Study on the structure and filtration properties of intercalated melt blown nonwoven materials

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Abstract: Based on the traditional melt blown process, PET high crimp elastic staple fibers were added to construct an intercalated melt blown two-component filter material. The changes in structure and filter performance of the material before and after intercalation, and whether the intercalation rate had any effect on these changes were analyzed in this paper. The results showed that the intercalation operation was carried out to solve the problems of poor compression resilience of single melt blown nonwoven material and high filtration resistance of existing filtration materials. A multivariate nonlinear model was developed in this paper to investigate the variation of the product structure under different technological parameters, and a mathematical expression between them was given. A random forest model was used to investigate the variation of product performance under different product structures. Using a combination of multivariate nonlinear model and random forest model, the values of the technological parameters, when the filtration performance was maximum were explored. It can be used as a guide for melt blown nonwoven material production.

Keywords: Melt blown nonwoven, Technological parameters, Filter performance, Structural variables, Multivariate nonlinear model

1. Introduction

With the further rapid development of world industrialization, the atmospheric environment has seen an increase in a variety of solid particles and bacteria floating invisible to the naked eye, posing a serious hazard to industries such as health care, food, pharmaceuticals, and precision machineries such as electronics and aerospace. In addition, there is an urgent need for people to avoid environmental pollution or epidemic diseases from affecting their health in their daily lives. In addition to alleviating pollution problems at the source, there is an urgent need to effectively use some anti-pollution materials to filter environmental pollutants[1]. The melt blown nonwoven material studied in this paper is an important raw material for the production of masks, which are in great demand in our society today. The melt blown process is a process in which polymer slices are melt extruded and then blown by high-speed hot airflow to form ultra-fine fibers and agglomerate into a net, which is then reinforced to make a nonwoven material with an agglomerated structure of ultra-fine fibers[2]. Ultra-fine fiber makes the nonwoven material has the characteristics of low fiber, and high porosity[3]. And infiltration plays a high efficiency, low resistance, effective interception of dust, bacteria, solid particles, and other outstanding advantages and is widely used[4].

However, since melt blown nonwoven fibers are very fine, their performance is often not guaranteed due to poor compression resilience in the process of use. Therefore, experts and scholars have created the intercalated melt blown method. The Z-type intercalated melt blown nonwoven material analyzed in this paper is a composite of PET short fibers and traditional polypropylene (PP) melt blown nonwoven fibers through the intercalated method[5]. This material introduces the unique advantages of PET fiber stiffness and good elasticity into traditional melt blown filter materials, and can obtain new air filtration materials with high porosity, fluffy structure, three-dimensional interlaced and disordered arrangement of fibers, low density, and high resistance to compressibility and elasticity of the new air filtration material[6].

In the production of interleaved melt blown nonwoven products, stable and good technological parameters are indispensable for the preparation of products with excellent performance. Due to the complexity of the intercalated melt blown process, many process parameters can affect the performance of the fiber web[7]. To facilitate the study, this paper made a summary analysis of the effect of technological parameters of this new material on the structure such as product thickness and porosity, and the effect of product structural variables on the filtration performance, taking the receiving distance and the velocity of hot airflow as the study objects. Most importantly, specific mathematical expressions for these effects were given, which show the relationship between technological parameters, structural variables, and filter performance more clear. A combination of multivariate nonlinear model and random forest model was used to investigate the values of technological parameters when the filter performance was better. It helps to provide a theoretical basis for the establishment of product performance regulation mechanisms and promotes the enrichment and development of melt blown nonwoven filtration materials.

2. Structural variables and performance testing

2.1. Structure Variables

1. Thickness

Measurement of the thickness of the melt blown nonwoven material formed was carried out according to the test standard for nonwoven thickness FZ/T60004-1991 using the digital fabric thickness meter of type YG141. Each sample was measured three times, and the data were recorded in the table each time.

