Study on filtration performance of elliptical fiber with different arrangements

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Abstract
The fibrous media composed of elliptical fibers is widely used owing to the high filtration efficiency. However, there are few studies on the arrangement of non-circular fibers, although the single non-circular fiber has been clearly investigated. In this article, two-dimensional numerical geometries of fibrous media with different elliptical fiber arrangements, namely, random distribution structure, dense–sparse structure, and bimodal structure, are developed for studying filtration performance. The results show that the large aspect ratio and solid volume fraction represent low particle penetration. When the particle diameter ($D_p$) is small, the quality factor of bimodal structure is higher than the dense–sparse structure, especially at $D_p = 50$ nm. For the large $D_p$, the opposite is true. Meanwhile, reducing fiber diameter ($D_f$) is more significant than increasing solid volume fraction in terms of improving penetration. As for dense–sparse structure, replacing the elliptical fibers in sparse layers with circular fibers can comprehensively improve the quality factor of fibrous media. However, if the replacement between elliptical fiber and circular fiber occurs in dense layer, it will result in high quality factor at $D_p \leq 500$ nm, while low quality factor at $D_p > 500$ nm.

Keywords
Computational fluid dynamics simulation, fibrous media, elliptical fiber, different arrangements, penetration

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Introduction
For the past few years, respirable particulate matter, such as PM$_{2.5}$, can cause harmful effects on the body’s respiratory system. The primary sources of particulate matter include combustion of fossil fuel, industrial sources, automobile emission, and biomass burning. At present, fibrous media has been extensively used in industry and home, since its excellent filtration capacity. Owing to the filtration efficiency and the pressure drop are key parameters to characterize the quality of fibrous media, it is essential to predict the performance of the fibrous media in product development. In the past, extensive works on the fibrous media had been conducted by previous scholars, who had contributed to the development of filtration theories.1–4 Due to these works, the filtration efficiency and the pressure drop as a function of parameters relating to the fiber diameter, thickness, flow characteristics, and so on have been empirically derived and verified under various experimental conditions. However, as for these filtration theories and engineering application in the past, most fibers have been assumed to be the circular section. Based on computational fluid dynamics (CFD) technology, many...
researchers studied the pressure drop and filter efficiency with different operating conditions and geometry parameters, including face velocity, particle size, and solid volume fraction (SVF). Hosseini and Tafreshi studied the impact of aerodynamic slip on the collection efficiency of circular fibers with random distribution. Based on the lattice Boltzmann-cellular automata (LB-CA) probabilistic model, Wang et al. simulated the filtration process of multi-layer fiber filters in filtration efficiency and pressure drop with different arrangements. The results show that the arrangements play a critical role in filtration performance. Fotovati et al. investigated the filtration performance of fibrous media with bimodal diameter distribution and showed the relationship between the quality factor and the quantity ratio of coarse/fine fibers. Similar to it, Kang et al. developed a two-dimensional (2D) numerical model with circular fibers, in which randomly distribution in the domain and the fiber diameters conform to normal distribution. As for non-circular fiber, Sun et al. developed an improved CFD model with the Y-shape fibers via inertia resistance and viscosity resistance, which are the default models in FLUENT. Hosseini and Tafreshi investigated the effects of fiber’s cross-sectional shape on the performance of fibrous media in slip and no-slip flow regime, concluding that the fiber geometries impose significant effects on filtration performance. They also investigated the characteristics of aerosol filtration media made up of trilobal fibers. Huang et al. used the LB-CA probabilistic model to simulate the particle filtration processes of four kinds of non-circular fibers, finding that the pressure drop of non-circular fibers is dependent on the orientation angle and the aspect ratio (AR). The numerical simulation by Jin et al. showed that the penetrations through fibrous media with the small fiber diameter are weaker than those with the large diameter, especially at a large SVF or inlet velocity.

From the research studies mentioned above, the fibrous media composed of non-circular fibers gradually become the focus. Therefore, elliptical fiber is chosen for further investigating due to being widely used comparing with other non-circular fibers (i.e. rectangular, trilobal, and triangular section). The prevalent semi-analytical models were set up based on circular fiber, which are difficult to be applied directly to non-circular fiber. So the non-circular fiber is usually converted into equivalent circular fiber. In actual conditions, the fibers are randomly distributed in space. What more, to improve the filtration performance, the dense layer is often incorporated into the common fibrous media. Meanwhile, the former research studies also rarely included bimodal structure with non-circular fiber. Hence, random distribution structure, dense–sparse structure, and bimodal structure are developed in this article for studying filtration performance.

