STUDY THE EFFECT OF PRESSURE ON AIRFLOW FIELD IN VORTEX SPINNING NOZZLE BY NUMERICAL SIMULATION

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ABSTRACT

Vortex spinning technology is with the help of high speed swirling airflow to twist fibers with open ends to form the yarn. Spinning parameters, such as nozzle pressure, has a great effect on yarn properties. In this study, different nozzle pressures were researched through spinning experiments, in addition, the homologous three- dimensional computational fluid dynamics model of the nozzle was built to simulate the numerical calculation of the airflow in vortex spinning nozzle. Realizable *k-epsilon* model was used to simulate the turbulence of airflow in the nozzle. Unstructured tetrahedral grids which are suitable for airflow with wall effects and complicated boundary layers were adopted to divided grids in the computational area. The computational model of the airflow field was solved and the characteristics of airflow in vortex spinning nozzle was obtained. Through the results of numerical simulation, the corresponding airflow field within the nozzle was analyzed which provides reference for setting of spinning parameters. The numerical simulation results show that the velocity vector and the static pressure increase with the nozzle pressure, the principle of the swirling airflow is decided by the pressure distribution, a large negative pressure with appropriate axial and tangential velocity within the nozzle is conducive to the generation of the fibers with open ends and the twist. Spinning experiment results showed that the optimum nozzle pressure is 0.5-0.6Mpa, which shows a good agreement with the numerical simulation results.

INTRODUCTION

Vortex spinning is with the help of high speed rotating airflow in the vortex tube to twist fibers to form the yarn [1]. It's a new spinning technology developed from air-jet spinning and improved in aspect of yarn property and flexibility of fiber materials [2]. High speed with short process, less hairiness, good resistance to pilling, better moisture absorption and release, and so on [3], are the prominent advantages of vortex spinning. Vortex spinning nozzle has a significant effect on the spinning processing and the yarn quality. Investigations have been carried out extensively and experimentally to study the characteristics in different types of swirling airflows to gain insight phenomena with the development of computer technology [4-9]. A reasonable agreement between CFD (computational fluid dynamics) predictions and experimental recorded flow characteristics were obtained in the studies of Sadiki A. and Wegner B. [10,11]. Oh et, al. [12] numerically studied the supersonic airflow within the main nozzle of the air jet loom. They derived the distribution of airflow pressure and velocity within the main nozzle and optimized the structure parameters of the nozzle. Rwei et, al. [13] numerically modeled the airflow field within the air texturing nozzle and analyzed the influence of parameters on air deformation of the nozzle. Zeng and Yu [14] obtained the characteristics of air flow within the first nozzle of air-jet spinning and studied the effect of airflow on fiber motion principle. Ulku [15] investigated experimentally the effect of some parameters on the structure and properties of vortex yarns. Computational fluid dynamics (CFD) software was used by many researchers [16-19] to simulate the three-dimensional numerical models for the airflow characteristics of vortex spinning nozzle, the stress field and the velocity field within the nozzle were obtained and analyzed in their studies. In this paper, three-dimensional computational fluid dynamics models were built to carry out the numerical simulation of the airflow in vortex spinning nozzle, spinning experiments were used to verify the simulation results. This study can provide a certain reference for setting up the nozzle pressure. Because the vortex yarn is usually hard, it is a compensation for the softness characteristics of viscose yarn, therefore, viscose fiber is widely used for vortex spinning, so this paper focuses the spinning parameters on viscose fiber.

NOMENCLATURE

ρ	[kg/m^3]	Air density
v	[m/s]	Fluid velocity vector
τ	[-]	Viscous stress tensor
P	[Mpa]	Air pressure
f	[g]	Gravity
T	[K]	Temperature
k	[W/mK]	Heat conductivity
c_p	[J /kgK]	Specific heat capacity
S_T	[%]	Viscosity dissipation rate

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NUMERICAL MODELING

Governing Equations

Realizable k-ε model is suitable for high Reynolds number, and can better simulates the jet flow, the pipe flow and the swirling airflow [20]. Reynolds number of the airflow of vortex spinning nozzle is far beyond the boundary value 10^4 [16], so the airflow is the turbulence airflow. Mass conservation equation (1), Navier-Stokes equation (2) and energy conservation equation (3) are the governing equations and were adopted in this paper:

$$\mathrm{div}\left(\rho\,\mathbf{v}\right)=0 \qquad (1)$$

$$\mathrm{div}\left(\rho\,\mathbf{vv}-\boldsymbol{\tau}\right)=-\mathrm{grad}\,p+\mathbf{f} \qquad (2)$$

$$\mathrm{div}\left(\rho\,\mathbf{v}T\right)=\mathrm{div}\left(\frac{k}{c_p}\,\mathrm{grad}\,T\right)+S_T \qquad (3)$$

