

ESTIMATION OF SEPARATION SIZE OF NONWOVEN METALLIC FILTER MEDIA BASED ON PROBABILITY MODEL

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ABSTRACT

Nonwoven metallic filter media are widely used in the manufacture of fine chemicals requiring extraordinary purity. Because their separation mechanism is complex, the design and selection of these filter media still rely on empirical knowledge. To optimize their design, the estimation method for the separation particle size is proposed.

Nonwoven filter media having a depth filtration mechanism can be regarded as multiple layers with a unit thickness that is thin enough to perform surface filtration. Since each layer represents an individual filter, the number of layers of the unit thickness media, n , is equivalent to the number of filtration trials. Thus, the partial separation efficiency, $\Delta\eta$, at a particle diameter, D_p , is expressed as follows.

$$\Delta\eta = 1 - p^n = 1 - \left(\int_{D_p}^{x_{\max}} f(x) dx \right)^n$$

where, p is the probability of particle passage, $f(x)$ is the probability density function for the pore size distribution. This distribution can be described as the size variation of the spaces bounded by randomly generated line segments.

The estimation results by this equation agree well with the experimental ones. As the number of layers (thickness) increases, the separation size decreases and the pressure drop increases.

Consequently, by using this estimation method based on the probability model, optimized nonwoven filter media with well-balanced performance between the separation size and pressure drop can be designed on a rational basis.

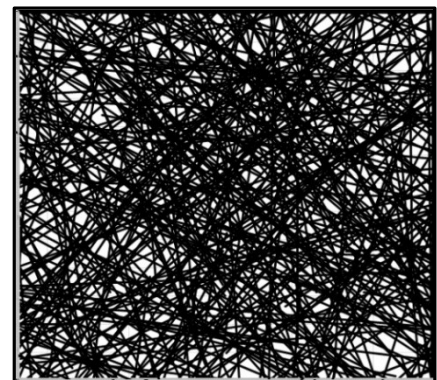


Fig. Filter medium represented by randomly generated line segments

KEYWORDS:

Depth Filtration, Filter Media Design, Filtration Efficiency, Metallic Filter Media, Nonwoven Filter Media, Probability Model

1. Introduction

Clarification of fluids (raw materials, intermediates, and final products) is essential in manufacturing processes such as those for food products, pharmaceuticals, and synthetic resins in order to obtain high-quality products. To do this, filtration is performed using metallic filter media that have several advantages, including excellent heat resistance, durability, and a high level of separation accuracy.

There are several types of metallic filter media, and they are selected according to their application and purpose. Among them, nonwoven metallic filter media are particularly used in the production of fine chemicals, where extremely high purity is required. This is because their depth filtration structure allows for efficient separation of even very small particles.

However, because the separation mechanism of nonwoven metallic filter media is complex, their design and selection still rely on empirical knowledge [1].

We have previously clarified the relationship between the thickness of nonwoven metallic filter media and their separation characteristics using a probability-based model. In this model, the nonwoven filter media are represented as multiple layers of thin surface filtration media. The separation efficiency of each thin surface filtration medium is derived from its experimentally obtained pore size distribution [2, 3].

In this paper, we propose an additional geometrical model that enables estimation of pore size distribution without the need for tedious experimental procedures. To achieve this, the structure of a thin nonwoven filter medium is represented using randomly generated line segments. The spaces bounded by these line segments are regarded as pore sizes. After confirming the applicability of this random generation model, partial separation efficiencies for media of various thicknesses are obtained through the probability model. Finally, an optimum designing procedure of nonwoven metallic filter media is presented.

2. Theoretical model

2.1 Probability model for depth filtration media [2, 3]

In a dilute slurry, particles with diameter D_p can only pass through the pores which are larger than the particle diameter. Thus, the passing probability of the particles is nothing more than the probability that pores larger than D_p are present in the filter medium. When pore size, x , is expressed in a probability density function, $f(x)$, for the pore size distribution, the probability of particle passage, p , is expressed by the following equation:

$$p = \int_{D_p}^{x_{\max}} f(x) dx \quad (1)$$

Therefore, the partial separation efficiency, $\Delta\eta$, at the particle diameter, D_p , is as follows [4].

$$\Delta\eta = 1 - p = 1 - \int_{D_p}^{x_{\max}} f(x) dx \quad (2)$$

To elucidate the filtration mechanism of depth filtration media, a unit thickness that is thin enough to perform surface filtration is defined. In this manner, the depth filtration media can be regarded as layers of thin filter media with each layer having the defined unit thickness.

