

Simulation of fiber movement in the high speed vortex during the rotor spinning process

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Abstract

A physical model of the air extraction rotor spinning channel was established in SolidWorks 2018 to explore the movement of the fiber in the rotor and the fiber transport channel. A fiber model was built using EDEM2018. Using the coupling software Fluent 19.0 and EDEM2018, a numerical analysis of the movement of fibers in the fiber transport channel and rotor was carried out. The research in this study provides a strong theoretical basis and technical support for further development of new rotor-spun yarns and optimization of key components with a short spinning process, high yarn-forming efficiency, and strong fiber adaptability.

Keywords

Fiber, rotor spinning, fiber transport channel, air flow, 3D model.

1. Introduction

The rotor spinning process is characterized by its short duration and high output speed. It is a new, high-speed, and high-efficiency yarn-spinning method with strong fiber adaptability and a wide application range. In particular, it is well suited for cotton waste, which is too short to be spun using the ring-spinning process [1]. This can effectively save labor and reduce the costs of materials and production. Rotor spinning uses high-speed airflow to complete the agglomeration and twisting of short fibers into yarn. Fibers, such as cotton and polyester, have a large aspect ratio and short length, are fine and flexible, and can be bent, twisted, and stretched lightly. Theoretical research on the rotor spinning process is the basis for improving yarn performance, developing new yarns, and upgrading special equipment.

The movement of fibers in an airflow field is a common phenomenon observed in various spinning methods, such as rotor spinning and air-jet-vortex spinning. This is a two-phase flow problem. Research on the motion characteristics and laws of fibers in a high-speed airflow field can further enrich the two-phase flow theory, which will also provide a strong theoretical basis and guide for optimizing yarn-spinning parameters and improving

the structure of the spinning unit [2–4]. The commonly used steps to study the motion characteristics of fibers in airflow are as follows: (1) building a fiber model, (2) analyzing the force on the fiber and establishing the dynamic equation of the fiber, (3) numerically solving the motion trajectory of the fiber in the flow field, and (4) analyzing the effect of the spinning parameters on the dynamic equation of the fiber along with the motion of the fibers. The main challenge in researching airflow/fiber two-phase flow is the establishment of a fiber mechanical model.

In the early stages of research (1966–1977), the model used to describe fibers was relatively simple. By ignoring the flexible characteristics of the fiber without bending, twisting, and stretching, a particle or an elongated cylinder was assumed to be the fiber model [5, 6].

The simple rigid geometric monomer model had significant limitations and could not simulate elastic deformations, such as the bending, torsion, and stretching that real fibers exhibit.

Therefore, a multi-rigid body-chain model was further established which was more complex than the single-body model and could better approximate the characteristics of real fibers. This model is

represented by multiple rigid geometries connected by connectors, such as elastic bonds, ball-and-socket joints, or hinges. The deformation of flexible fibers can be achieved by changing the relative displacement and rotation angle of the connector [7]. Therefore, the dynamic properties of individual fibers can be obtained by tracking the motion of each segment. Based on the shape of the rigid geometry, flexible fiber models can be summarized into four categories: the ball-chain-model [8–11], ellipsoid-chain-model [12], point-chain-model [13], and cylindrical-chain-model [14, 15].

Early research primarily focused on laminar flow fields with low Reynolds numbers [16–18]. With the development of computer numerical simulation technology, an increasing number of researchers begun to explore fiber movement in a turbulent flow field with a high Reynolds number [13]. Two- and three-dimensional models of fiber movement were explored in an airflow field during the spinning process [19, 20].

The motion and morphology of a single fiber in the airflow field of the rotor spinning unit were studied, particularly in the fiber transport channel [11, 21]. In research on single-fiber motion, from two-dimensional to three-dimensional simulations, the fiber model has

changed from an inextensible point-chain to a flexible ball-socket-joint, from unidirectional coupling to two-way coupling of fiber with the airflow, other fibers, or rotor wall [22, 23]. It can be observed that numerical simulation of the fiber motion during rotor spinning was gradually optimized. The above research is of great significance for deeply understanding the spinning mechanism of rotor spinning and providing a guide to production.

Based on a previous study, the movement of multiple fibers in the flow field of a rotor spinning unit was carried out using a computer, considering spinning parameters, such as the rotor speed, rotor diameter, angle of the rotor wall, and type of fiber collection groove [24].

Current studies on multiple fibers have mostly focused on particles or fiber models without flexibility. Thus, a large gap exists between the rigid model and the actual morphological characteristics of the fibers. Research on the rotor-spinning process has focused on the movement of fibers in the fiber transport channel, which is a special tube [25]. However, research on fiber motion in other complicated spinning elements, such as the rotor and carding zone, is rare due to the difficulty of overcoming existing challenges. This is of critical importance for industrial textiles. Therefore, this study focuses on the movement distribution and morphological changes of multiple flexible fibers in rotor and fiber transport channels to highlight the rotor spinning industry.

2. Model establishment

2.1. Model of rotor spinning unit

Using SolidWorks 2018, a model of the air-extraction type rotor spinning channel was established, shown in Figure 1. The radius of the rotor was 27 mm, and the fiber-collection-groove was a T-type. The grid was divided into CFD, and a Fluent-EDEM coupling analysis model was established.

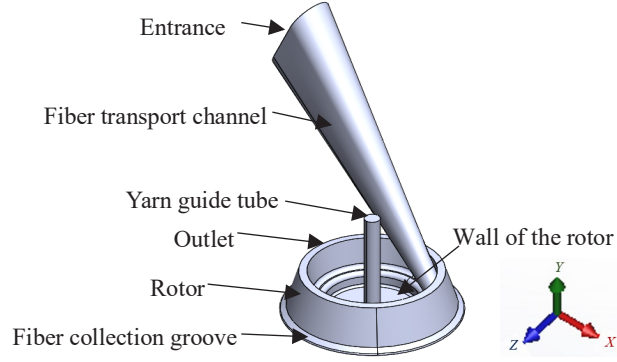


Fig. 1. Rotor spinning channel model

2.2. Physical model of the airflow field

The airflow in the rotor spinning channel is turbulent flow [26], and the model satisfies the conservation of energy and momentum. The mass-conservation differential equation is given by Eq. (2.1). The momentum conservation differential equation is given by Eqs. (2.2) and (2.3). The standard k-ε model was used in Fluent to numerically simulate the airflow field. A smooth-wall function was applied to the airflow near the wall. A simple algorithm was applied to solve the coupling effect between the solid and airflow, as shown in Eqs. (2.4) and (2.5) [27].

$$\frac{\partial(\rho\mu_k)}{\partial x_k} = 0 \quad (2.1)$$

$$\frac{\partial(\rho u_i u_k)}{\partial x_k} = -\frac{\partial P}{\partial x_i} + \frac{1}{Re} \frac{\partial \tau_{ij}}{\partial x_j} \quad (2.2)$$

with

$$\tau_{ij} = \mu \left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) - \frac{2}{3} \mu \frac{\partial u_k}{\partial x_k} \delta_{ij} \quad (2.3)$$

$$\frac{\partial}{\partial x_i} (\rho k u_i) = \frac{\partial}{\partial x_j} \left[\left(\mu + \frac{\mu_t}{\sigma_k} \right) \frac{\partial k}{\partial x_j} \right] + G_k \quad (2.4)$$

$$+ G_b - \rho \varepsilon - Y_M$$

$$\frac{\partial}{\partial x_i} (\rho \varepsilon u_i) = \frac{\partial}{\partial x_j} \left[\left(\mu + \frac{\mu_t}{\sigma_\varepsilon} \right) \frac{\partial \varepsilon}{\partial x_j} \right] \quad (2.5)$$

$$+ C_{1\varepsilon} \frac{\varepsilon}{k} (G_k + C_{3\varepsilon} G_b) - C_{2\varepsilon} \rho \frac{\varepsilon^2}{k}$$