Computation Area

Four main components of vortex spinning nozzle: guided body, vortex tube, cone body and doffing tube, are showed in Figure 1. The guided body plays the role of agglomeration and guide; the vortex tube is a major part for yarn twisting ; the cone body plays a supporting role on yarn twisting; the doffing tube is associated with the yarn drawing-in. Computation area is showed with blue shading in Figure 1. The parameters of the nozzle structure are set as following: jet orifice number of the vortex tube is 5, with diameter 0.5 mm; jet orifice number of the doffing tube is 5, with diameter 0.3 mm; the guided needle length is 1 mm, and the distance between guided body and jet orifice outlet d is 1 mm.

Three-dimensional computation region (the computational model) corresponding to the three-dimensional airflow field inside the nozzle is showed in Figure 2. In Figure 2, Z is pointing in the yarn outlet axial direction, while, X and Y are increasing in the outward radial direction following a right-handed Cartesian coordinate system. In this study, the following four sections will be focused: Z-Z section, S1-S1 section, S2-S2 section, and S3-S3 section, which are labeled in Figure 2. S1-S1 section is the cross-section on jet orifice outlet; S2-S2 section is the cross-section on guided needle tip, it is very close to the jet orifice outlet; S3-S3 section represents expanding export between the vortex tube chamber and the cone body.
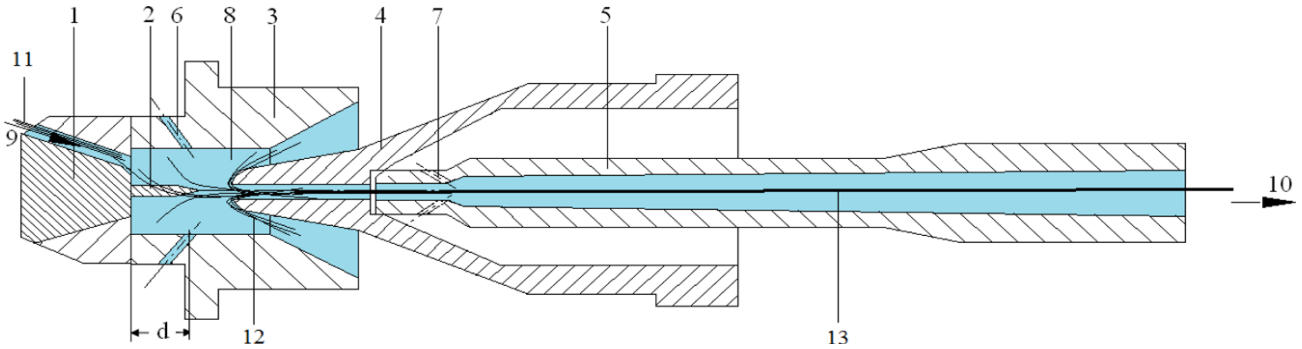
1-guided body; 2-guided needle; 3-vortex tube; 4-cone body; 5-doffing tube; 6-jet orifice of vortex tube; 7-jet orifice of doffing tube; 8-twisting chamber; 9-fiber inlet; 10-yarn export; 11-drafted fiber bundle; 12-open-end trailing fibers; 13-resultant yarn; d-distance between guided body and jet orifice outlet

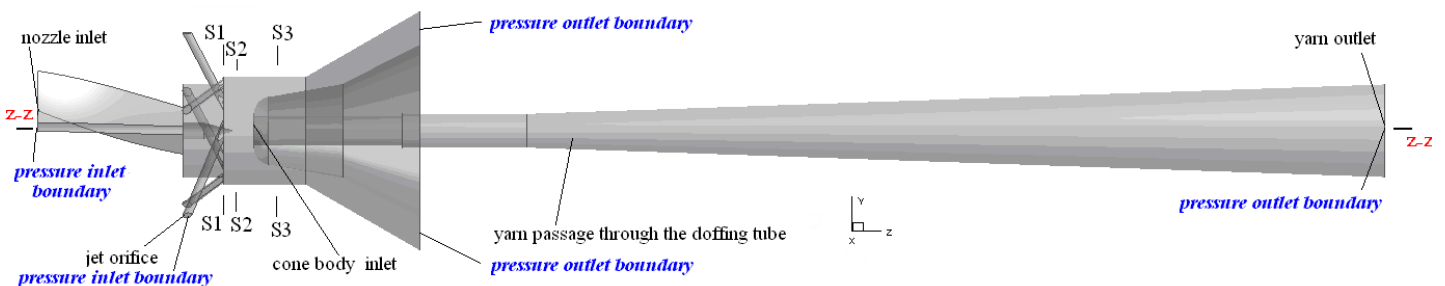**Figure 1** Cross-sectional view of nozzle structure

