%), assume that the voltage $x2 = 15.4$, the solution filling speed $x3 = 0.8$, the concentration $x4 = 15.2$, the changing of air flow resistance on distance x_1 (see Fig.3(a)) is observed;

Fix the distance (cm), the solution filling speed (ml/h) and the concentration (%), assume that the distance $x1 = 10.25$, the solution filling speed (ml/h) $x3 = 0.725$, the concentration $x4 = 14.9$, the changing of air flow resistance on voltage x_2 (see Fig.3(b)) is observed;

Fix the distance (cm), the voltage (kV), the concentration (%), assuming that the distance $x1 = 8$, the voltage $x2 = 10$, the concentration $x4 = 14$, the changing of air flow resistance on solution filling speed x3 (see Fig.3(c)) is observed;

Fix the distance (cm), the voltage (kV), the solution filling speed (ml/h), assume that the distance $x1 = 11.25$, the voltage $x2 = 15.85$, the solution filling speed $x3 = 0.825$, the changing of air flow resistance on the concentration x_4 (see Fig.3(d)) is observed ;



(a) (b) (c) (d)

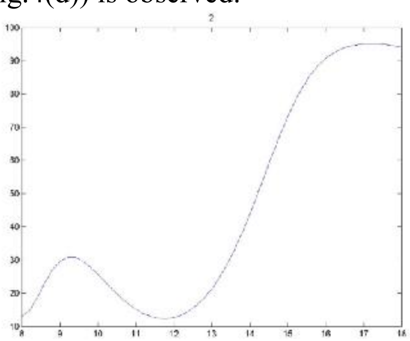
Fig. 3. Changing of air flow resistance corresponding on the Fourth Variable when the Three Variables are Fixed

Fix the voltage (kV), the solution filling speed (ml/h) and the concentration (%), assume that the voltage $x2 = 15.4$, the solution filling speed $x3 = 0.8$, the concentration $x4 = 15.2$, the changing of permeability on distance x_1 (see Fig.4(a)) is observed;

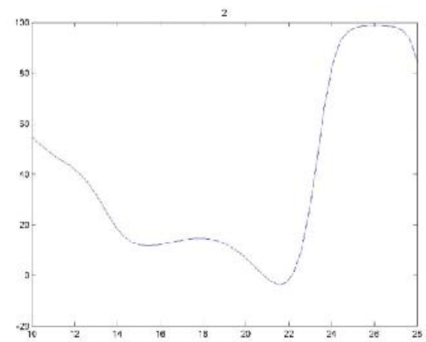
Fix the distance (cm), the solution filling speed (ml/h) and the concentration (%), assume that the distance $x1 = 10.25$, the solution filling speed $x3 = 0.725$, the concentration $x4 = 14.9$, the changing of permeability on the voltage x_2 (see Fig.4(b)) is observed;

Fix the distance (cm), the voltage (kV) and the concentration (%), assume that the voltage $x1 = 8$, the voltage $x2 = 10$, the concentration $x4 = 14$, the changing of permeability on the solution filling speed x_3 (see Fig.4(c)) is observed;

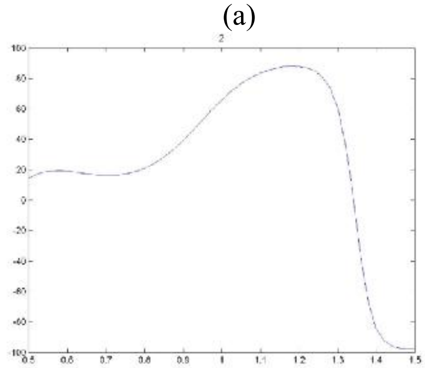
Fix the distance (cm), the voltage (kV) and the solution filling speed (ml/h), assume that the distance $x1 = 11.25$, the voltage $x2 = 15.85$, the solution filling speed $x3 = 0.825$, the changing of permeability on the concentration x_4 (see Fig.4(d)) is observed.



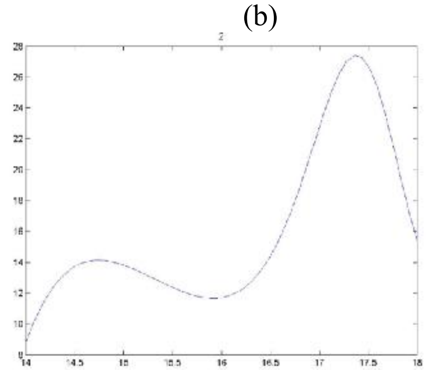
(a)



(b)



(c)



(d)

Fig.4 Changing of Permeability corresponding on the Fourth Variable when the Three Variables are Fixed

From above, the changing pattern of each variable can be seen when other three variables are fixed.