Where ρ is the air density, P the gas pressure, u_i the velocity component of the

airflow in direction x_i ; Re the Reynolds number, and τ_{ij} is the aerodynamic viscosity coefficient, δ_{ij} the Kronecker delta function, G_k the generation term of the turbulent flow energy K caused by the gradient of the average velocity, G_b is the generation term of the turbulent flow energy caused by the buoyancy, Y_M the total dissipation rate of pulsatile expansion in the compressible turbulent flow, σ_k and σ_ε are the Prandtl numbers corresponding to the turbulent flow energy and dissipative energy, respectively $C_{1\varepsilon}=1.42$, $C_{2\varepsilon}=1.68$, $C_{3\varepsilon}=0.09$.

2.3. Fiber model and equation of motion

The physical model of fibers was established, shown in Figure 2. The motion of the fiber in the airflow field of the spinning unit is a fluid-structure coupling problem. The Lagrangian and Eulerian methods are commonly used to study fluid-structure coupling. In this study, the Lagrangian method was used to simulate the motion and distribution characteristics of fibers in an airflow field, using fibers as discrete phases and simplifying them as discrete particles. In addition, the Eulerian method was used to treat the airflow field as a continuous phase to explore the motion of fiber particles in the airflow field of the spinning channel, as demonstrated by Eq. (2.6).

$$m_p \frac{dv_p}{dt} = F_c + F_{f \rightarrow p} + m_p g \quad (2.6)$$

Where, m_p is the particle mass, v_p the particle velocity, F_c the contact force



Fig. 2. Physical model of fiber

that accounts for particle-particle and particle-wall interactions, $F_{f \rightarrow p}$ the force of airflow on the particles, g the gravitational acceleration vector, ω_p the angular velocity vector, J_p its moment of inertia tensor, and M_c is the net torque generated by tangential forces that causes the rotation of the particle.

The Hertz–Mindlin (No Slip) model was used in EDEM2018 to represent the contact force on the fibers. Consequently, F_c in Eq. (2.6) can be broken down into normal and tangential forces, as demonstrated by Eqs. (2.7) and (2.8) (normal force) and Eqs. (2.9) and (2.10) (tangential force)

$$F_n = \frac{4}{3} E \sqrt{R} \delta_n^{\frac{3}{2}} \quad (2.7)$$

$$F_n^d = -2 \sqrt{\frac{5}{6}} \beta \sqrt{S_n m v_n^{\text{rel}}} \quad (2.8)$$

$$F_t = -S_t \delta_t \quad (2.9)$$

$$F_t^d = -2 \sqrt{\frac{5}{6}} \beta \sqrt{S_t m v_t^{\text{rel}}} \quad (2.10)$$

Where, F_n is the normal force, F_t the tangential force, F_n^d the normal damping force, F_t^d the tangential damping force, E Young's modulus, R equivalent radius, δ_n normal overlap, δ_t tangential overlap, β the coefficient $\beta = \frac{\ln e}{\sqrt{\ln^2 e + \pi^2}}$, S_n the normal stiffness, S_t the tangential stiffness, m the equivalent mass, and v_n^{rel} and v_t^{rel} the normal and tangential components of the relative velocity, respectively.

The fluid interaction force, $F_{f \rightarrow p}$ can be divided into two parts: $F_{\nabla p}$ (pressure gradient force) and F_D (drag force), as demonstrated by Eq. (2.11), (2.12), and (2.13).

$$F_{f \rightarrow p} = F_{\nabla p} + F_D \quad (2.11)$$

$$F_{\nabla p} = -V_p \nabla p \quad (2.12)$$

Fig. 3. Boundary conditions of the rotor model

$$F_D = \frac{1}{2} C_D \rho_f A' |u - v_p| (u - v_p) \quad (2.13)$$

Where V_p is the volume of the particle, ∇_p the local pressure gradient, C_D the drag coefficient, ρ_f the fluid density, A' the projected particle area in the flow direction, and $u - v_p$ the relative velocity between the particle and fluid.

The relative particle Reynolds number was used in all situations concerned, defined using the particle diameter and relative particle-fluid velocity, as demonstrated by Eq. (2.14).

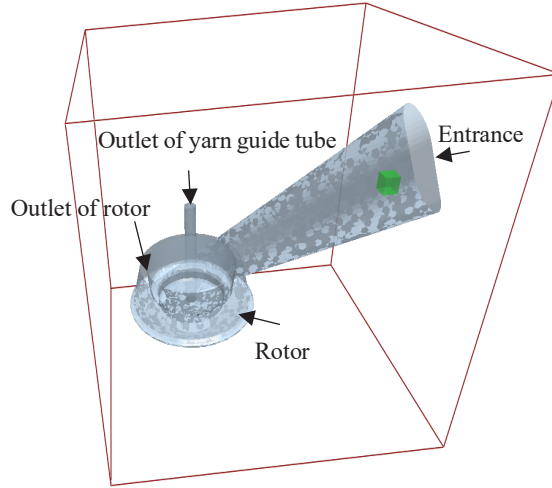
$$Re_p = \frac{\rho_f |v_p - u| d_p}{\mu_f} \quad (2.14)$$

Where Re_p is the particle relative Reynolds number, μ_f the fluid viscosity, and d_p the particle diameter.

2.4. Boundary conditions

The air flow velocity at the inlet of the fiber transport channel is 50 m/s, the rotating speed of the rotor 50 000 r/min, the pressure at the outlet - 8 000 Pa, and the pressure at the outlet of the yarn guide tube is 0 Pa, as shown in Figure 3.

Assuming that the fiber is cotton, the fiber density is 1.54 g/cm³, the fiber fineness 2.12 dtex, Young's modulus of the fiber 300 MPa, the speed of the carding roller



5000 r/min, the diameter of the carding roller 65 mm, the sliver weight 18 g/10 m (1800 tex), the yarn is 10^s (58.31 tex), and the twist coefficient is 350, that is, 458 twist/m.

$$\begin{aligned} \text{Number of fibers holding by the feeding roller} &= \\ \frac{\text{Linear density of sliver}}{\text{Linear density of fiber}} &= \frac{1800}{2.12} \times 10 = 8490 \end{aligned}$$

$$\begin{aligned} \text{Draft ratio between the sliver and the yarn} &= \\ \frac{\text{Linear density of sliver}}{\text{Linear density of yarn}} &= \frac{1800}{58.31} = 30.87 \end{aligned}$$

$$\begin{aligned} \text{Winding speed of yarn} &= \\ \frac{\text{Speed of the rotor}}{\text{twist number of yarn}} &= \frac{50000}{458} = 109 \text{ m/min} \end{aligned}$$

$$\begin{aligned} \text{Feeding speed of sliver} &= \\ \frac{\text{Winding speed of yarn}}{\text{Draft ratio between sliver and the yarn}} &= \frac{109}{30.87} = 3.53 \text{ m/min} \end{aligned}$$

$$\begin{aligned} \text{Draft ration between carding} \\ \text{roller and feeding roller} &= \\ \frac{\text{Linear speed of carding roller}}{\text{Linear speed of feeding roller}} &= \\ \frac{5000 \times 65 \times 3.14 \times 10^{-3}}{3.53} &= 289 \text{ m/min} \end{aligned}$$

$$\begin{aligned} \text{Number of fibers in carding zone vertical section} &= \\ \frac{\text{Number of fibers holding by the feeding roller}}{\text{Draft ratio between carding roller and feeding roller}} &= \\ \frac{8490}{289} &\approx 30 \end{aligned}$$

It can be observed from the above calculation that approximately 30 fibers were transported to the fiber transport channel by the carding roller in each cycle. Therefore, 30 fibers were built in the EDEM.

