Numerical Study on the Principle of Yarn Formation in Murata Air-Jet Spinning

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Abstract

A realizable $k$-$\varepsilon$ turbulence model was adopted to study the airflow characteristics inside the two nozzles including the slotting-tube of Murata air-jet spinning (MJS). Actions of the two nozzles and the accepted principle of yarn formation were both discussed. The results show that some factors in the first nozzle, such as weak opposite swirling balloon in upstream of the jet orifice, vortex breakdown in downstream of the jet orifice and opposite direction airflows between the grooves and the twisting chamber, do good to produce longer wrapper fibers and form twist difference between the edge fibers and the core ones. The airflow in the second nozzle rotates in the opposite direction to that in the first nozzle, to untwist the swirling balloon that formed by the first nozzle. On the other hand, simulation results well supported the theoretical analysis of the principle of the yarn formation proposed by Stalder and Krause.

Key Words: Swirling airflow, Fibers, Nozzle, Yarn, MJS

1. Introduction

In the Murata air-jet spinning (MJS), since air is used for twisting, unlike mechanical twisting, there is no limitation in delivery speed caused by twisting. So it is accepted as one of the most promising technologies and can offer advantages in respect of processing speed and cost. At present, there are two points of view on the principle of air-jet spun yarn formation: some researchers [1–3] have suggested that the edge fibers, separated from the main strand, converge with the yarn at a later stage. They are thus twisted in the same direction as the core, but to a lesser extent. These fibers are then twisted in the opposite direction from downstream of the second nozzle, thus forming wrappers. This principle contradicts the one suggested by the manufacturers and Stalder [4], who maintains that the edge fibers wrap the false twisted core in the opposite direction while passing through the first nozzle. Untwisting downstream of the second nozzle produces considerably more twist in these fibers, thus giving the yarn its strength. And the latter principle has been accepted by most researchers including Krause [5]. However, the principle of yarn formation mainly based on theoretical analysis still needs further study.

It is well known that the structure, formation and quality of yarn are closely related to the flow characteristics, so it is important to study the airflows in the nozzles. However, only Yu and Zhang [6] and Zeng and Yu [7] used experimental and numerical methods, respectively, to study 2D airflow characteristics in the first nozzle so far. This cannot show some properties of the swirling flows inside the two nozzles because swirl flow is very complex and exhibits a strong three-dimensional behavior characterized by curved streamlines [8].

Base on the above reasons, the present work is to simulate the flow fields passing through the two nozzles of MJS using the realizable $k$-$\varepsilon$ turbulence model [9]. Simulation results are presented in the third section and the influence of flow characteristics on yarn properties are also discussed. With these works, actions of the two nozzles and the accepted principle of yarn formation are both demonstrated.

2. Theoretical basis

2.1 Nozzle structure

Ignoring the influence of the fibers or strands, airflow in
the nozzle will be a classical fluid flow problem. Normally the first and second nozzles are made cylindrical and diverged conical shapes in spinning process, respectively. Figures 1 and 2 show the profiles of the first nozzle with the slotting-tube and that of the second nozzle, respectively, used in the 3D simulation. And in the two computed zones, Cartesian coordinate systems are used. The origins of the coordinates system are located at the center of the two nozzle inlets. The $z$-axis is taken as the streamwise direction and the $x$-$y$ plane is perpendicular to the $z$-axis (i.e., the nozzle inlet). According to the principle of yarn formation [4, 5] and spinning experiments [10–12], the optimized geometric parameters of the two nozzles are shown in Table 1.

2.2 Governing equations and turbulence model

Since high-velocity compressed air is forced into the twisting chamber through the injectors from the air reservoirs, its Mach number is large (on the range of 0.6 to 0.9) [6], so an inviscid perfect gas flow in the absence of

### Table 1 Specifications of the computed nozzles.

<table>
<thead>
<tr>
<th>Nozzles</th>
<th>Jet length $L$ (mm)</th>
<th>Twisting chamber diameter $D$ (mm)</th>
<th>Orifice diameter $d$ (mm)</th>
<th>Orifice angle $\theta$ (°)</th>
<th>Orifice position $l_1$ (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>First $^a$</td>
<td>33 $^a$</td>
<td>2</td>
<td>0.45</td>
<td>45</td>
<td>11</td>
</tr>
<tr>
<td>Second</td>
<td>33</td>
<td>1.8 $^c$</td>
<td>0.26</td>
<td>86</td>
<td>3</td>
</tr>
</tbody>
</table>

$^a$ the slotting-tube has four-rectangular-groove, and groove’s length $l_2$, depth $h$ and width $w$ are 8 mm, 0.8 mm and 0.3 mm, respectively.