2. Porosity

The filter performance of nonwoven material is closely related to its porosity and pore size distribution, which can be calculated by the formula to calculate the porosity of melt blown filter material[8]. The equation:

$$n = \left(1 - \frac{m}{\rho\delta}\right) \times 100\% \tag{1}$$

Where: n is the porosity, %; m is the mass per unit area of the sample, g/m^2; ρ is the fiber density, g/m^3; δ is the thickness of the sample, mm.

3. Compression resilience

The YG141 digital fabric thickness meter is used to test and calculate the compressive resilience energy of the sample by changing the load and pressure time. Its calculation formula is,

$$\text{compression resilience} = (h_2 - h_1)/(h_0 - h_1) \tag{2}$$

Where: h_0 is the original thickness of the material, mm; h_1 is the thickness of the material after compression and rebound, mm; h_2 is the thickness of the material after compression, mm.

2.2. Product Performance

1. Filtration resistance/filtration efficiency

Filtration resistance and filtration efficiency are both measures of the ability to impede the passage of material particles through a melt blown nonwoven material. It is measured using the G506 automatic filtration performance tester.

2. Air permeability

Air permeability is a very important performance indicator for filter materials, and air permeability directly affects the filter resistance of the material. Generally speaking, the better the air permeability, the smaller the resistance. Automatic air permeability measurement is carried out by the YG461H automatic air permeability meter.

3. Effects of interpolation on structural variables and performance

3.1. Distribution of structural variables and performance indicators

The distribution of structural variables and performance indicators before and after interpolation were plotted for each. By observing the distribution range of each feature before and after interpolation, it is clear that the interpolation rate has different effects on the value of each feature after interpolation.

3.2. The relationship between interpolation rate and each index

Table 1 The relationship between interpolation rate and features

features	Thickness	Porosity	Compression resilience	Filtration resistance	Filtration efficiency	Air permeability
correlation coefficient	0.280	0.127	-0.358	0.240	0.018	-0.043

As Table 1 showed, it was concluded that the intercalation rate showed a weak correlation with thickness, porosity, filtration resistance, filtration efficiency, and permeability, and the intercalation rate showed minimal or no correlation with compression resilience. It can be seen structural variables and product properties of the material before and after intercalation in Figure 1 and Figure 2.