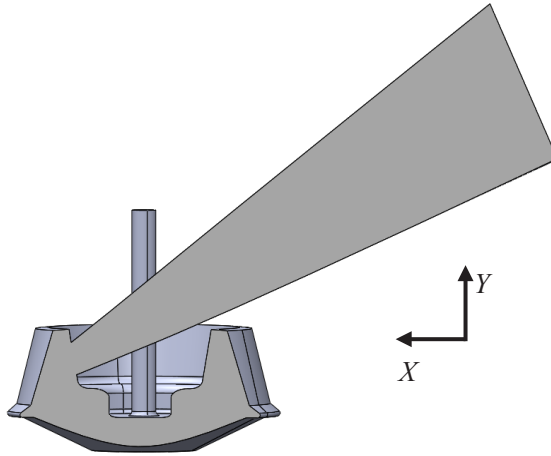


Fig. 4. Vertical section of transport channel at $Z= 8.5$ mm

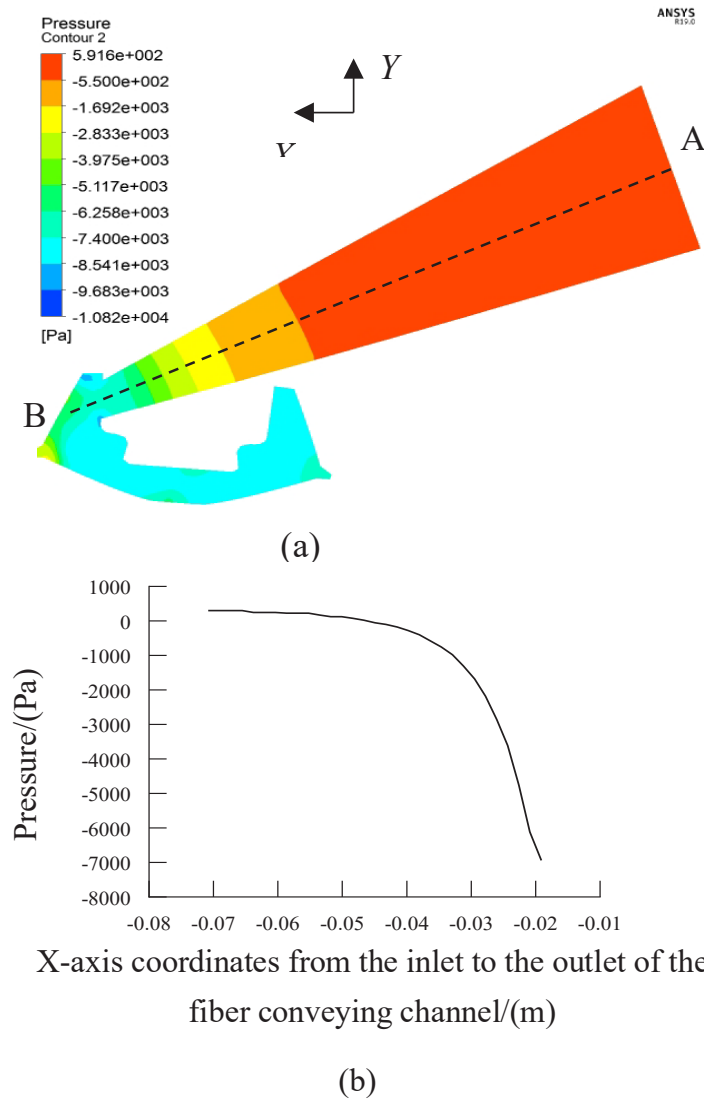


Fig. 5. Pressure on the AB line segment on the $Z=8.5$ mm vertical section of the fiber transport channel. (a) Pressure values from simulations, (b) data obtained from the A-B line

3. Simulation analysis of fiber movement in the spinning unit

In this study, the movement of fiber in the fiber transport channel and rotor was simulated. Furthermore, the movement principle of the fibers in the rotor-spinning channel was analyzed.

3.1. Pressure and velocity of the airflow in the fiber transport channel

In this study, the section of the unit at $Z=8.5$ mm was selected, shown in Figure 4, to explore the pressure distribution in the fiber transport channel. An auxiliary line AB was made at the cross section of the inlet-outlet of the fiber transport channel, as shown in Figure 5. Furthermore, the pressure value on AB was extracted as a data line. As shown in Figure 5(a), the pressure decreases continuously from the inlet to the outlet of the fiber transport channel. From Figure 5(b), it can be observed that the pressure at the inlet is +591.6 Pa and that at the outlet – 7400 Pa. Moreover, the slope of the curve indicates that the rate of pressure reduction increases with the proximity of the outlet. This pressure gradient variation is conducive to fiber extension and transport to the rotor.

As shown in Figure 6, the velocity of the airflow in the fiber transport channel exhibits a gradient trend. The curve in Figure 7 was obtained by extracting the airflow value at line AB from a section of the fiber transport channel. This indicates that the airflow in the fiber transport channel accelerated from the inlet to the outlet. The airflow velocity at the outlet of the fiber transport channel reached a maximum value of 118.4 m/s. After the collision with the rotor wall, it decreased slightly.

3.2. Motion simulation of fibers in the fiber transport channel

- (a) $t=0.0001$ s (b) $t=0.0003$ s.
 (c) $t=0.0005$ s (d) $t=0.0007$ s
 (e) $t=0.0009$ s

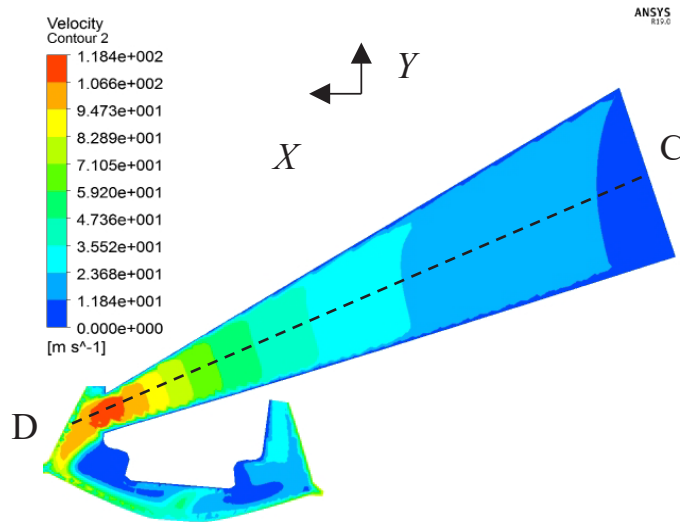


Fig. 6. Speed distribution of fiber channel at the $Z=8.5$ mm section

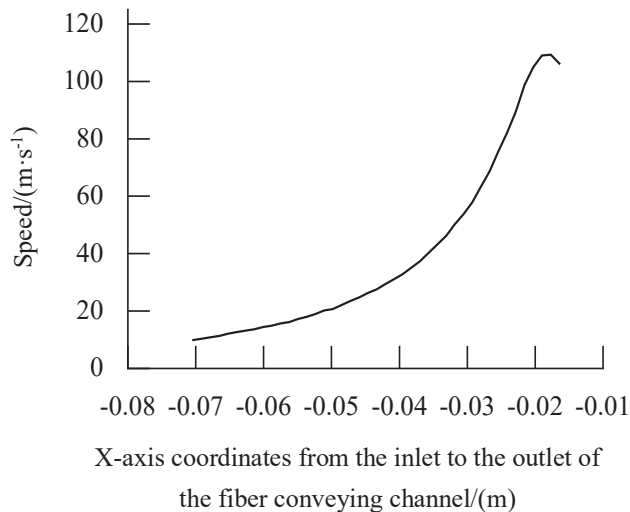


Fig. 7. Airflow velocity distribution on CD line section at the $Z=8.5$ mm section of the fiber transport channel