$^b$ the position of the jet orifice is the distance from the nozzle inlet to the jet orifice

$^c$ diameter $D_1$ of the twisting chamber of the outlet in the second nozzle is 4 mm.
body forces is considered. In addition, steady adiabatic flow is also assumed since the nozzle is very short and the twisting process occurs in a very short time. Therefore, the generalized conservation equations are expressed as follows [13]:

\[
\text{div} (\rho V \phi - \Gamma_k \text{grad} \phi) = S_k
\]

(1)

where \( \rho \) is the air density, \( V \) is a velocity vector, \( \phi \) stands for the conserved property, \( \Gamma_k \) is the diffusion coefficient, and \( S_k \) is the source term which is specific to a particular meaning of \( \phi \). And to complete the system of the equations, the equation of state of a perfect gas \( (\rho = \rho T) \) is added.

It is well known that Reynolds stress tensor is unknown and has to be modeled in order to close the Reynolds Averaged Navier–Stokes equations. The standard \( k-\varepsilon \) model is the key representative. However, One of its primary limitations is the assumption of isotropy for the eddy viscosity. Therefore, it is not optimized to simulate the flow in the nozzle because of the anisotropy of the swirl flow [14, 15]. Since one of the noteworthy features is that the coefficient \( C_p \) in the eddy viscosity formula \( (\mu_t = C_p \rho k^2/\varepsilon) \) is a function of mean strain and rotation rates, the angular velocity of the system rotation, and the turbulence fields, the realizable \( k-\varepsilon \) turbulence model [9] has shown substantial improvements on the standard \( k-\varepsilon \) model where the flow features include strong streamline curvature, vortices and recirculation. Hence, the realizable \( k-\varepsilon \) turbulence model is adopted. And the modeled transport equations for \( k \) and \( \varepsilon \) are:

Turbulence kinetic energy \( k \) equation:

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

\[
- \rho \varepsilon - Y_M
\]

(2)

Turbulence rate of dissipation \( \varepsilon \) equation:

\[
\frac{\partial}{\partial x_i} (\rho \varepsilon u_i) = \frac{\partial}{\partial x_i} \left[ (\mu + \frac{\mu_t}{\sigma_k}) \frac{\partial \varepsilon}{\partial x_i} \right] + \rho C_1 S \varepsilon - \rho C_2 \frac{\varepsilon^2}{k + \sqrt{\varepsilon}}
\]

(3)

where \( C_1 = \max [0.43, \eta/(\eta+5)] \) and \( \eta = \beta k/\varepsilon \). And in these equations, \( G_k \) represents the generation of turbulence kinetic energy due to the mean velocity gradients, \( Y_M \) represents the contribution of the fluctuating dilatation in compressible turbulence to the overall dissipation rate. \( \sigma_k \) and \( \sigma_\varepsilon \) are the turbulent Prandtl numbers for \( k \) and \( \varepsilon \), respectively. The constants used in this model are defined as follows [9]: \( C_2 = 1.9, \sigma_k = 1.0, \sigma_\varepsilon = 1.2 \).

2.3 Boundary conditions

The inlet boundary: The airflow in the nozzles is a more complex flow with multiple inlets and different conditions. Because the pressure of the air reservoir is known, pressure inlet condition is used at the jet orifices. While the fibers or strands output from the front roller and go into the first nozzle, the outer air is supplied into the nozzle, so velocity inlet boundary can be set at the first nozzle inlet. Notes that, the computed result of the first nozzle is used as the boundary condition for the inlet of the second nozzle in this simulation.

The outlet boundary: At the nozzle outlet, the pressure is supposed to be the external pressure.

The wall boundary: At the wall, non-slip boundary condition is applied.

3. Results and discussion

All numerical simulations presented here are obtained using a commercial CFD package FLUENT 6.1. Since the first and second nozzle pressures interact with each other to determine yarn strength [16], the first and second nozzle pressures of 2.5 and 3.5 \( \times \) 10^5 Pa are used as the initial conditions according to spinning experiments [2, 16], respectively. In order to meet the convergence and accuracy requirements, the best grid structures of the two nozzles are shown in Fig. 3. The total numbers of grid points of the two nozzles are 197,695 and 173,552, respectively.

Comparison of the computed and experimental [6] axial and tangential velocity components near the jet orifices are presented in Fig. 4 for the first nozzle without slotting-tube. It can be observed from figures that the model predictions...
differ from the experimental results in the quantitative sense. The model predicts lower velocity and a smaller near-wall zone. The difference between numerical simulation and experiment can be attributed to the variation in inlet conditions, as the supplement of air through the nozzle inlet is ignored in the measurement. However, in a qualitative sense, the model predicts the velocity distributions quite well, as seen from the figures.