Furthermore, we can fix two independent variables to see the variation of air flow resistance and permeability on the other two independent variables is observed.

Fix the solution filling speed (ml/h) and the concentration (%), assume that the solution filling speed x3=1.4 and the concentration x4=17.6, the change of air flow resistance about x1, x2 (see Fig.5(a)) is observed;

Fix the voltage (kV) and the concentration (%), assume that the voltage x2 =19 and the concentration x4=16, the change of air flow resistance about x1, x3 (see Fig.5(b)) is observed;

Fix the voltage (kV) and the solution filling speed (ml/h), assume that the voltage x2 =19 and the solution filling speed x3=1, the change of air flow resistance about x1, x4 (see Fig.5(c)) is observed;

Fix the distance (cm) and the concentration (%), assume that the distance x1=17.6 and the concentration x4=0.6, the change of air flow resistance about x2, x3 (see

Fig.5(d)) is observed;

Fix the distance (cm) and the solution filling speed (ml/h), assume that the distance x1=17 and the solution filling speed x3=1.4, the change of air flow resistance about x2, x4 (see Fig.5(e)) is observed;

Fix the distance (cm) and the voltage (kV), assume that the distance x1=13 and the voltage x2=19, the change of air flow resistance about x3, x4 (see Fig.5(f)) is observed.