Figure 8 shows the motion of fibers in the fiber transport channel. As shown in Figure 8 (a), the fibers were relatively dense. When the fiber entered the fiber transport channel, the influence of the airflow on the fiber speed was small. The speed of each fiber was the same as that of the mark ruler. As shown in Figure 8 (b), at $t=0.0003$ s, the fiber moved along the lower wall of the fiber transport channel. The pressure and velocity gradients of the airflow change (as shown in Figure 4 and Figure 6), which increases the speed of the fiber in the fiber transport channel. The speed of each fiber was different because of the inconsistent speed changes of the fibers.

Therefore, in Figure 8 (c), the distance between the fibers is relatively dispersed at $t=0.0005$ s. In Figure 8 (d), when $t=0.0007$ s, due to the tapered structure of the fiber transport channel, the closer the outlet, the smaller the cross-section, and the fiber moves close to the lower wall of the fiber transport channel. As shown in Figure 8 (e), the fibers completely flowed out of the fiber transport channel. Because a part of the fiber collided with the wall of the rotor, its speed was reduced. The speed ranges of the fibers in each period, depicted in Figure 8, are listed in Table 1. At $t=0.0001$ s, the minimum fiber speed is 25.1 m/s, and the maximum fiber speed is 84.2 m/s at $t=0.0007$ s.

Time/(s)	Speed/ $\square\text{m}\cdot\text{s}^{-1}\square$
0.0001	25.1
0.0003	28.4~41.0
0.0005	52.1~60.4
0.0007	53.6~84.2
0.0009	24.2~79.5

Table 1. Speed of fiber at different moments

3.3. Motion simulation of fiber in the rotor

The fiber enters the rotor from the fiber transport channel, slides into the collection groove after being impacted by the rotor wall, and rotates with the rotor. With an increase in the number of fibers in the collection groove, a fiber strip is finally formed, and a twist is added to the stripe owing to the high-speed rotation of the rotor, along with the yarn drawing out through the yarn guide tube.

As shown in Figure 9, the fiber speed ranged from 85.9 m/s to 89.6 m/s. The speed of the fiber at the junction of the fiber transport channel outlet and the slip surface of the rotor is low, with a distribution range of 85.9–86.7 m/s, as shown by circle 1 in Figure 9. The fibers flowing out of the fiber transport channel collide with the rotor wall and are deformed. In this process, part of the kinetic energy is converted into elastic potential energy, and the speed is reduced. The fiber entering the rotor is driven by high-speed rotating airflow and gradually accelerates to 89.6 m/s, as indicated by circle 2 in Figure 9.

As shown in Figure 10, the direction of the fiber speed in the collection groove of the rotor was the same as that of the rotor.

As shown in Figure 11, the speeds of the 30 fibers were inconsistent. In a high-speed rotating rotor, the air velocity is unstable because of turbulence, resulting in different speeds of the fibers under the airflow. Maintaining a stable airflow field within the rotor spinning channel during the spinning process is crucial for improving yarn stability, reducing breakage, and ensuring high-quality yarn.

As shown in Figure 12, the rotational kinetic energy of the 30 fibers was

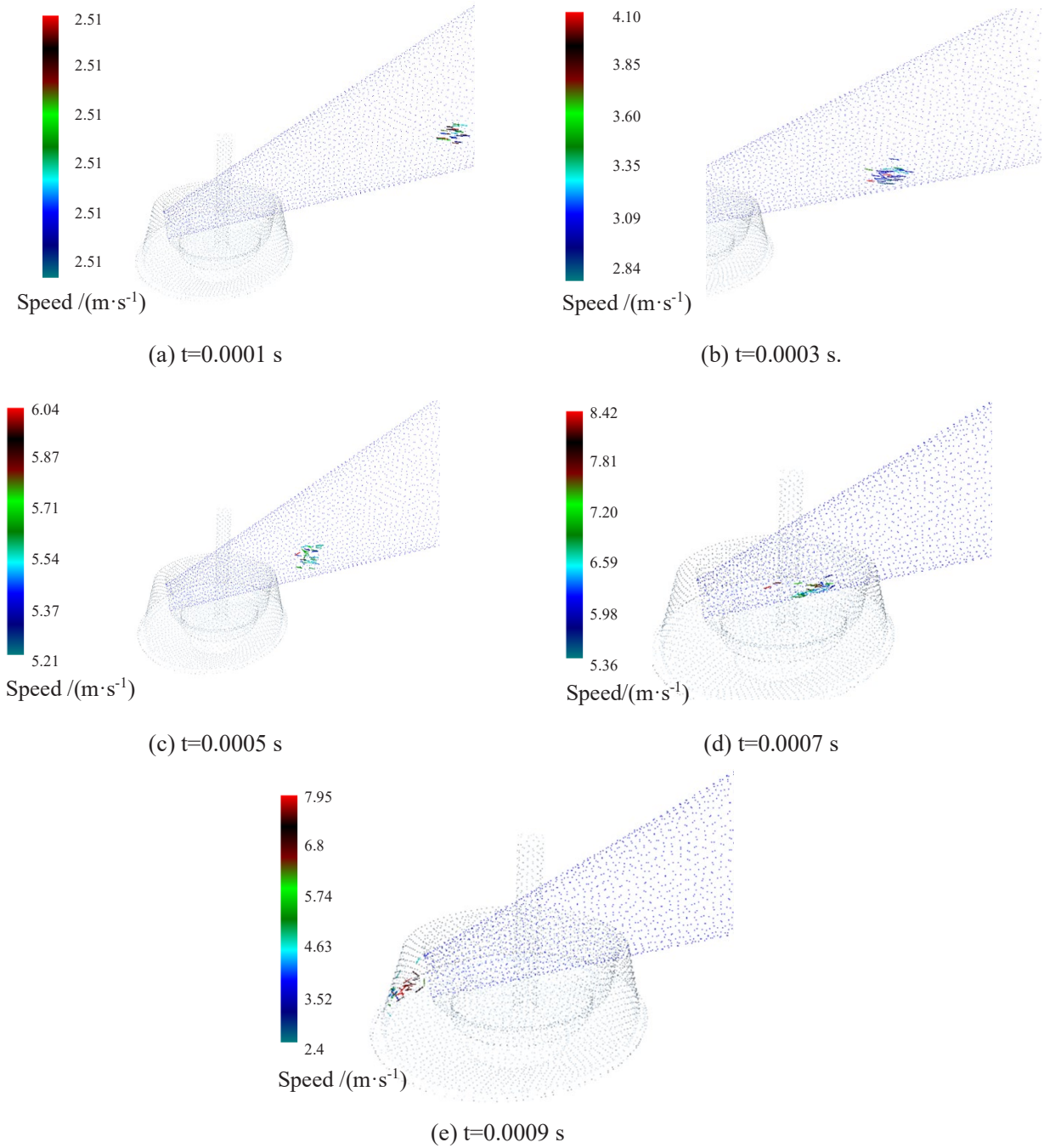


Fig. 8. Fiber movement in the fiber channel

distributed in the range of 2.65×10^{-9} to 3.04×10^{-9} J. The rotational kinetic energy of most fibers was 3.04×10^{-9} J, while a small percentage of the fibers had rotational kinetic energies ranging from 2.65×10^{-9} to 2.98×10^{-9} J, as shown in Figure 13. The difference in the rotational kinetic energy between the fibers was caused by the instability of the airflow in the rotor. The difference in the rotational kinetic energy between each fiber was small, which indicates that the airflow