For the first nozzle with slotting-tube, as shown in Fig. 5 (a, b), a weak swirling balloon is formed in upstream of the orifices due to reverse flow near the wall caused by inverse jet, and its direction of twist is contrary to that of the downstream. It’s helpful to untwist edge fibers that are imparting twist, and the gripping of edge fibers by main body strand are postponed. Hence, the twist difference between edge fibers and main body of fiber strand is formed. The vortex breakdown in downstream of the orifices (Fig. 5 (a)), which is similar to that discussed by Wang et al. [17], disturbs fluid and helps to produce more edge fibers, hence yarn tenacity is increased. Flow separation and subsequent reattachment behind the sudden expansion are also observed in Fig. 5(a) because a similar backward-facing step flow is formed due to the grooves.

On the other hand, the simulation is able to shed light on the untwisted action of the slotting-tube. As shown in Fig. 5(c), there are air currents in mutually opposite direction in the grooves and the twisting chamber. Therefore, as the fiber strand passes through the twisting chamber, fibers lying at the edge of the strand (i.e. in shear layer) will get a composite force, which includes centripetal force of swirling flow and counterforce of airflow in the grooves. This does good to loosen fiber strands and produce more edge fibers, which subsequently become wrapper fibers. And then yarn tenacity is increased. The result is supported by the experimental study of Gao [18].

The computed results show that the airflow in the second nozzle rotates in the opposite direction to that in the first nozzle (Fig. 6). Hence fiber strands can be untwisted when they pass through the second nozzle. The reverse jet cannot happen in upstream of the jet orifice (Fig. 6(a, b)). This may be because the core axis of the jet orifice is almost vertical to that of the swirl chamber and the channel of the swirl chamber diverges gradually to discharge freely. It can be clearly seen from Fig. 6(a) that the distribution of velocity has a saddle shape near the jet orifices due to the strong swirl [19]. And then flow velocity, which shows a wake-like profile, declines gradually as the swirl intensity decays with

Fig. 4 Comparison of the computed velocity profiles with the experimental results of Yu and Zhang [6].

Fig. 5 Velocity vector plots of the first nozzle with slotting-tube: (a) the $y$-$z$ plane at $x=0$ mm; (b) the $y$-$z$ plane at $x=0.6$ mm; (c) cross section of slotting-tube across $z$-axis at $z=26$ mm.
the axial distance [15]. The radial profiles of the velocity show a low velocity in the core region surrounded by high-velocity annular region. Velocity vector and streamline at the cross section show a spiral-type distribution (Fig. 6(c)). The distance between the windings of the spiral increases with radius in the core region and reaches a peak value, thereafter, it decreases with radius. It will help that the wrapper fibers of air-jet spun yarn impart lateral pressure to the core fiber strand, which in turn, improved yarn tenacity.

The streamlines of the two nozzles are shown in Fig. 7. They are all helical except the streamlines in the core zone of the second nozzle. Because velocity in the core zone is lower than that in the shear layer (near the wall), fluid elements are swirling at the different rate and the swirl angle in the shear layer is large. On the other hand, in the first nozzle, airflow swirling directions are in mutually opposite direction in the core zone and the shear layer, this may be because there is a flow-reversal region near the wall of the jet orifice upstream. Therefore, when fiber strand passes through the first nozzle, besides the edge fibers wrap the false twisted core in the opposite direction, a twist difference between the edge fiber and the core one is formed. For the second nozzle, streamlines in the core zone of the second nozzle are nearly straight or little crimple along streamwise direction. It means that in the second nozzle the twist of the main strand will be removed, and the low-twist surface fibers that are produced by the first nozzle will be untwisted to a greater degree than their original twist and will wrap tightly on the yarn body [2, 20]. So actions of the two nozzles and the principle of the yarn formation [4, 5] are both demonstrated.

4. Conclusions

With the FLUENT software, the 3D airflow characteristics in the two twisting nozzles of MJS were simulated and studied. There is a helically rotating airflow in the twisting chamber, which is difficult to observe directly. Edge fibers may be prevented from being inserted prematurely into main fiber strand due to weaken opposite swirling balloon in the upstream of the orifice of the first nozzle. This helps to form twist difference between the edge fibers and the core ones. In addition, some factors, such as vortex breakdown in the downstream of the jet orifices and weak opposite airflow in the grooves, will help to loose fiber strand and produces more long wrapper-fibers. In the second nozzle, swirling airflow is opposite to that of the first nozzle. A low velocity in the core region surrounded by high-velocity annular region and a spiral-type streamline at the cross section are both observed. The functions of the two nozzles were demonstrated.

On the other hand, fluid trajectories in the two nozzles show the edge fibers are twisted with a lesser in the opposite direction of the core fibers while fiber strand passing through the first nozzle. Simulation results well supported the theoretical analysis of the principle of the yarn formation proposed by Stalder [4] and Krause [5].

Acknowledgements

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References