**Flow model**

As for the fibrous media, the air flow is governed by the Stokes equation. The continuity and momentum equations are given as:

\[
\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0 \quad (1)
\]

\[
\frac{\partial p}{\partial x} = \mu \left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2}\right) \quad (2)
\]

\[
\frac{\partial p}{\partial y} = \mu \left(\frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2}\right) \quad (3)
\]

CFD software FLUENT is adopted to solve equations (1)–(3). It is noted that all simulations are carried out at room temperature and pressure. For creating 2D geometry of fibrous media, first, the computation domain is estimated in MATLAB. Then, a reference elliptical fiber is generated in the domain. After then, the other fibers can be set up by copying, moving, and rotating the reference elliptical fiber repeatedly with random distance and angle until the SVF reaches the set value. Finally, all the coordinate data are imported to the AutoCAD to materialize the geometry via a text file. In order to avoid bad mesh, no overlap between fibers is allowed. Figure 1 shows the equivalent circle diameters for elliptical section with AR = 3, indicating that the differences between different
equivalent circles are considerable. For ease of expression, we just use area-based circle to represent the corresponding elliptical section and compare the prediction results of particle penetration with other equivalent circles. In this article, the equivalent diameter ($D_f$) of elliptical fiber is 5 µm unless otherwise specified. Taking the random distribution structure as an example, Figure 2 shows the 2D geometry of fibrous media.

As shown in Figure 2, the inlet and outlet boundary conditions are set as “velocity inlet” and “pressure outlet,” respectively. Meanwhile, the lateral surfaces of the computational domain are set as “symmetry” boundary condition, that is, particle colliding with the symmetry boundaries will be reflected without loss of momentum. The inlet boundary condition is placed at a distance 100 µm upstream of the fibrous media to ensure the particles are not released in an area affected by the flow field about the fibers. And the outlet is placed at a distance 25 µm downstream of the fibrous media. In order to facilitate the following analysis of different structures, the porous area is evenly divided into three layers and the gap of each layer is 5 µm. The inlet and outlet boundaries are “escape” and the surface of fibers is “trap.” For the air flow on the fiber surfaces, the no-slip boundary condition is adopted. This is because for the flow condition and fiber size, the continuum flow prevails, that is, $Kn_f = 2\lambda / d_f \ll 1$. The computational domain is meshed by uniform triangular elements. It is worth noting that each simulation is repeated three times and averaged owing to the randomness of geometry in this article.

**Particle model**

**Eulerian method**

In the particle filtration, the Brownian diffusion predominately influences the particles smaller than 100 nm in diameter, while inertia collision and interception become dominant for particle diameter larger than 500 nm. With the particle diameter ranges from 50 to 1000 nm in this article, the convective-diffusive equation is considered for the particles smaller than 500 nm based on the Eulerian approach, which is characterized by the following equation. The user-defined scalar (UDS) is developed to solve the convective-diffusive equation

$$u \frac{\partial n}{\partial x} + v \frac{\partial n}{\partial y} = D \left( \frac{\partial^2 n}{\partial x^2} + \frac{\partial^2 n}{\partial y^2} \right)$$

where $n$ is the particle concentration and $D$ is the diffusion coefficient and can be written as

$$D = \frac{\sigma C_c T}{3 \pi \mu d_p}$$

$$C_c = 1 + \frac{2.468 \lambda}{D_p} + \frac{0.826 \lambda \exp \left( \frac{-0.904 D_p}{2 \lambda} \right)}{D_p}$$

where $\sigma = 1.38 \times 10^{-23} \text{J/K}$ is the Boltzmann constant, $\propto$ is the air viscosity, $T$ is the temperature, $\lambda$ is the mean free path of the air molecules, and $C_c$ is the Cunningham correction factor.