stability in the rotor was good during the simulation process.

As shown in Figure 14, the stress range of 30 fibers falls between 1.17×10^{-3} N and 1.22×10^{-3} N. The stress values of the fiber and corresponding fiber number are shown in Figure 16. It can be observed that the fiber stress depends on the unevenness of the velocity and pressure in the rotor, as well as on the time at which each fiber enters the rotor. The uneven

force of the fibers reflects the complexity of the fiber condensation mechanism in a high-speed rotating rotor. The total stress direction of the fiber points along the rotor axis is shown in Figure 15. This force distribution aids in the transfer and stripping of fibers at the bottom of the rotor, which is a necessary condition for yarn formation.

The total energy of the fibers in the rotor is in the range of 9.67×10^{-6} J to

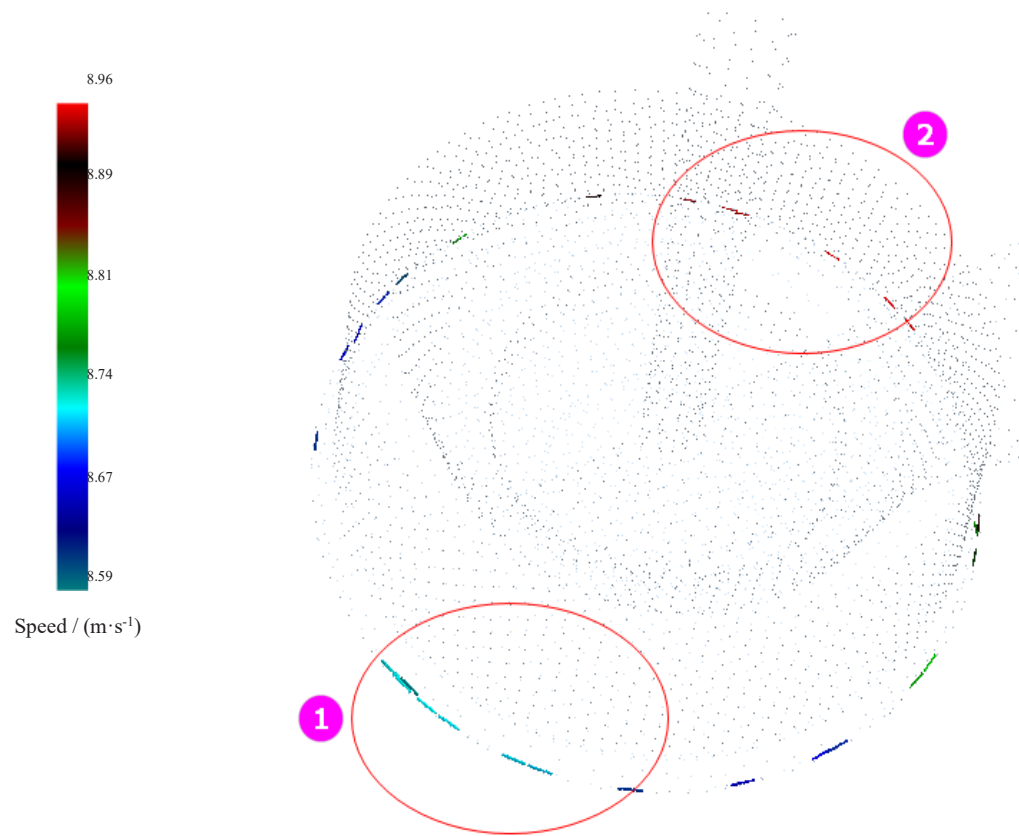


Fig. 9. Fiber velocity in the rotor collecting groove

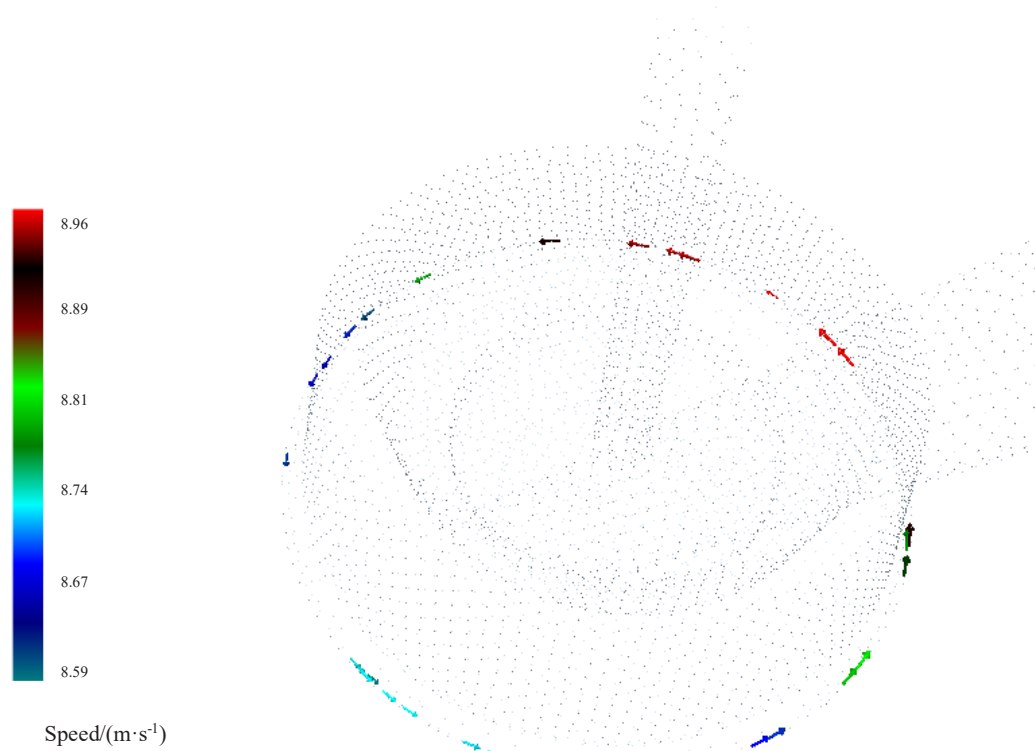


Fig. 10. Vector illustration of the speed of fiber in the collecting groove

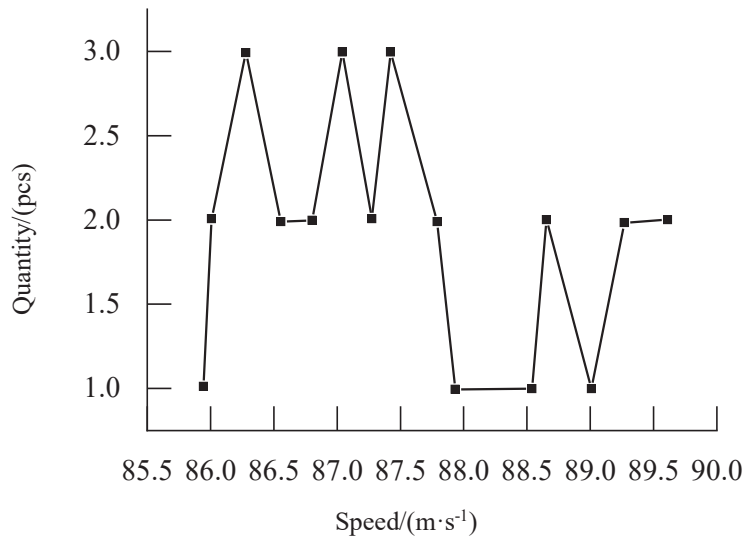


Fig. 11. Fiber speed-quantity distribution graph