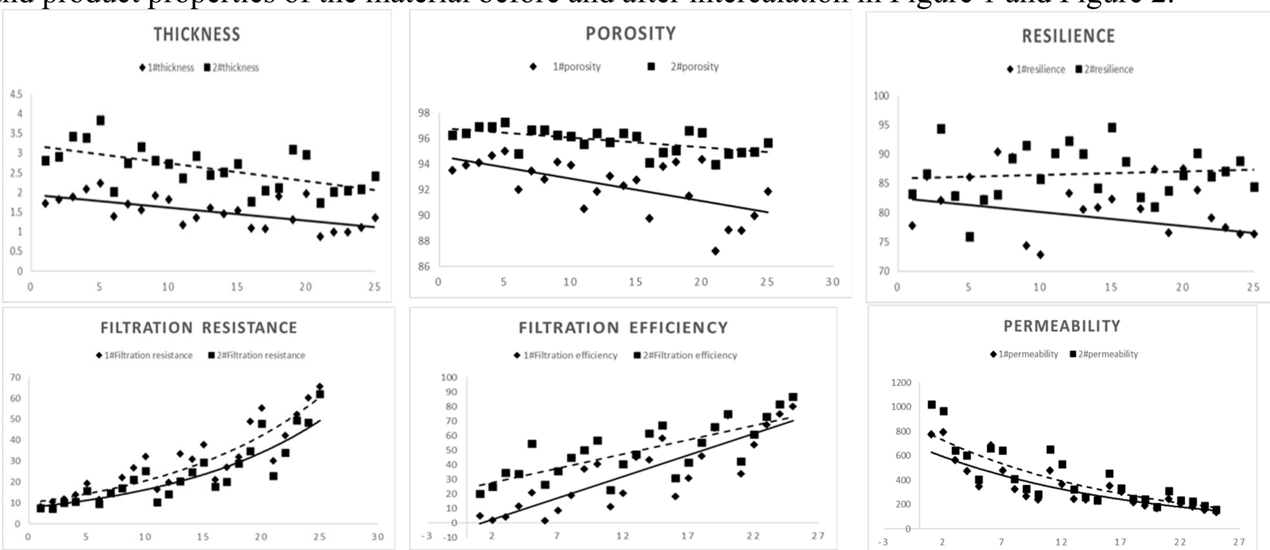


Figure 1 structure and filter performance of the material before and after intercalation

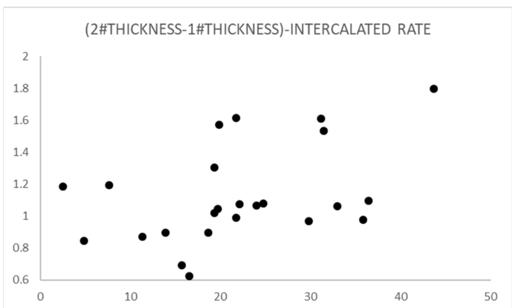


Figure 2 Relationship between intercalation rate and material thickness

4. Influence of process parameters on structural variables

(1) Multiple nonlinear regression model

A multiple nonlinear regression model is usually used to study the relationship between changes in one dependent variable depending on multiple independent variables, and if the relationship between the two can be portrayed in linear form, a multiple linear models can be developed for analysis. Multiple linear regression models are usually used to describe the stochastic linear relationship between the variables y and x_i.

$$y = \beta_0 + \beta_1 X_1 + \cdots + \beta_k X_k + \xi \tag{3}$$

Where: $x_1, \ldots x_k$ are non-random variables; y is a random variable; $\beta_0, \ldots \beta_k$ are regression coefficients; ξ is a random error term.

if k observations of y and x are made and n sets of observations $y_i, x_{1i}, \ldots x_{ki} (i = 1,2, \ldots, n)$ are obtained, they satisfy the following relation.

$$y_i = \beta_0 + \beta_1 X_{1i} + \cdots + \beta_k X_{ki} + \xi_i \tag{4}$$

Expressed in the matrix as:

$$y = \begin{bmatrix} y_1 \\ y_2 \\ \vdots \\ y_n \end{bmatrix}, x = \begin{bmatrix} 1 & x_{11} & \cdots & x_{k1} \\ 1 & x_{12} & \cdots & x_{k2} \\ \vdots & \vdots & \ddots & \vdots \\ 1 & x_{1n} & \cdots & x_{kn} \end{bmatrix}, \beta = \begin{bmatrix} \beta_0 \\ \beta_1 \\ \vdots \\ \beta_n \end{bmatrix}, \quad \xi = \begin{bmatrix} \xi_1 \\ \xi_2 \\ \vdots \\ \xi_n \end{bmatrix} \tag{5}$$

At this point, the model is written as: $Y = X\delta + \xi$.

If the independent variables $x_1, \ldots x_m$ and the dependent variable y are all nonlinear, or some are nonlinear and some are linear, then a multiple nonlinear regression equation is appropriate. For example, the binary quadratic polynomial regression equation is:

$$y = a + b_{11}x_1 + b_{21}x_2 + b_{12}x_1^2 + b_{22}x_2^2 + b_{11\times 22}x_1x_2 \tag{6}$$

Make

$$b_1 = b_{11}, b_2 = b_{21}, b_3 = b_{12}, b_4 = b_{22}, b_5 = b_{11\times 22} \tag{7}$$

$$x_3 = x_1^2, x_4 = x_2^2, x_5 = x_1 \cdot x_2 \tag{8}$$

In this way, the binary quadratic polynomial regression equation can be established by calculating each partial regression coefficient according to the method of multiple linear regression analysis[9].