On the assumption that particles will be trapped once they contact with fibers, particles concentration at the inlet and fiber surfaces are 1 and 0, respectively. At the outlet boundary, $\partial n / \partial x = 0$ is applied. Figure 3 shows the simulation result, where the particle concentration decreases gradually because of fiber capture.

**Lagrangian method**

For the particle diameter larger than 500 nm, the Lagrangian method is adopted by solving the force balance equations

$$\frac{d u_p}{dt} = \frac{18 \mu}{D_p \rho_p C_c} (u - u_p) + n(t)$$
The first term on the right-hand side of equations (7) and (8) is the drag force, while the second term is the Brownian force. The Brownian force can be written as

\[ n(t) = G_i \sqrt{\frac{\pi S_o}{\Delta t}} \]  

(9)

where \( S_o \) represents the spectral intensity of the noise given and \( G_i \) is a random number selected from the normal distribution

\[ S_o = \frac{216vkt}{\pi^2 \rho_p D_f^2 S^2 C} \]  

(10)

The discrete phase model (DPM) is adopted to solve equations (7) and (8). For the standard DPM, the particles are treated as point masses. Therefore, the effects of interception would be ignored, which can result in large error when the particle diameter is close to the fiber size. In this article, a subprogram is developed to monitor the distance between the particle and the fiber surfaces. When the distance is less than or equal to \( D_p / 2 \), the particle will be captured and the trajectory of it will stop. The Brownian motion in DPM is also incorporated by solving the energy equation. The trajectories of particles are shown in Figure 4. The filtration efficiency of fibrous media can be determined by the number of particles it can remove from the aerosol flow

\[ E = \frac{N_{in} - N_{out}}{N_{in}} \]  

(11)

where \( N_{in} \) and \( N_{out} \) are the numbers of entering and exiting particles, respectively. For accurately predicting the efficiency of fibrous media by interception and inertia collision, particle density released from the inlet is set as \( 2 \times 10^6 / \text{m}^3 \) based on the test results. In this article, the inlet velocity \( (V=0.04 \text{ m/s}) \), equivalent fiber diameter \( (D_f=5, 3, 2.5, \text{ and } 2 \mu \text{m}) \), the SVF (7.5% and 10%), and AR (1.5, 2, and 3) are investigated. The AR represents the ratio of the major axis to the minor axis of ellipse. So the largest Stokes number is about 0.029, indicating that the particle rebound can be ignored.

During the numerical simulation, the mesh will affect the simulation results, and the mesh number on the flow characteristics is extremely important to ensure the accuracy of the simulation results. In order to ensure the quality of simulation while saving the computing resources, the effect of mesh density on the pressure drop is considered. The mesh independence is tested for the random distribution structure with SVF = 5%, AR = 3, and \( D_f = 5 \mu \text{m} \). To do so, we increased the number of mesh points on the perimeter of the elliptical fiber. Starting from 20, the number of mesh point is increased up to 60. The results of mesh density analysis are presented in Figure 5. As can be seen, increasing the mesh density results in an initial increase in the pressure drop. However, further increase in the mesh density beyond 50 points does not show any significant changes. For all structures of fibrous media in this article, a 50-point mesh is used to ensure the accuracy of simulation results.

**Numerical approach and validation**

The SIMPLE algorithm is employed for the calculation of the pressure and velocity. In this article, owing to the low fluid velocity and small size of fibrous media, the Reynolds number is so small that the airflow through the fibrous media is considered to be laminar. The second upwind schemes are adopted to discretize the equation, and the convergence criterion for all parameters is set as \( 10^{-6} \).
semi-analytical models have been developed to estimate the filtration efficiency and the pressure drop as a function of fiber, particle, and airflow properties for circular fiber. In this article, two equations for filtration efficiency and pressure drop are adopted, which are frequently used in literature. That is because simulating fibrous media and solving its flow field is complicated, which makes the semi-analytical models attractive to people. The expression of fibrous media’s pressure drop and total filtration efficiency are shown as

$$\Delta P = f(a) \frac{\mu t u}{D_f^2}$$

(12)

$$E = 1 - \exp \left( \frac{-4 a t \eta}{\pi D_f (1 - \alpha)} \right)$$

(13)

where $\mu$, $t$, $u$, $D_f$, $\alpha$, $\eta$ are the viscosity of air, the thickness of fibrous media, face velocity, fiber diameter, SVFs of fibrous media, and single-fiber efficiency (SFE), respectively. $f(a)$ is a function of SVF which has various forms based on different theories. Among those theories, Davies’s experimental correction is obtained to calculate the pressure drop of fibrous media and is proved to be accurate for SVF ranges from 0.6% to 30%, which meet the SVF setting ranges in this article. Dimensionless pressure drop can be represented as

$$f(a) = 64 \alpha^2 \left( 1 + 56 \alpha^3 \right)$$

(14)