10.5×10^{-6} J, as shown in Figure 17. The fiber energy near the junction between the rotor wall and the outlet of the fiber transport channel is within the range of 9.67×10^{-6} J to 9.84×10^{-6} J, as shown in the circle of Figure 7. According to the kinetic energy formula $E = 1/2mv^2$, the kinetic energy is proportional to the square of the velocity. The fiber collides with the wall of the rotor after exiting the fiber transport channel, which results in a reduction in its speed (as illustrated in Figure 9), and consequently, its kinetic energy. To prevent fiber accumulation at this location, it is necessary to select a reasonable slip angle for the rotor wall and an inclination angle for the fiber transport channel to ensure that the spinning process is successful.

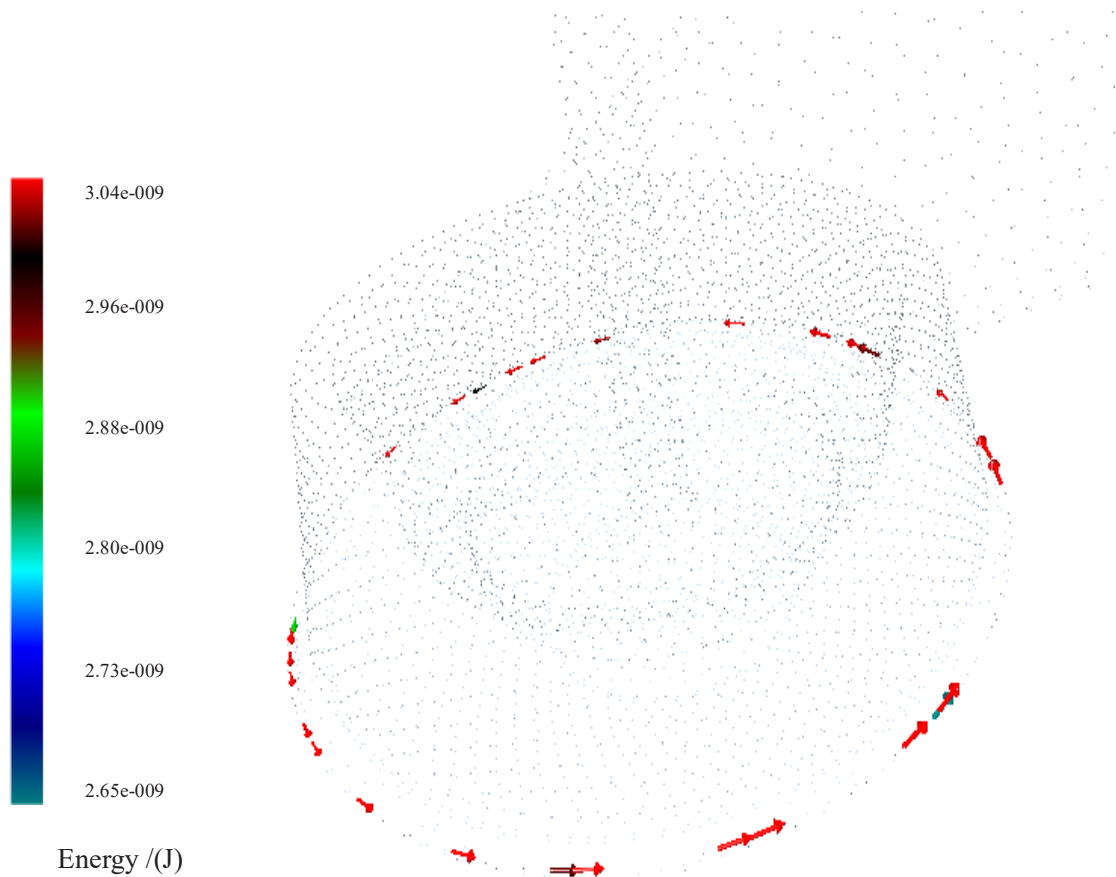


Fig. 12. Fiber rotation kinetic energy vector

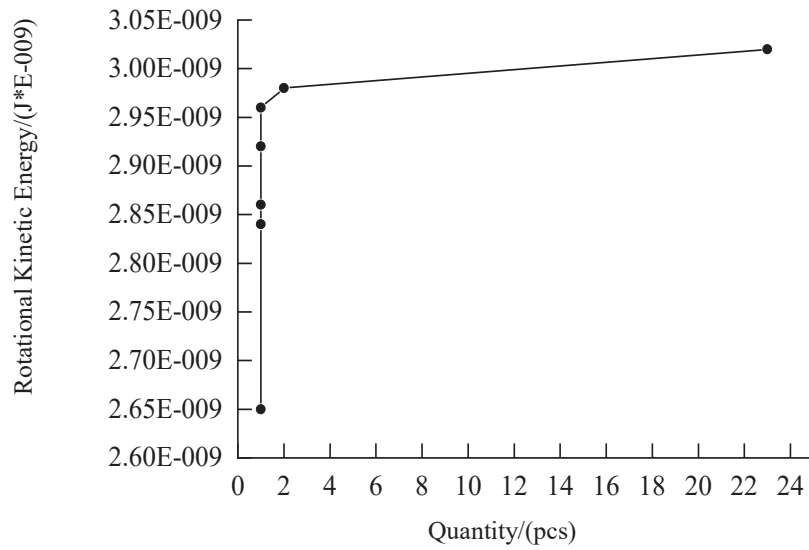


Fig. 13. Fiber rotational kinetic energy-quantity distribution diagram

The speeds of the airflow and fibers in the time segment from 0.0001 s to 0.0015 s in the fiber transport channel are shown in Figure 18. The speed of the airflow in the fiber transport channel is consistently greater than that of the fiber, which promotes the extension of the fiber and can improve yarn quality.