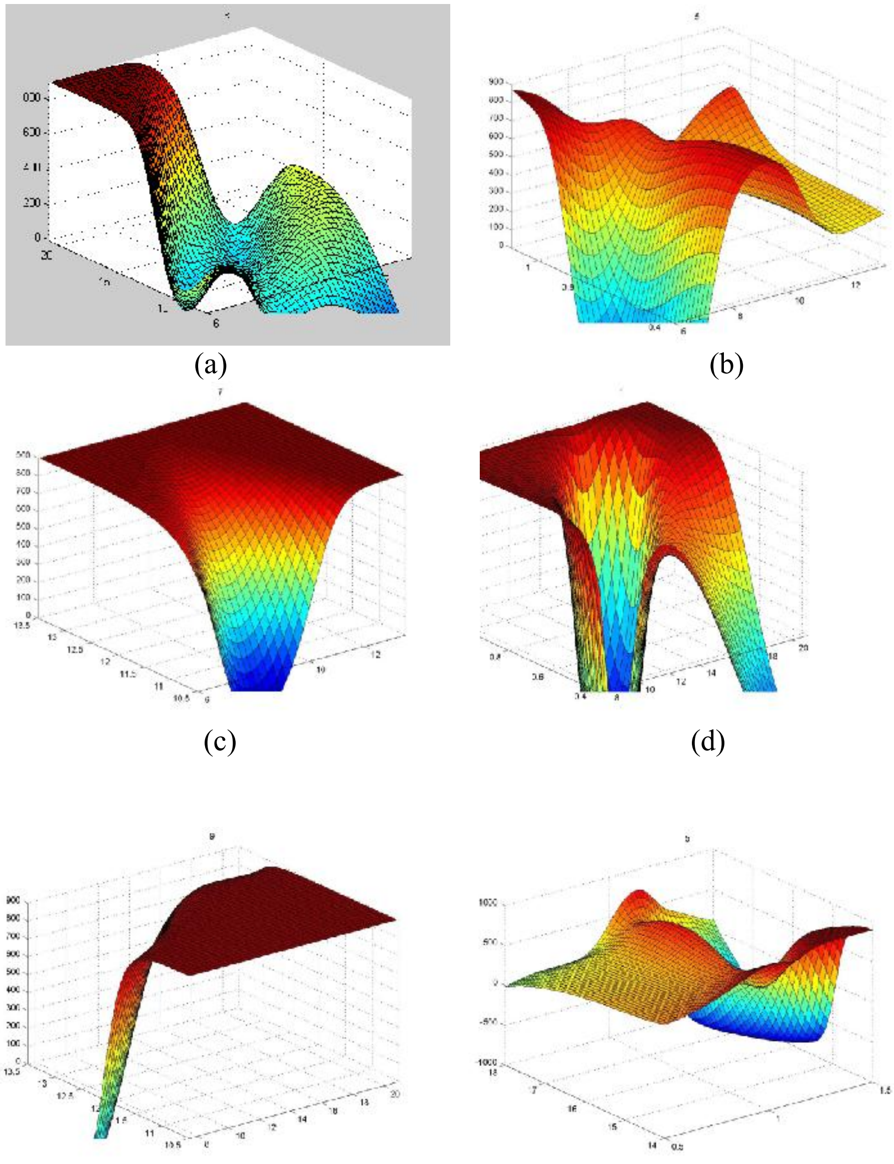


Fig.5 Changing of Air flow resistance corresponding on Other Two Independent Variables when the Two Independent Variables are Fixed

Fix the solution filling speed (ml/h) and the concentration (%), assume that the solution filling speed x3=0.9 and the concentration x4=15.6, the change of permeability about x1，x2 (Fig.6(a) is observed;

Fix the voltage (kV) and the concentration (%), assume that the voltage x2=13.6 and the concentration x4=14.8, the change of permeability about x1，x3(Fig.6(b) is observed;

Fix the voltage (kV) and the solution filling speed (ml/h), assume that the voltage x2 =13.6 and the solution filling speed x3=0.7, the change of permeability about x1， x4 (Fig.6(c) is observed;
Fix the distance (cm) and the concentration (%), assume that the distance x1=12 and the concentration x4=15.6, the change of permeability about x2，x3(Fig.6(d) is observed;
Fix the distance (cm) and the solution filling speed (ml/h), assume that the distance x1=10 and the solution filling speed x3=0.7, the change of permeability about x2，x4(Fig.6(e) is observed
Fix the distance (cm) and the voltage (kV), assume that the distance x1=13 and the voltage x2 = 19, the change of permeability about x3， x4(Fig.6(f) is observed.