The SFE can be obtained as the combination of interception ($E_R$), inertial impaction ($E_I$), and Brownian motion ($E_D$).

$$\eta = 1 - (1 - E_R)(1 - E_I)(1 - E_D)$$

(15)

The filtration efficiency due to interception, inertial impaction, and Brownian motion is given as

$$E_R = \frac{1 + R}{2 Ku} \left[ \frac{2 \ln(1 + R) - 1 + SVF + \left( \frac{1}{1 + R} \right)^2}{1 - \frac{SVF}{2} - \frac{SVF}{2} (1 + R)^2} \right]$$

(16)

$$E_I = \frac{St \cdot J}{4 Ku}$$

(17)

$$E_D = 2.9 Ku^{-1/3} Pe^{-2/3} + 0.62 Pe^{-1}$$

(18)

$$Ku = \frac{-\ln(\alpha)}{2} - \frac{3}{4} + \alpha - \frac{\alpha^2}{4}$$

(19)

$$R = \frac{D_p}{D_f}$$

(20)

$$St = \frac{\rho_p D_p^2 C u}{18 \mu d_f}$$

(21)

where $R$ is the ratio of particle to fiber diameter, $Ku$ is the Kuwabara factor, and $St$ is the Stokes number.

The particle diameter ranges from 50 to 1000 nm ($D_p = 50, 100, 300, 500, 1000$ nm) are considered in each analysis. Figure 6 shows the comparison of penetration per thickness ($\ln(P) / t$) between simulation results and the semi-analytical models based on circular fiber. It is clear that the simulation results fit well with the semi-analytical models. For the case with SVF = 5% and $D_f = 5 \mu m$, the maximum error is about 4.32% at $D_p = 50$ nm. As for the case with SVF = 10%, the maximum error is about 13.4% at $D_p = 1000 \text{nm}$ and the mean error is about 7.29%. Obviously, the filtration characteristics of fibrous media can be truly reflected by numerical simulation.

**Results and discussion**

As mentioned above, the semi-analytical models are promoted based on circular fiber. Therefore, in this article, four differently equivalent methods are proposed to predict the penetration per thickness and compare with corresponding.
elliptical fiber. As shown in Figures 7 and 8, it is clear that there is good agreement between simulation results and the prediction results by area-based circle. Perimeter-based and pressure-based circle\(^8\) underestimates the penetration per thickness, especially at \(D_p = 50\) and 1000 nm. The errors between circumscribed circle and simulation results is the largest among these methods. For the area-based circle, the maximum error is about 14.26% at \(D_p = 50\) nm with SVF = 7.5%, AR = 1.5, and the mean error less than 6%.

Figure 7 shows the variation of the penetration per thickness for the case with the same AR but different SVFs. With the same AR, the higher SVF represents more contact surfaces. It means that particles are more likely to collide with fibers and are captured. For the case with SVF = 10%, the smallest penetration per thickness is about −6000 at 50 nm, while the penetration per thickness is about −4000 and −2500 for the SVF = 7.5% and 5%, respectively. It can also be seen that the change of penetration per thickness at 300 and 500 nm is smaller than 500 with the increases of SVF from 5% to 10%. That is because when the particle diameter is between 300 and 500 nm, the effects of either diffusion or inertia are not significant.

Figures 8 and 9 show the influences of AR on the penetration per thickness. The penetration per thickness decreases by increasing the AR. Similarly, the elliptical fiber with larger AR has more contact surfaces. Hence, no matter which mechanism becomes dominant, the elliptical fiber with large AR represents greater particle removal capacity.