4. Conclusions

In this study, the fluid mechanics method was used to study the motion characteristics of flexible fibers in the airflow field of a high-speed rotating rotor, offering a theoretical foundation for the yarn-forming mechanism of rotor spinning. By utilizing Fluent19.0 and

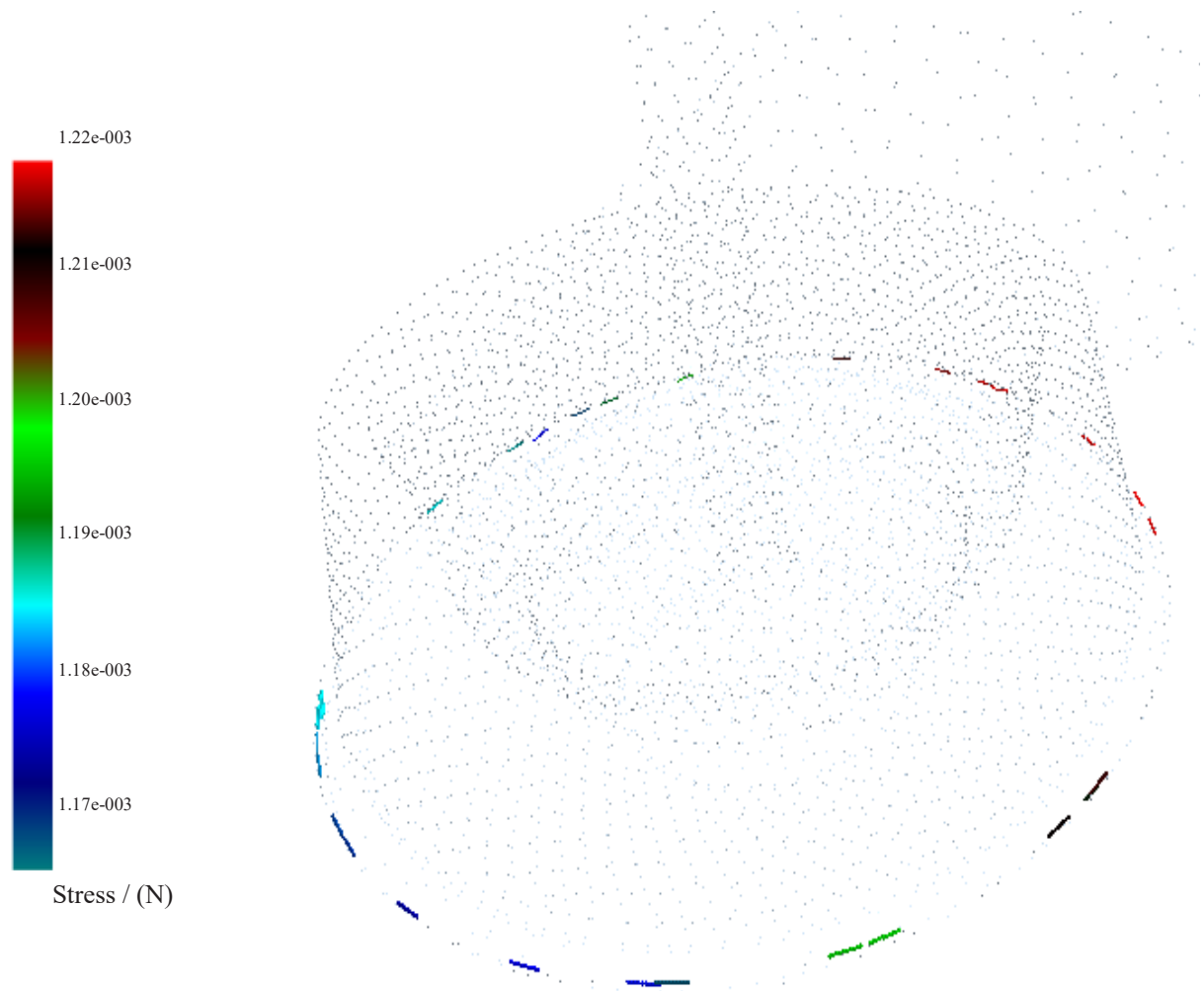


Fig. 14. Fiber stress in the rotor

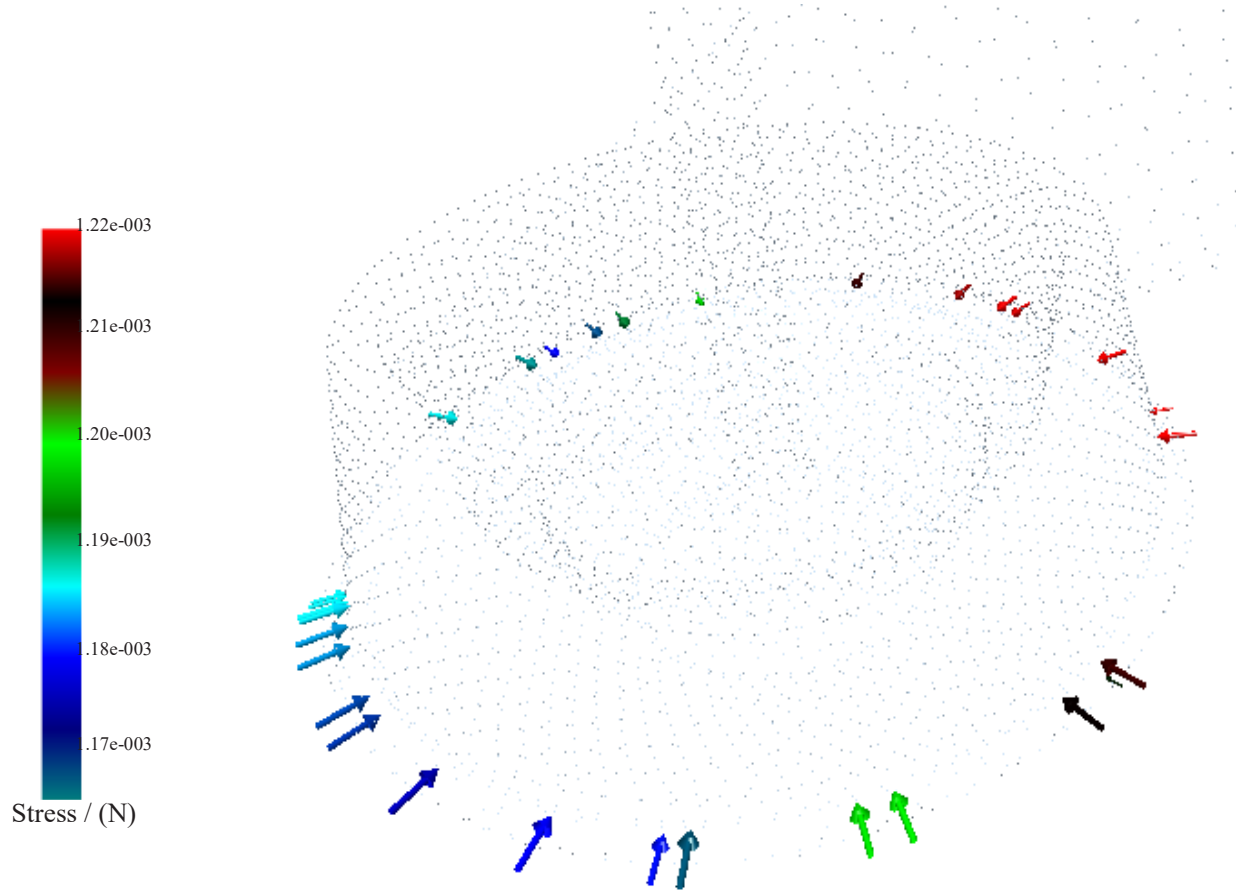


Fig. 15. Stress vector distribution of fiber in the rotor

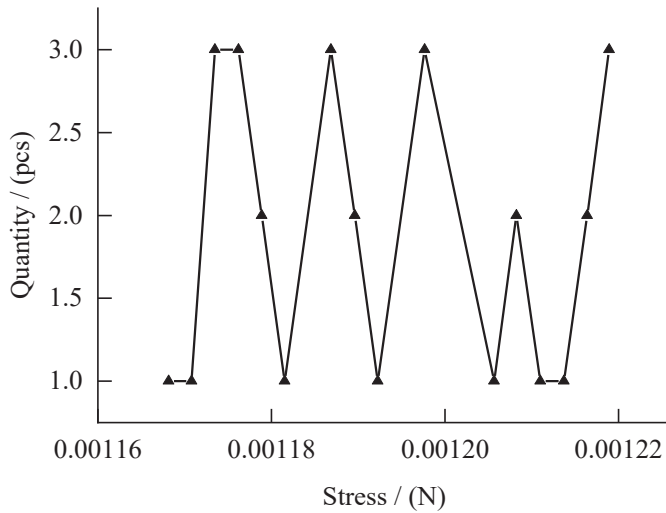


Fig. 16. Fiber stress and its quantity distribution diagram

EDEM2018 coupling software along with the standard $k-\varepsilon$ turbulence model and Hertz-Mindlin (No Slip) model, the motion of fibers in the rotor and fiber transport channel were analyzed.

The fiber speed is accelerated in the fiber transport channel. The speed of fiber is 25.1 m/s at the inlet of the fiber transport channel and 84.2 m/s in the collection groove. However, the speeds

of the different fibers do not change at the same time. This leads to further differences in fiber speed and diversity in the morphology of the fiber heads.