Figure 2 Three-dimensional computation region (the computational model) corresponding to the

three-dimensional airflow field inside the nozzle

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Computational Grid

The inner structure of vortex spinning nozzle is complicated and the interior space is small, therefore, unstructured tetrahedral grids which are suitable for airflows having wall effects and complicated boundary layers were adopted. Based on grid independent tests, a grid size of 1084596 tetrahedral cells is adopted, therefore, the computational grid of airflow field in vortex spinning nozzle is showed in Figure 3. The grids of the jet orifices and the twisting chamber in vortex tube were refined (as shown in Figure 4).
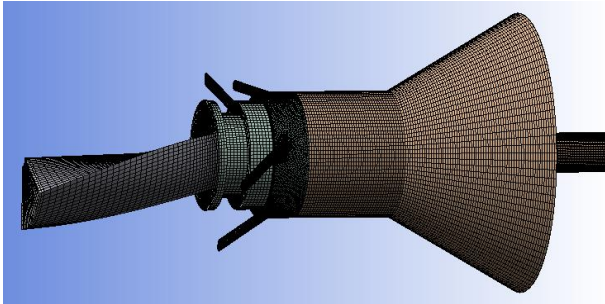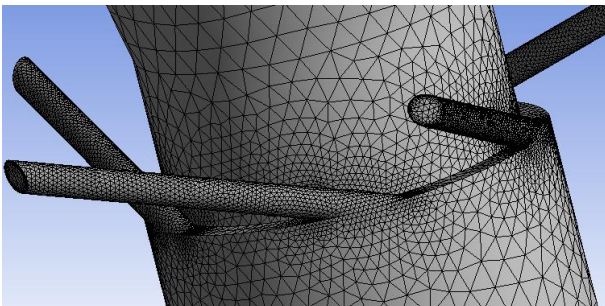

Figure 3 Computational grids

Figure 4 Refinement grid of jet orifice

Boundary Conditions

The boundaries of the three-dimensional airflow field inside the nozzle as shown in Figure 2.

Pressure inlet boundary:

a. jet orifice inlet: the pressure is 0.6, 0.5. 0.4MPa, respectively;

b. nozzle inlet: the pressure is set as atmospheric pressure;

Pressure outlet boundary:

a. doffing tube outlet: the atmospheric pressure is prescribed for the pressure;

b. cone body outlet: the atmospheric pressure is prescribed for the pressure;

A value of 5% is considered for the turbulence intensities in the flow inlet and outlet. The pressure loss range is10~15% in this study.

Solid wall: following the no-slip boundary condition; wall-function method was adopted in this study, because of the first node was arranged within the scope of the logarithmic law layer (namely, the first node was configured to the strong turbulent area) when meshing the grids, the range of Y+ was 60~100.

Numerical Solver

The pressure-based methodology has shown more appropriate predictions in case of airflow field in vortex tube [16]. Therefore, in this study, the implicit pressure-based algorithm included in the flow simulation package designated ANSYS FLUENT® V16.0 (2015) was adopted. On the base of the simulation results, velocity field and pressure field within the nozzle were analyzed.