Because each layer represents an individual filter, the number of layers of the unit thickness media, n , is equivalent to the number of filtration trials. Thus, Eq. (2) can be revised as follows.

$$\Delta\eta = 1 - p^n = 1 - \left(\int_{D_p}^{x_{\max}} f(x) dx \right)^n \quad (3)$$

2.2 Random generation model for nonwoven filter media

To estimate the partial separation efficiency using Eq. (3), the pore size distribution of the filter media is needed. In our previous studies, as described above, the pore size distribution was measured using image analysis. However, when developing new filter media, it is desirable to estimate the pore size distribution without preparing physical specimens.

To address this issue, we propose a new geometrical model. In this approach, line segments with a specified width, corresponding to the fiber diameter, are randomly generated in two dimensions and stacked computationally until a predetermined unit weight is reached.

Figure 1 shows images of the nonwoven filter media generated by the random generation model, with 100 line segments (left) and 500 line segments (right). The diameter of the line segments is 22 μm , identical to that used in the experiments.

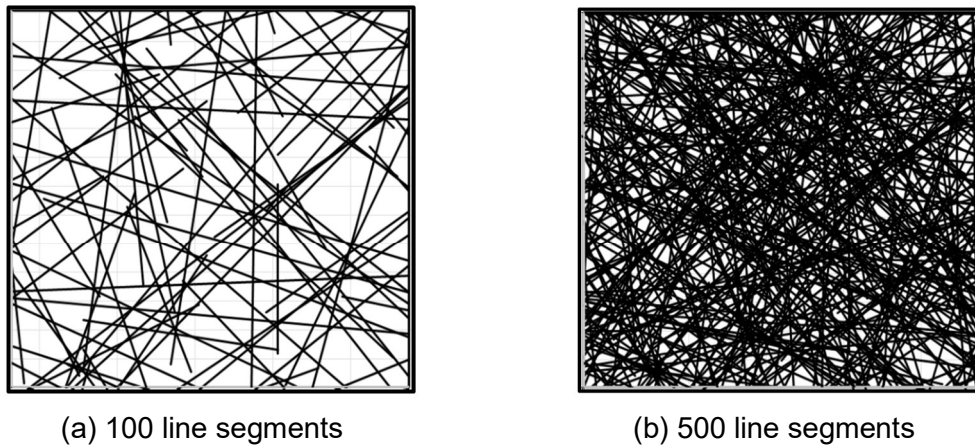


Fig. 1 Images of nonwoven filter media represented by randomly generated line segments

3. Experiments

3.1 Specimens

Table 1 shows the specifications of the tested filter media. Nonwoven filter media made of narrow stainless steel fibers with a diameter of 22 microns were used in this experiment. The thickness was 0.15 mm, which is thin enough to perform surface filtration. Woven wire mesh (500 mesh) was also used as a comparison specimen.

Table 1 Specifications of tested filter media

	Nonwoven filter medium	Woven wire mesh
Type	Sintered metal fiber	Twilled
Material	Stainless steel, AISI316L	Stainless steel, SUS316
Designation	Single layer	500 mesh
Fiber / wire diameter [μm]	22	25
Nominal pore size [μm]	60	25
Density [kg/m^3]	0.30	0.16

3.2 Filtration test

To measure the separation size and the partial separation efficiency of the filter media, a filtration test was performed. The partial separation efficiency, $\Delta\eta$, is defined by the following equation:

$$\Delta\eta = 1 - \frac{f_o(D_p)}{f_i(D_p)} \quad (4)$$

where, $f_i(D_p)$ and $f_o(D_p)$ represent the number base distributions of particles before and after filtration.