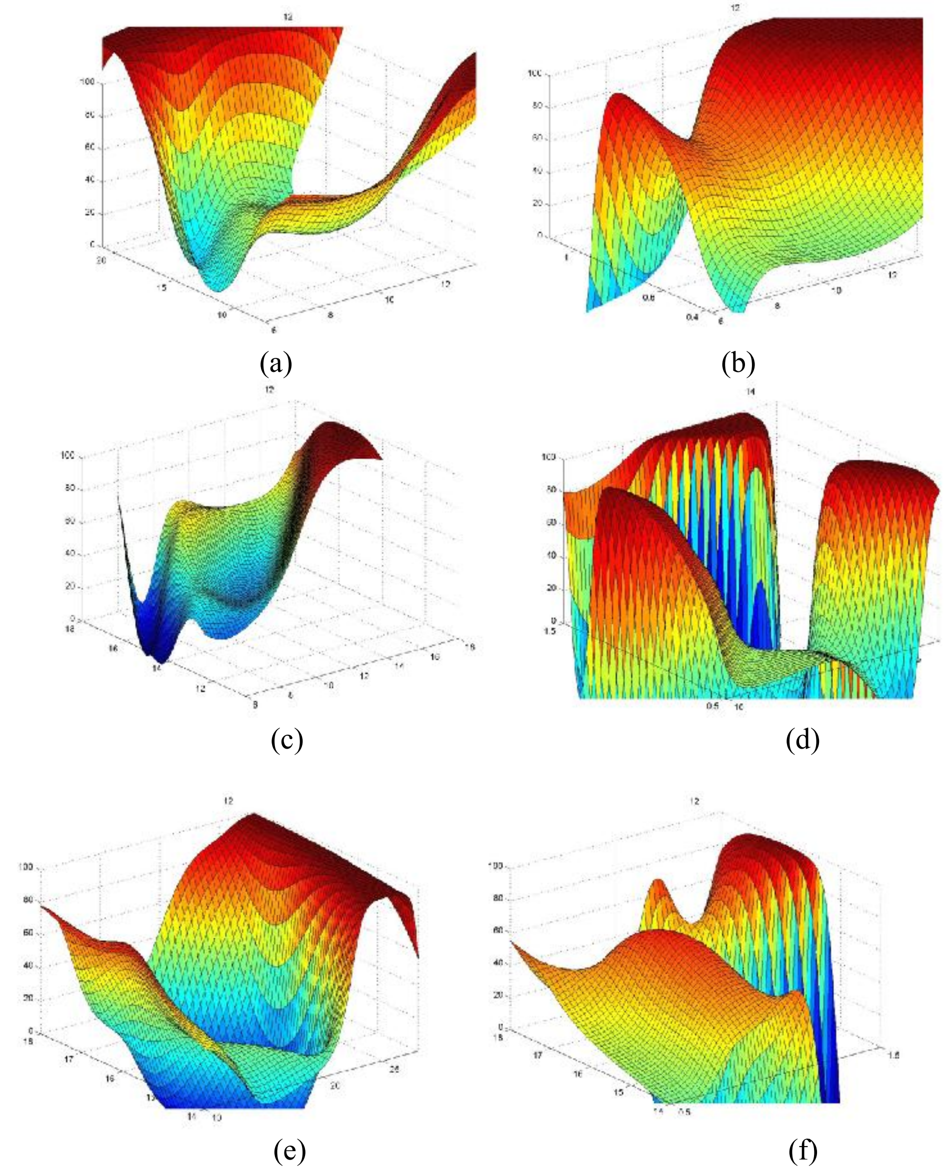


Fig.6 Changing of the permeability to Other Two Independent Variables When Two Independent Variables Are Fixed

Obviously, for the characteristics of electrospun nanofiber nonwovens, we hope that: the air flow resistance shall be much smaller and the permeability shall be much larger, although they are mutually contradictory, we can apply the idea of multi-objective optimization.

We can select the appropriate function to integrate $f(x1,x2, x3,x4)$ and $g(x1,x2, x3,x4)$ in §3 into a function, thus to treat it as a single objective optimization problem[13].

According to the features of this problem, after many explorations, following functions are selected

$$Y(x1,x2, x3,x4) = 4 * e^{-(0.1f(x1,x2, x3,x4))^{0.7}} + 4\left|\tanh(0.01g(x1,x2, x3,x4))\right|$$

Multi-objective optimization problem: Solving the minimum value of air flow resistance function $f(x1,x2, x3,x4)$ and maximum permeability function $g(x1,x2, x3,x4)$, transforms to solving the maximum value of $Y(x1, x2, x3, x4)$.

Model validation: 50000 samples were randomly selected within the range of distance, voltage, rate, and concentration. After operation by MATLAB（2012b）, three sets of parameters (Table 2) corresponding to the maximum value of $Y(x1,x2, x3,x4)$ are found, that is, the selection of the ideal parameters.

Table 2 Optimal parameter list

No.	Distance (cm)	Voltage (kV)	Speed (ml/h)	Concentration (wt%)
1	13.19018	23.57029	1.38097	17.86805
2	10.60839	17.47107	1.475973	16.28703
3	12.41272	25.52918	1.446435	16.62865

Their corresponding values of $Y(x1,x2, x3,x4)$ are respectively 8.135611, 8.134624, 8.115814, and their corresponding air flow resistance and permeability are as shown in Table 3.

Three samples #1, # 2 and # 3 are obtained by experiment according to the date in Table 3. Use TSI8130 automated filter tester to measure their respective air flow resistance, permeability and relative error rate (Table 3).

Table 3: The air flow resistance and permeability for the maximum value of $Y(x1,x2, x3,x4)$.

No.	Resistance by calculation	Permeability by calculation	Resistance by experiment	Permeability by experiment	The relative error of resistance	Relative error of permeability
1	75.71549	99.20566	86.4	92.29	12.366%	7.49%
2	67.82757	98.85092	81.8	91.95	17.081%	7.51%
3	82.51219	99.19354	90.9	90.15	9.228%	10.03%

As can be seen from Table 3, the average relative error is 12.89 and 8.34, the experimental results are Ideal. Therefore, a mathematical model of electrospinning nanofibers Nonwovens is derived from neural network, which creates a new passage to scientifically study electrospinning nanofibers Nonwovens.

Conclusion:

50 groups of parameter combinations by using the orthogonal experimental design idea were taken and 50 samples were made according to these parameters, and its air flow resistance and permeability were measured. The relationship between the four parameters and the two target parameters was obtained by neural network. Furthermore, the optimal parameters of air flow resistance and permeability were obtained by using the idea of two-parameter optimization. Compared with the experimental results, the average relative error is 12.89 and 8.34. The experimental results show that the error is also ideal.

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