Grid independency test

Keep the number of the near wall grids fixed, the number of the other grids increase with the law of $\sqrt{2}$ times. Take the velocity of S2-S2 section and ±4mm away from this section as an example. We selected 3 sets of grids: coarse (1084596), fine ($\sqrt{2}$ ×1084596), very fine (2×1084596) to conduct the grid independency test, the result can be seen in Figure 5. From Figure 5, we can see that the grid density has a little influence on the velocity result, in order to reduce the amount of calculation, 1084596 was selected in this study to carry out the simulation.
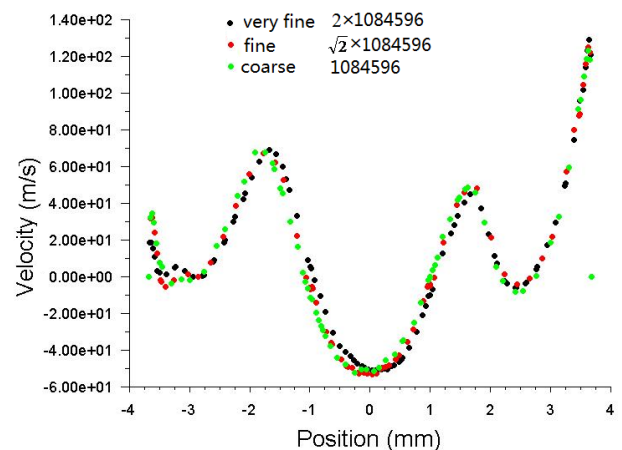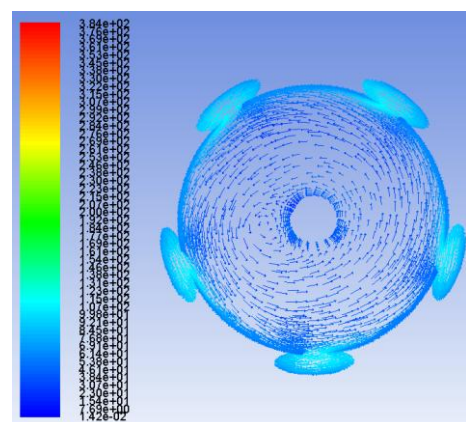

Figure 5 Grid independency test result

Numerical Simulation Results

In vortex spinning, the nozzle pressure plays an important role in the yarn twisting, the greater the nozzle pressure, the higher the rotational airflow speed formed, therefore, the greater the yarn twist [21]. In order to reduce the amount of calculation, three nozzle pressures, 0.4Mpa, 0.5Mpa and 0.6Mpa, were selected to conduct the numerical simulation in this paper.
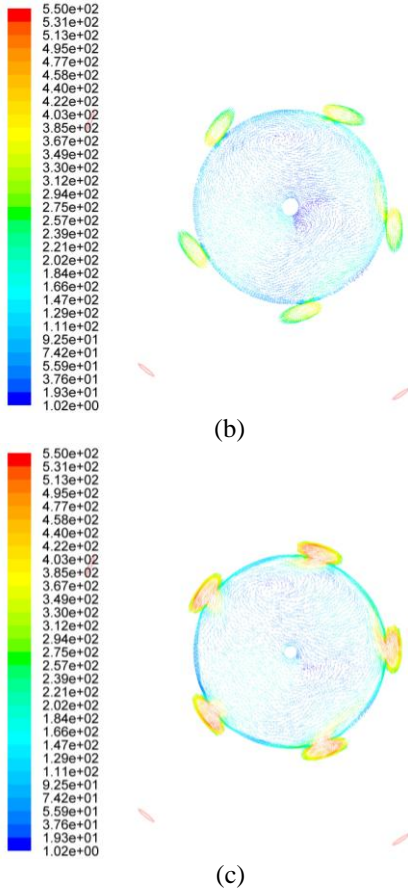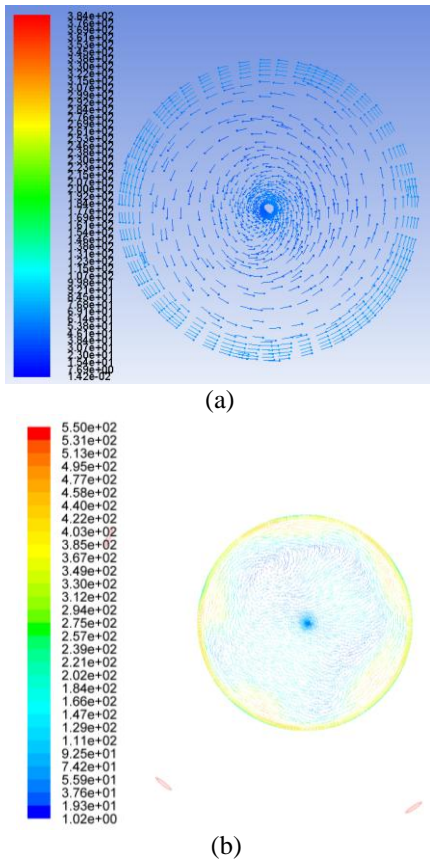