The particles used in this experiment were polystyrene latex (45 microns) suspended in electrolytic liquid (NaCl_{aq} , 1 wt%) to prepare a dilute slurry (50–100 ppm). In order to prevent clogging of the pores by particles, the volume of slurry supplied to the tested filter was limited to 100 mL for a filtration area of 10 cm^2 , thereby ensuring that the number of particles was lower than the number of pores. This slurry was filtered at the vacuum pressure of -35 kPa, and the number of particles at each particle size in the slurry was counted before and after filtration by using a particle analyzer (Multisizer 3, Beckman Coulter).

4. Results and discussion

4.1 Pore size distribution

The pore size distributions of the nonwoven filter medium with unit thickness and the woven wire mesh were measured by image analysis. The pore size distribution of the nonwoven medium followed a gamma distribution [5].

On the other hand, the pore size distribution of the woven wire mesh followed a normal distribution (Fig. 2).

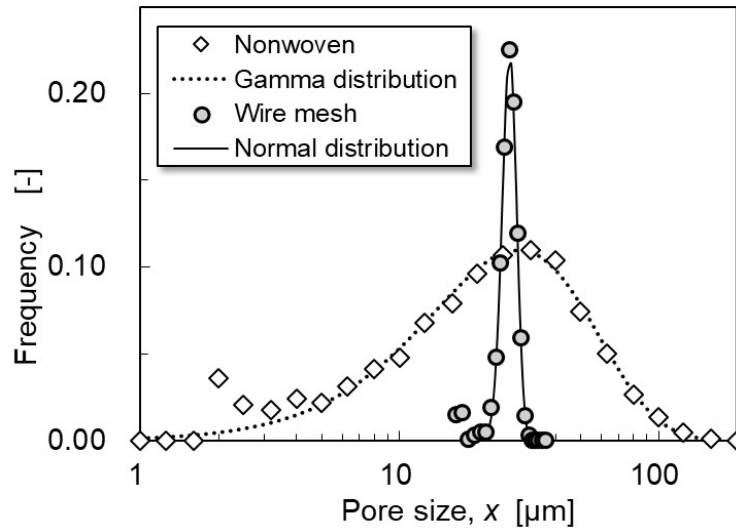


Fig. 2 Pore size distributions of nonwoven metallic filter medium (unit thickness) and woven wire mesh (twilled, 500 mesh)

The pore size measured by image analysis is two-dimensional and different from the practical pore size involved in the capturing of particles (Fig. 3). Thus, the relationship between the measured pore size, x , and the practical pore size, x_c , is defined by the following equation.

$$v = \frac{x_c}{x} \quad (5)$$

By comparing the separation sizes estimated by Eq. (3) with the experimental ones, v was found to be 1.7 and 1.0 for nonwoven filter media and wire meshes, respectively.

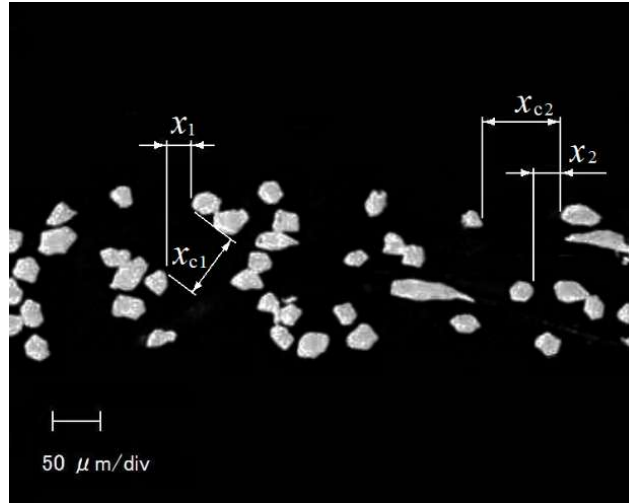


Fig. 3 Sectional view of a nonwoven filter medium
 x_1 and x_2 ; two-dimensionally measured pore size
 x_{c1} and x_{c2} ; practical pore size for capturing particles

Figure 4 illustrates the distributions of projected area diameters (Heywood diameters) for the spaces enclosed by the line segments (Fig. 1). As the number of line segments increases, the pore size distribution gradually approaches the gamma distribution. When the number of line segments increases to 500, the distribution becomes similar to that of an actual filter medium, as described later.