As shown in Figures 7 and 8, the equivalent method of the area-based circle can well describe the particle penetration of fibrous media composed of elliptical fibers, combined semi-analytical models. Nevertheless, the area-based circle cannot directly and accurately predict the pressure drop of elliptical fiber with different ARs. To solve this problem, we calculate the pressure drop of elliptical fiber with AR = 1.5, 2, and 3 in SVF ranges from 5% to 10%. Even though the pressure drop predicted by area-based circle shows large error, it also shows a good linear relationship with true pressure drop. Therefore, it can be amended by linear function. As shown in Figure 10, after the amendment by linear function, the area-based circle shows accurate prediction of pressure drop with corresponding elliptical fiber, and the mean error is about 6.12% for different AR.

For the dense–sparse structure, it can be divided into two categories, one of which is increasing the SVF and the other is decreasing the \(D_f\) as shown in Figure 11. Meanwhile, the dense layer in different positions (left, middle, or right) is investigated in detail to reflect the filtration characteristics. Such as “Dense layer-Left” means the dense layer is placed in left position. For the purpose of reducing the error caused by the randomness of models as much as possible, we just change the dense layer with the sparse layer in X coordinate. Simultaneously, the bimodal structure is translated by the dense–sparse structure, which is composed of coarse and
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It should be clear that in addition to the uniform model, SVF just represents the SVF in one-third of the porous area. If no declaration is made, SVF = 5% is the default.

According to the above analysis, the larger AR stands for lower penetration, therefore taking AR = 3 for further investigation. Figure 12 shows the penetration per thickness with different media structures. It can be seen that the penetration per thickness of bimodal structure is higher than other dense–sparse structures. What more, for dense–sparse structure, although the overall difference is relatively small, the dense layer in the middle shows low penetration per thickness at all particles in general.

It is critical for the quality of the fibrous media to evaluate the filtration efficiency and the pressure drop simultaneously, high-quality fibrous media with high filtration efficiency and low pressure drop. The quality factor \( Q = -\ln(1 - P) / \Delta P \) is adopted to evaluate the filtration performance in this article. Figure 13 shows the quality...
factor of different structures. No matter which dense structure, when the particle diameter is smaller than 300 nm, the quality factor of bimodal structure is higher than other dense–sparse structures. That is because when particle diameter is smaller than 300 nm, the diffusion of particles is strong. Therefore, comparing with dense–sparse structures, the bimodal structure can also show good filtration capacity when the diffusion is dominant. Meanwhile, due to the accumulation of fibers in the specific layer, the dense–sparse structures will lead to high pressure drop. For the particle diameter larger than 300 nm (inertia-based), the advantage of dense layer is gradually reflected, which leads to higher quality factor than bimodal structure.

The ultimate goal of increasing SVF and reducing $D_f$ is to increase contact surfaces. Hence, the dense–sparse structure (the dense layer in the middle) is chosen for further analysis. Figure 14 shows the increased length of dense–sparse structure than the random distribution structure with SVF = 5%, $D_f = 5 \mu m$. Figure 15 shows the increased filtration efficiency per increased length with different dense structures (fine fiber or high SVF in the middle layer) at $D_p = 50–1000 \, \text{nm}$. Obviously, the effects of decreasing $D_f$ is more significant than increasing SVF in promoting filtration capacity. For two kinds of dense structures ($D_f = 2.5 \, \mu m$; SVF = 10%), they have similar increased contact surfaces than initial structure (random distribution structure with $D_f = 5 \, \mu m$ and SVF = 5%). However, the $\Delta E / \Delta \text{Length}$ of $D_f = 2.5 \, \mu m$ is about 250 at $D_p = 50$ and 1000 nm, while the $\Delta E / \Delta \text{Length}$ of SVF = 10% is about 200. Meanwhile, it can also be seen that the dense–sparse structure has a limited effect on reducing penetration for the particle diameter at 300 nm, hence the curve ($\Delta E / \Delta \text{Length}$) showing in “V” type. Meanwhile, with the increase in contact surfaces by decreasing $D_f$ or increasing SVF, the growth trend of filtration efficiency gradually decreases.

In order to further study the filtration capacity of each layer and the differences between elliptical fiber and circular fiber, the dense–sparse structure (structure-A) constituted by fine fiber ($D_f = 2.5 \, \mu m$) is taken as an example.
Figure 16 shows the contrast structures, namely structure-B and structure-C.