The technological parameters are known to determine the structural variables and the correlation analysis between them leads to the result that they have a strong correlation. It is known from the data that the process parameters (distance and hot airflow velocity) are functions with continuity for the structural variables (thickness, porosity, and compression resilience), the technological parameters are independent variables and the structural variables are dependent variables and the independent variables do not affect each other. Thus, a multiple nonlinear regression model could be established for them in this article.

(2) Multivariate nonlinear model of distance and airflow velocity on the thickness

The distance and thickness scatter plots were plotted and simple curves were fitted under the same airflow velocities conditions. The high R^2 of the polynomial fit function indicates a good fit. The scatter plots of distance and thickness at different airflow velocity were put together and fitted polynomially, and it was found that the distance and thickness at different airflow velocities could be fitted as a quadratic polynomial function, and the fit was good. As shown in Figure 3.

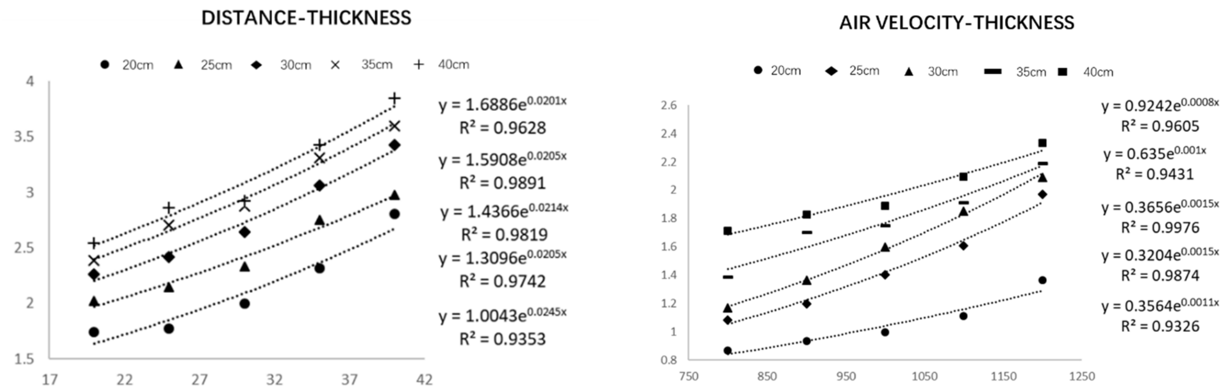


Figure 3 Fitting of distance and airflow velocity to material thickness

Considering the actual situation of the accepted distance and thickness, we can infer that there is a continuous functional relationship between, thickness and distance. Through the multivariate nonlinear model construction method, we downscaled the multivariate nonlinear model of airflow velocity and distance to thickness into a linear model of a single variable distance to thickness with a fixed airflow velocity, thus turning the airflow velocity into an independent variable affecting the coefficients of the linear model, and then polynomially fitting the coefficients of the airflow velocity and the quadratic polynomial, the final fitted polynomial function is as follows.

$$\text{Parameters}\begin{cases} a = -0.3168*D^4 + 0.9104*D^3 - 0.829*D^2 + 0.1993*D + 0.4625 \\ b = -0.2891*D^3 + 0.4262*D^2 - 0.0515*D + 0.5919 \\ c = -0.5184*D^2 + 1.2242*D + 1.7035 \end{cases} \tag{9}$$

$$T = a*S^2 + b*S + cT$$

Where: D is distance; S is hot airflow velocity; T is thickness.

The resulting multivariate nonlinear regression model of distance and airflow velocity on thickness is plotted with distance, hot airflow velocity, and thickness in three dimensions as shown in Figure 4.