(a)

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(b)

(c)

Figure 7 (a)-(c) The view of the velocity vector (m/s) of cross-section S2-S2 when nozzle pressures are 0.4Mpa, 0.5Mpa and 0.6Mpa, respectively

(c)

Figure 6 (a)-(c) The view of the velocity vector (m/s) of cross-section S1-S1when nozzle pressures are 0.4Mpa, 0.5Mpa and 0.6Mpa, respectively

(a)
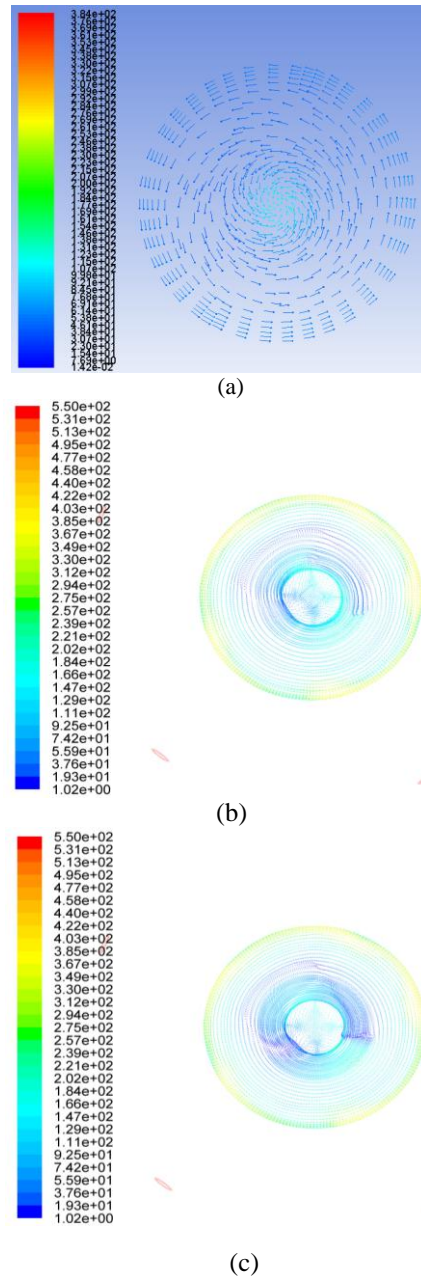

(a)

(b)

(b)

(c)

Figure 8 (a)-(c) The view of the velocity vector (m/s) of cross-section S3-S3 when nozzle pressures are 0.4Mpa, 0.5Mpa and 0.6Mpa, respectively

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Generally, vector is expressed by the arrow with different colors and length. The swirling airflow in the nozzle could be decomposed into axial direction, radial direction and tangential direction. The axial velocity is conducive to the fiber movement, the radial velocity associates with the separation and aggregation of the fibers, and the tangential velocity decides the number of the twist of the resultant yarn [22].

This paper focuses on the velocity in three cross-sections, S1-S1, S2-S2 and S3-S3. In order to more specifically express the direction of the velocity, i.e., the positive direction of the axial velocity is the direction of the yarn movement, i.e, the direction of the yarn outlet.

In the radial velocity, most of the area within the vortex tube is positive, which is conducive to the fiber separation to form the free-end fibers. With the increase of the radial velocity, the degree of the fiber separation is higher, and the wrapped fibers are more. From the simulation results (Figure 6-8), we can see that the maximum airflow velocity has reached to the supersonic speed. In the area of vortex tube above the doffing tube, the direction is both positive and negative, that is to say, this area has a certain vortex flow.

From Figure 6-8, we can also see that the airflow field is divided into two regions --- external region and internal region based on the flow characteristics and its function. In addition, with the increase of the pressure, the velocity vector of cross-sections S1-S1,S2-S2 and S3-S3 increase.