Figure 17(a) shows the filtration efficiency of structure-A in each layer at different particle diameters, while (b) shows the filtration efficiency per length (E/Length) in each layer. Compared with the dense layer in the middle, the filtration efficiencies of the left layer and the right layer are much lower. As shown in Figure 18(b), when \( D_p \leq 300 \text{ nm} \), the E/Length of each layer is mainly affected by the combination of particle concentration and layer structure. With the increases in particle diameter, the differences between the left and right layer are gradually reduced. When \( D_p \geq 500 \text{ nm} \), the E/Length is dominant by layer structure, and the left and right layers show similar filtration efficiency per length even if the particle density is different in each layer.

We also know that with the same area, the elliptical fiber represents higher pressure drop than circular fiber as shown in Figure 11. Therefore, for comparison study, we try to transfer the elliptical fibers in the left and right layers to circular fibers as shown in Figure 16(b). Figure 18 shows the quality factor of different structures. The funny fact is that the quality factor of structure-B is higher than structure-A, although the differences at \( D_p = 300 \text{ and } 500 \text{ nm} \) are small. This phenomenon is caused by two factors. First, as for dense-sparse structure, the sparse layers do not undertake the main filtration but result in a high pressure drop compared with circular fiber. Second, the differences between diffusion and inertia also contribute to it. For small particle (i.e.50 nm), owing to the Brownian motion, the diffusion is dominant and most particles can be easily captured even if for the circular fiber. For large particle (i.e.1000 nm), the inertia is significant and most particle will flow around fibers. Due to the accumulation of fine fibers in the dense layer, it shows absolutely higher E/Length compared with sparse layers when \( D_p \geq 500 \text{ nm} \).

For comparing, the structure-C is developed. According to Figure 18, when \( D_p \leq 500 \text{ nm} \), the quality factor of structure-C higher than structure-A and structure-B. For \( D_p > 500 \text{ nm} \), the opposite is true. As mentioned above, owing to the Brownian motion, the circular fiber can also show good filtration efficiency with low pressure drop. Hence, for small particle (i.e.50 nm), the circular fiber shows significant advantage in quality factor than elliptical fiber. Meanwhile, as the particle diameter increases, such advantages gradually decrease. For large particles (i.e.1000 nm), the advantage of having more contact surfaces of elliptical fiber is considerable.

Conclusion

In this article, different structures of fibrous media are developed to investigate the filtration performance with various conditions. Basically, the larger the contact surfaces, the more likely the particles will collide with fibers. Hence, the large
Figure 15. The increased filtration efficiency per increased length via (a) decreasing $D_f$ and (b) increasing SVF.

Figure 16. The dense–sparse structure for elliptical and circular fibers: (a) structure-A, (b) structure-B, and (c) structure-C.

Figure 17. The dense–sparse structure (structure-A): (a) The filtration efficiency in each layer. (b) The filtration efficiency per length in each layer.
The quality factor for structure-A, structure-B, and structure-C.

Figure 18. The quality factor for structure-A, structure-B, and structure-C.

AR and SVF represent low penetration for all particles. Compared with other equivalent methods, the area-based circle can well predict the penetration of fibrous media composed of elliptical fibers. Meanwhile, the pressure drop can also be accurately predicted via linear correction based on the area-based circle. Owing to the characteristics of diffusion and inertia, when \( D_p \) is small, that is, \( D_p = 50 \) nm, the quality factor of the bimodal structure is higher than dense–sparse structures. However, when \( D_p \) is large, that is, \( D_p = 1000 \) nm, the opposite is true. Based on the dense–sparse structure, reducing \( D_p \) of the dense layer is more significant than increasing SVF in terms of improving penetration. For the dense–sparse structure, replacing elliptical fibers in the left and right layers, which are not undertaking the main filtration, with circular fibers can comprehensively improve the quality factor of fibrous media. Meanwhile, for the middle layer, which undertakes the main filtration, when \( D_f \) is less than 500 nm, the quality factor of circular fibers (structure-C) is higher, and when \( D_p \) larger than 500 nm, the quality factor of elliptical (structure-A and structure-B) fibers is higher.

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