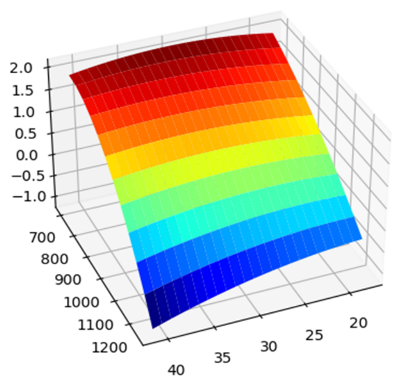


Figure 4 fitting of material thickness under different distances and hot airflow velocity

(3) A multivariate nonlinear model of distance and airflow velocity on porosity

Multivariate nonlinear regression modeling of distance and airflow velocity on porosity using the same idea as above.

Where: D is distance; S is hot air velocity; H is porosity.

The three-dimensional plot of distance, hot air velocity, and porosity is shown in Figure and Figure 6.

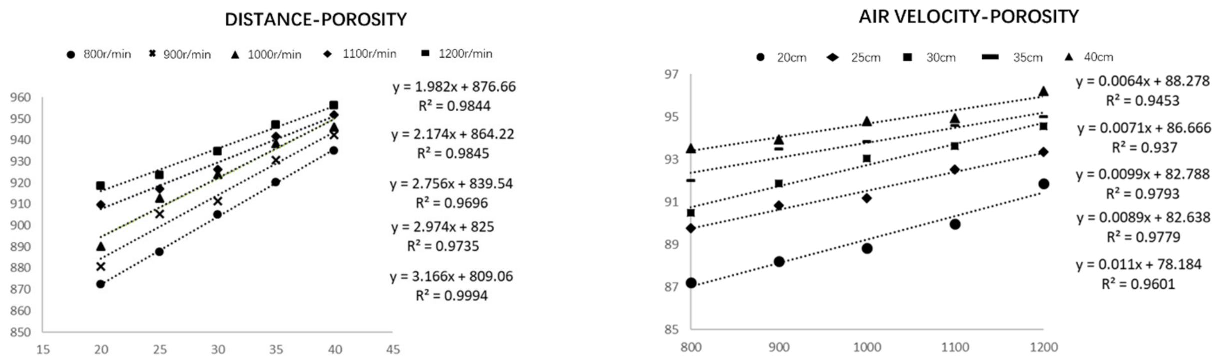


Figure 5 Fitting of distance and hot airflow velocity to material porosity

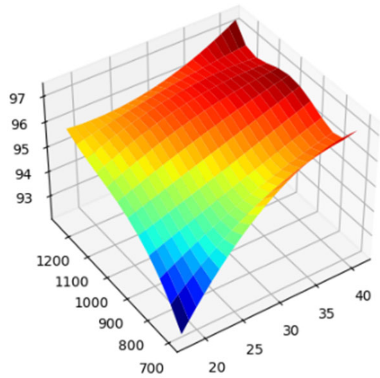


Figure 6 fitting of material porosity under different distances and hot airflow velocity

5. Relationships between structural variables

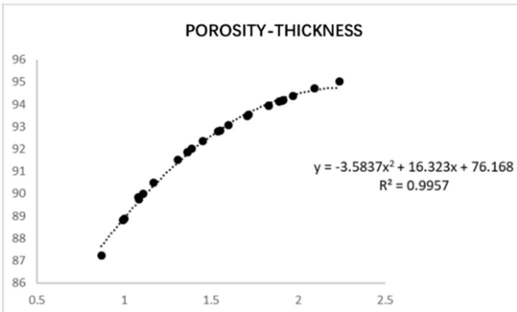


Figure 7 Thickness and porosity fitting under different distance and airflow velocity parameters

A high positive correlation existes between thickness and porosity. The thickness-porosity scatter plot was plotted in Figure 7 and a linear fit was performed for this bivariate based on the principle of the best R^2. The fitted relationship between the two is shown as:

$$porosity=-3.5837*thickness^2+16.323*thickness+76.168 \quad (10)$$

Reason analysis: Thickness and porosity show a high positive correlation. When the receiving distance is larger, the higher the airflow velocity, the more fluffy and loose melt blown fibers, as shown by the enhanced thickness of the filter media, fiber network pore size reduction, and higher porosity. So from the essence of the reason can analyze the thickness and porosity into a positive relationship[10].