(a)

(b)
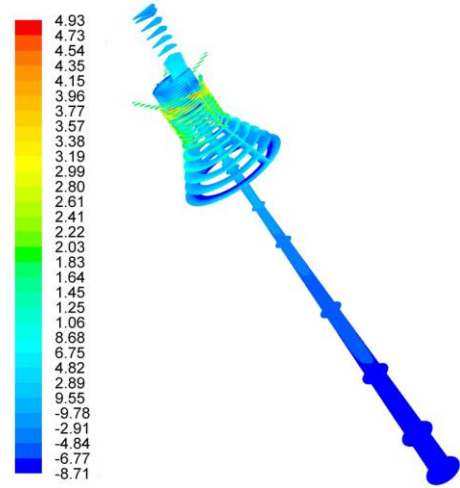
(c)

Figure 9 (a)-(c) The view of pressure field (10^5Pa) of cross-sections along Z-Z axis in the nozzle when pressures are 0.4Mpa, 0.5Mpa and 0.6Mpa, respectively

Figure 9 shows the distribution of static pressure along Z-Z axis cross-sections when pressures are 0.4Mpa, 0.5Mpa and 0.6Mpa, respectively. The static pressure of airflow in the jet orifice area within the nozzle is relatively high. The closer the jet orifice outlet, the lower the airflow static pressure value, the airflow static pressure value reaches the minimum at the outlet of jet orifice.

From Figure 9, we can also see that the static pressure of the airflow is mostly less than the atmospheric pressure, so the pressure in the nozzle is mostly negative, in addition to the inner regions of jet orifices and twisting chamber. Because of the existence of the negative pressure within the nozzle, the fibers is sucked into the nozzle. In the larger diameter area in the nozzle, the static pressure value of airflow is close to the atmospheric pressure, but the pressure value reduces rapidly within a short distance in the link area of large diameter and small diameter sections. And from Figure 9 (a) - (c), we can see that the static pressure increase with the increase of the pressure.
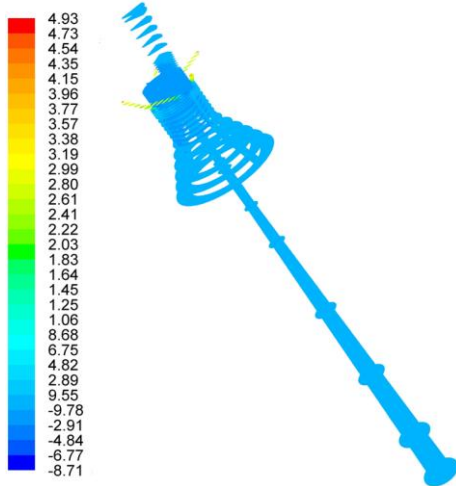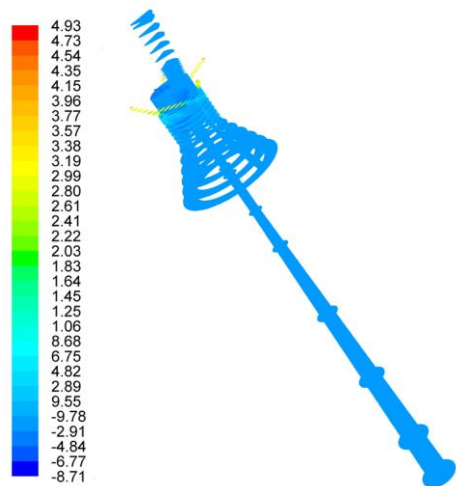
SPINNING EXPERIMENTS

Experimental Preparation

In this research, viscose fiber is used with the length×fineness of 38mm×1.22dtex, the weight of sliver used for spinning experiments is 3.0g/m, strength of fiber is 2.32cN/dtex, elongation of fiber is 20.89%.

The yarn tenacity was tested by Uster Tensorapid. Yarn irregularity performance was tested by Uster Tester 3. Hairiness was measured by Uster Tester 4. Test environment: temperature: 20±2 ℃; humidity: 65±3%.

The quality indicators of vortex spinning yarn: tenacity, coefficient of variation of tenacity, irregularity of yarn (CV_m), hairiness (s3) and so on.

In the experiments, the spinning apparatus was a Murata 861 machine, spinning speed is kept as 320m/min, total draft is 150, the resultant yarn is 20tex.