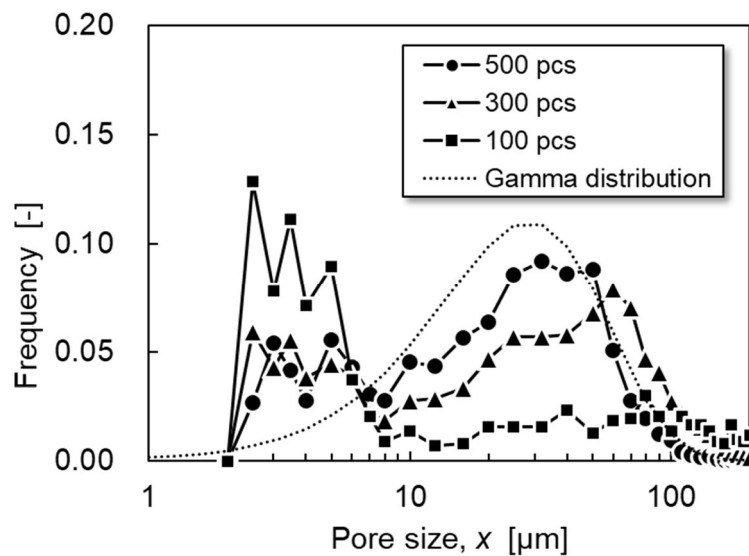
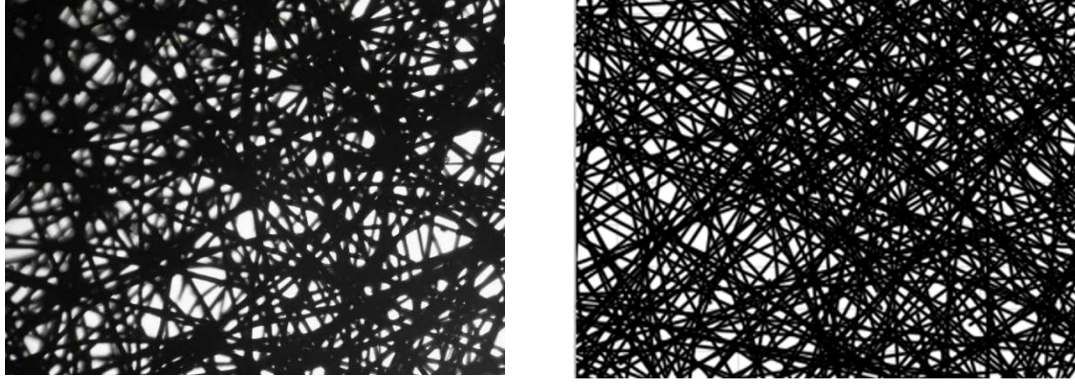


Fig. 4 Pore size distributions of the random generation model according to the number of line segments

Figure 5 compares the binarized image of an actual filter medium with that of a randomly generated one. Although there are slight differences in fiber diameters, the randomly generated filter medium well represents the actual filter medium.



(a) Actual filter medium

(b) Randomly generated medium, 500pcs

Fig. 5 Images of an actual filter medium and a randomly generated filter medium

Figure 6 compares the pore size distribution of the actual filter medium with that of the randomly generated one. When the number of line segments reaches 500, corresponding to the condition in which the unit weight matches that of the actual filter medium, the distribution of the randomly generated filter medium closely reproduces the gamma distribution of the actual filter medium.

$$f(x) = \frac{1}{\Gamma(\alpha)\beta^\alpha} x^{\alpha-1} e^{-\frac{x}{\beta}} \quad (6)$$

where, $\alpha = 2.8$ and $\beta = 16$ in this analysis.

Several researchers have previously suggested the possibility of such an approach [6–8], and we have now been able to confirm its feasibility.