6. Relationships between material Performance

There is a strong correlation between material performance. The R^2 of the three models is close to 1, which indicates that the model works well and confirms that there is a strong linear relationship between the average filtration resistance, average filtration efficiency, and air permeability as Figure 8 shows.

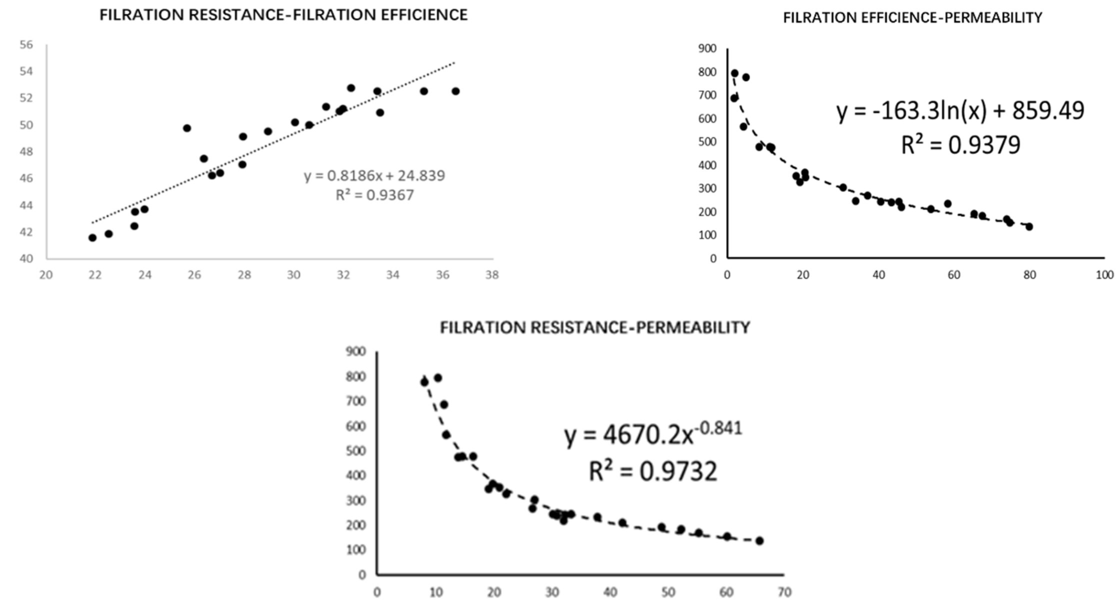


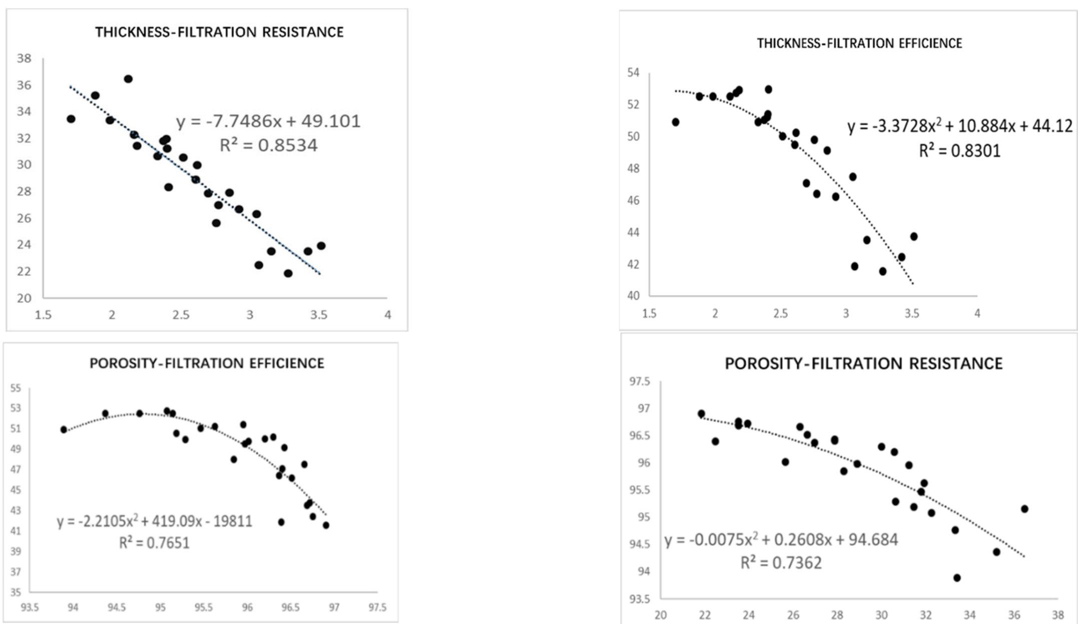
Figure8 relations of material performance.

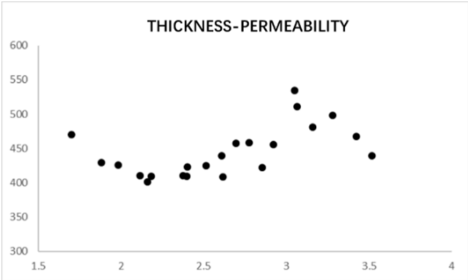
The linear fit function between the filtration efficiency and the filtration resistance is calculated as:

$$\text{filtration efficiency} = 0.8186 * \text{filtration resistance} + 24.839 \quad (11)$$

7. Relationship between structural variables and product performance

7.1. Relationship between structural variables and product performance





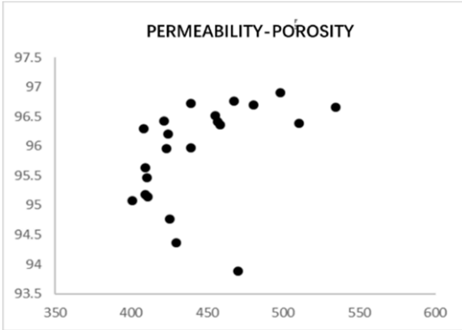


Figure 9 Scatterplot of structural variables and product performance

Reason analysis: The closer the acceptance distance and the stronger the hot airflow velocity of the technological parameters , the finer and messier the fibers will be, and the flecks will easily appear. The smaller the average pore size of the fiber network, the smaller the voids, and the enhanced porosity, which is manifested as enhanced thickness, reduced permeability, increased filtration resistance, and improved filtration efficiency. As shown in Figure 9 above.

The conclusions are as follows:

1. There is a strong negative non-linear correlation between the thickness& the porosity of the sample and the filtration efficiency and filtration resistance of the sample.

2. There is no obvious functional relationship between the compression resilience of the sample and the filtration efficiency, filtration resistance, and permeability of the sample.

7.2. Finding optimal filtering efficiency using random forests

(1) Algorithm Introduction

Regression random forest is a common and effective algorithm in the field of machine learning and data analysis, which belongs to a class of Bagging algorithms that use the Bootstrap random resampling technique and node random splitting technique to construct multiple decision trees, and train and predict the samples based on multiple decision trees, and the predicted value is the weighted mean value of the target variable of the leaf nodes. Figure 10 represents the schematic diagram of the implementation of the RF algorithm.