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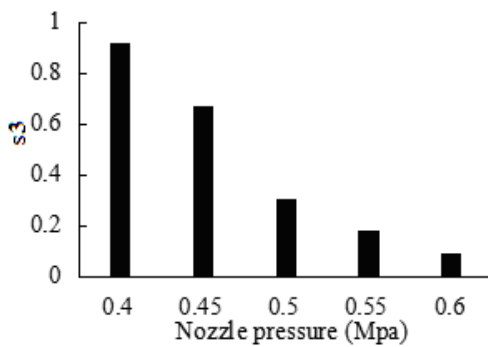**The effect of nozzle pressure on yarn properties**

In vortex spinning, the nozzle pressure plays a very important role in the yarn twisting, the greater the nozzle pressure, the higher the vortex speed formed by rotational airflow, therefore, the greater of the yarn twist. Five nozzle pressures, 0.4Mpa, 0.45Mpa, 0.5Mpa, 0.55Mpa and 0.6Mpa, were selected to conduct the spinning experiments.
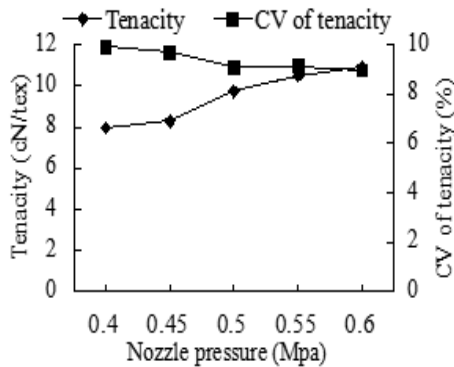
(a) Tenacity and its coefficient of variation
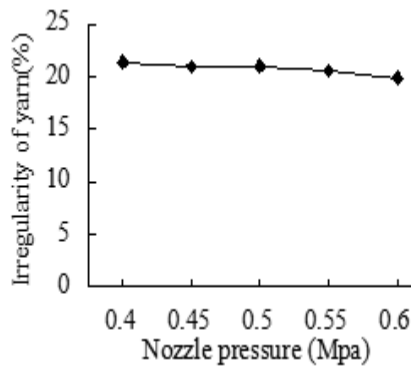
(b) Irregularity of yarn (CV_m)

(c) s3

Figure 10 Effect of nozzle pressure on pure viscose yarn performance

As illustrated in Figure 10, with the increase of nozzle pressure, the yarn tenacity increases, coefficient of variation of tenacity decreases gradually. This is because with the nozzle pressure increases, the speed of rotational airflow increases. In addition, the airflow speed inside the nozzle is divided into three directions: tangential airflow along the inner wall of the vortex tube which is used to twist the yarn; the radial airflow toward to yarn core which is in favor of the yarn body wrapped tightly; the axial airflow, the direction is

same with the yarn output, is in favor of in-taking yarn strands. The higher the nozzle pressure, the bigger the airflow velocity in three directions, and consequently the higher the yarn twists, the tighter the yarn wrapped. As the nozzle pressure increases, the irregularity of yarn (CV_m) reduces, and hairiness decreases. Therefore, the best nozzle pressure is 0.6Mpa. While the pressure is in 0.5-0.55Mpa, the qualities of yarn are preferred and almost the same (except the hairiness, s3), from the view of economic benefits or cost, the pressure can also be set at 0.5-0.55Mpa. Above all, the nozzle pressure is set at 0.5-0.6Mpa.

Spinning experiments were carried out to verify the obtained optimum spinning parameters, the yarn quality test results are shown in Table 1.

Table 1 Yarn quality test results

	Yarns produced with obtained optimum spinning parameters		
Experiment number	1	2	3
Nozzle pressure (Mpa)	0.50	0.55	0.60
CV_m (%)	20.27	20.19	19.98
-50% thin (number/km)	340	320	300
+50% thick (numbe/km)	560	560	510
+200%nep (number/km)	610	630	780
CV of tenacity (%)	8.07	9.12	8.60
Tenacity (cN/tex)	9.47	9.59	9.63
Elongation (%)	12.26	12.24	12.43
Work of fracture(mJ)	33.57	32.99	33.92
s3	0.40	0.08	0.04

CONCLUSIONS

Different nozzle pressures were studied by spinning experiments, and the corresponding three- dimensional computational fluid dynamics model was built to conduct the numerical simulation of the airflow in the vortex spinning nozzle. The numerical simulation results show that the velocity vector and the static pressure increase with the nozzle pressure, the flow principle of the swirling airflow in the nozzle is decided by the distribution of the nozzle pressure, a large negative pressure with appropriate axial and tangential velocity within the nozzle is conducive to the generation of the open ends fibers and twist. The spinning experiments show that, the greater the nozzle pressure, the bigger the yarn twists, hence the yarn quality is better. Numerical simulation and spinning experiments show a good agreement with spinning experiments. Given the economy or cost, the optimum pressure is 0.5-0.6Mpa in the case of viscose yarn.

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