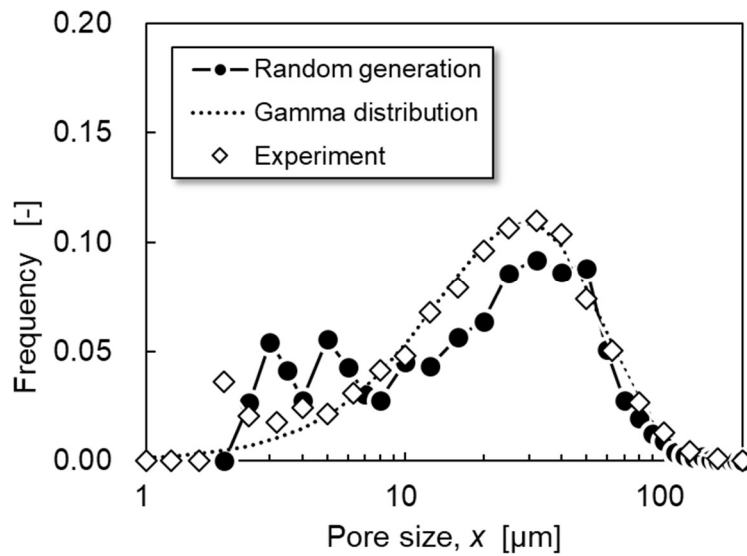


Fig. 6 Comparison of the pore size distributions between the random generation model and the experiment

4.2 Effect of filter thickness on separation efficiency [2, 3]

Figures 7 and 8 represent the partial separation efficiencies calculated by Eqs. (3) and (6), and those determined by the filtration test. The calculation results agree well with the experimental ones.

In the case of wire meshes (Fig. 7), the separation size and the separation sharpness (slope of the efficiency curve) are almost the same regardless of the number of layers. This is because the variation in pore size of wire meshes is small, allowing particles that pass through one layer of the mesh to also pass through subsequent layers.

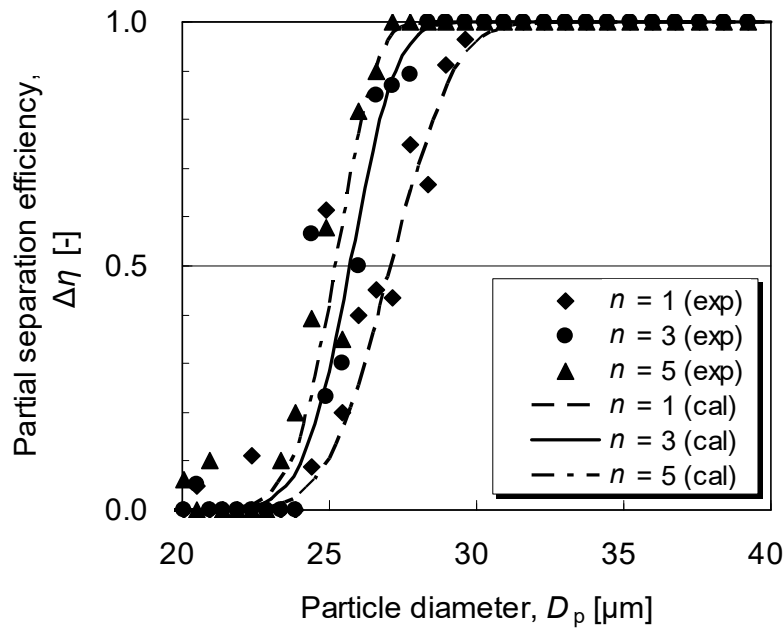


Fig. 7 Comparison of calculated partial separation efficiencies with experimentally determined ones for laminated woven wire mesh (500 mesh)

On the other hand, in the case of nonwoven filter media (Fig. 8), the separation size decreases and the separation sharpness improves as the number of layers increases. This is because particles that have passed through one layer of a medium may not necessarily pass through subsequent layers due to the broad pore size distribution of the medium.