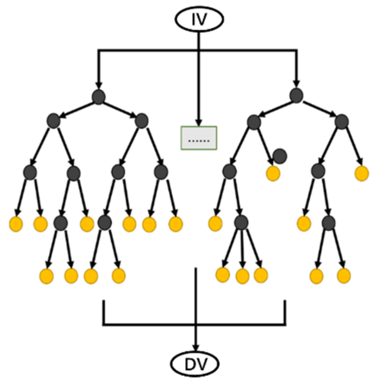


Figure 10 Structure of random forest algorithm

(2) Solution results

According to Figure 11, [1.75-2.25] and [94-95.5] were selected as the ranges of thickness and porosity for the exhaustive method, and 1000 sets of data were obtained for each. Using the model obtained by random forest regression learning (R^2 of 0.943), the prediction of filtration efficiency for these 1000 sets of thickness and porosity data was performed, and some prediction results were obtained as shown in Table 2.

Table 2 Random forest prediction results

Thickness	Porosity	Predicted filtration efficiency
1.88	94.747	52.203
2.07	95.234	52.494
2.13	94.811	52.735
1.93	94.604	52.638
1.85	95.416	50.475
1.77	95.262	52.649
…	…	…

Comparing 1000 filter efficiency predictions, the highest filter efficiency prediction and the corresponding material thickness and porosity were selected as: thickness:1.74mm; porosity: 94.504%; filter efficiency prediction: 53.36%.

Based on the multivariate relationship between thickness and bivariate process parameters and the multivariate relationship between porosity and bivariate process parameters, the backward calculation made the thickness and hot airflow velocity at maximum filtration efficiency of 24 mm and 800 (r/min). The process of the way was shown in Figure 11

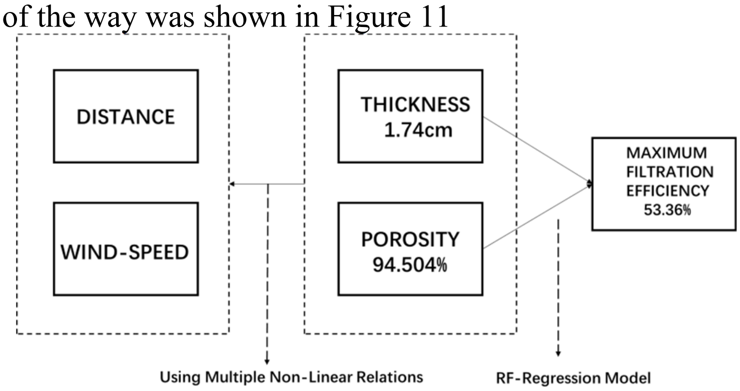


Figure 11 Using random forest to find the best filtering efficiency

8. Conclusion

The test of the influence between the manufacturing process parameters, structural variables, and material properties of Z-type melt blown nonwoven filter materials shows that:

(1) After interpolating the melt blown nonwoven material, the thickness, porosity, and compression resilience rate of the material are significantly improved; reducing filtration resistance of the material. Due to the increase in the porosity of the material, the final performance of the material is also greatly improved.

(2) At the same distance, with the increase of hot air velocity, the material thickness and porosity are enhanced, and at the same hot air velocity, as the receiving distance increases, the material thickness, and porosity of the material increase.

(3) There is a very strong correlation between the filtration efficiency and filter resistance, when the process parameters affect the distribution of the filter material fibers so that the fibers are fluffy and messy, the average pore size of the fiber mesh is reduced, and the particles are more easily intercepted by the fiber mesh, so that the filtration resistance is increased, and the filtration efficiency is greatly enhanced.

(4) The porosity of the intercalated melt blown material becomes larger than that of a single melt blown nonwoven material, so the filtration efficiency of the intercalated melt blown nonwoven material will be slightly lower than that of a single material.

(5) When the thickness of the material is stable, the filtration efficiency of the filter material increases significantly as the porosity of the filter material increases.

(6) Using the multivariate nonlinear model and the random forest model, the material thickness was 1.74mm, the porosity was 94.5%, and the hot air velocity was 800 (r/min) when the filtration efficiency was maximized.

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