Pressure and velocity gradients exist in the airflow in the fiber transport channel. The speed of the fiber accelerates in the fiber transport channel, and the speed of the airflow in the fiber transport channel consistently exceeds that of the fiber, which is conducive to fiber straightening and transportation, and is good for improving the quality of the yarn.

Simulation of the motion of fibers in a high-speed airflow during rotor spinning provides a theoretical basis for further optimizing the design of the spatial geometric position between the fiber transport channel and rotor wall, weakening the shock of airflow-wave, and reducing the accumulation of fibers in the rotor when they have just arrived at the wall of the rotor.

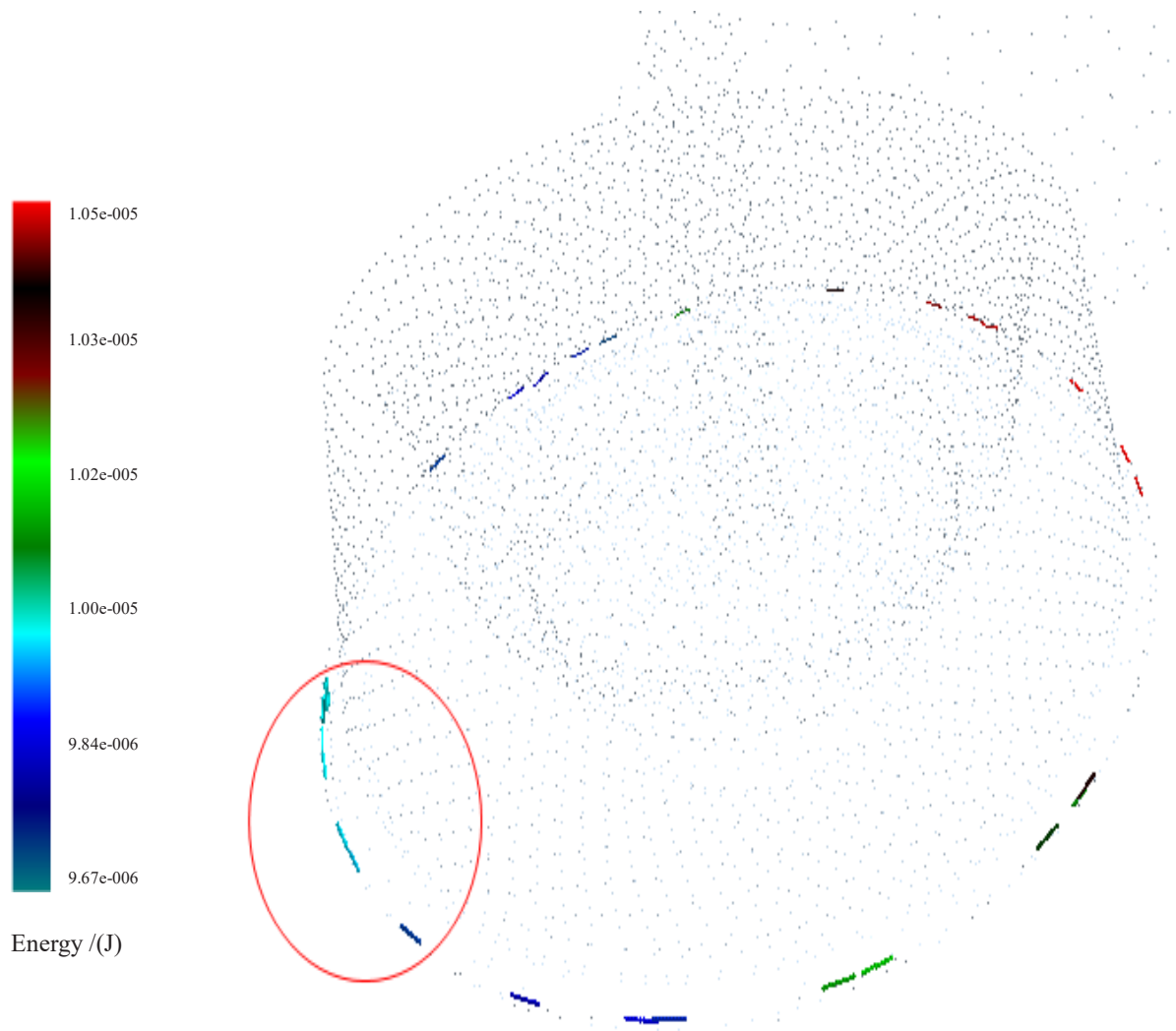


Fig. 17. Energy distribution of fibers in the rotor

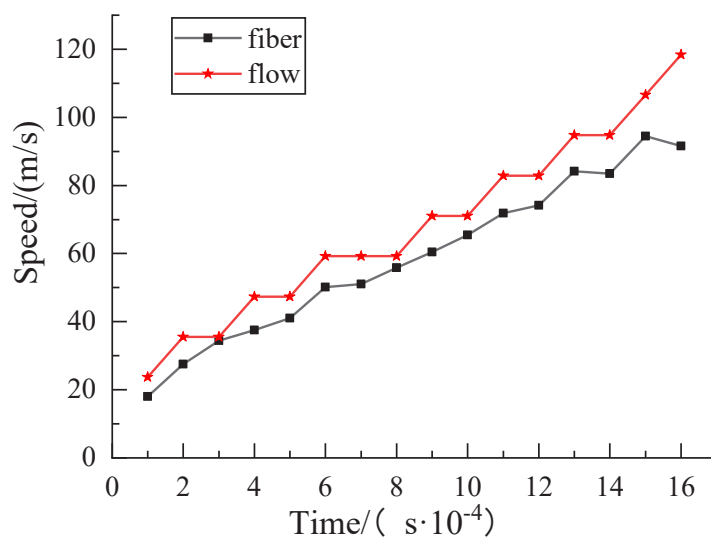


Fig. 18. Speed of fiber and airflow at different moments in the fiber transport channel

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