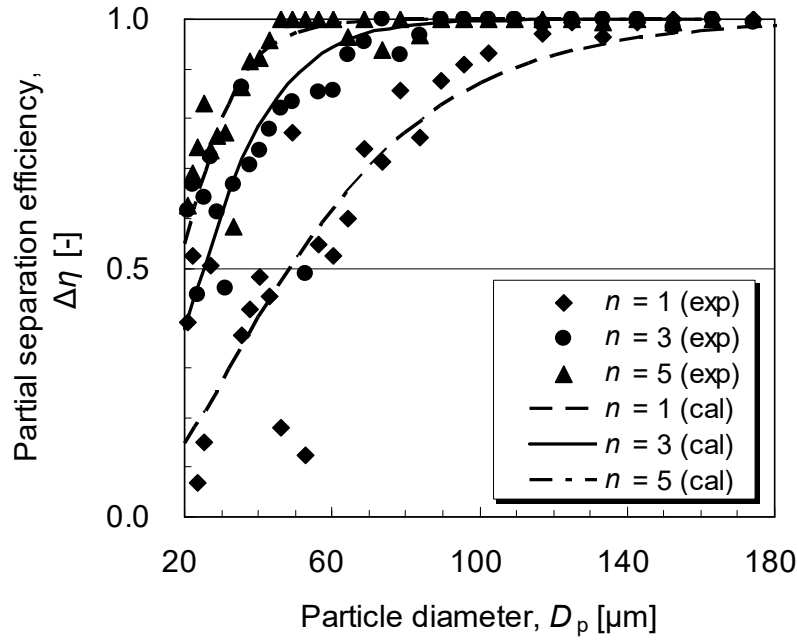


Fig. 8 Comparison of calculated partial separation efficiencies with experimentally determined ones for laminated nonwoven filter media

Figure 9 shows the relationship among the number of layers, the separation size, and the pressure drop of the nonwoven filter media. As the number of layers (thickness) increases, the separation size decreases and the pressure drop increases. The pressure drop of the filter media follows Darcy's law and should be kept as low as possible in filtration processes.

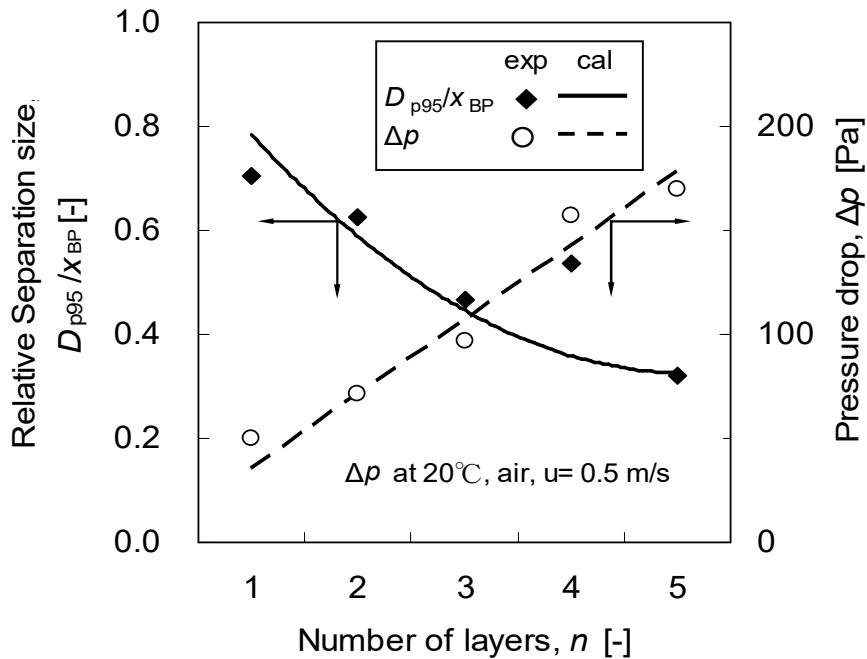


Fig. 9 Relationship among the number of layers, separation size, and pressure drop (experimental and calculated results)

Consequently, by using this estimation method based on the probability model and the random generation model, optimized nonwoven filter media with a well-balanced performance between the separation size and pressure drop can be designed on a rational basis.

5. Conclusion

The separation mechanism of nonwoven metallic filter media with a depth filtration structure was investigated both theoretically and experimentally. Increasing the thickness of the nonwoven filter media resulted in smaller separation sizes and improved separation sharpness. The random generation model of line segments accurately represented the pore size distribution of actual nonwoven filter media, and the probability model enabled the estimation of separation sizes. These models can be used for the rational design of optimum nonwoven filter media with high separation efficiency and low pressure drop.

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