NUMERICAL SIMULATION AND ANALYSIS OF AIRFLOW IN THE CONDENSING ZONE OF COMPACT SPINNING WITH LATTICE APRON

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1. Introduction

The air negative pressure plays a very important role in compact spinning as it is utilized to condense the fiber bundle in a pneumatic compact spinning mechanism [1, 2]. To eliminate the spinning triangle, which leads to improving the quality of spun yarn in terms of hairiness and strength, a few studies have been reported [3–5]. Numerical simulation technique is one among the significant approaches that are used to solve numerous problems in traditional ring spinning [6]. The compact spinning system was built on the foundation of the traditional ring-spinning system [7]. However, numerous researchers consider it to be a modern spinning technique [8–10]. The first compact spinning system was introduced to industrial application at ITMA in 1995 [11, 12]. Compact spinning is classified into pneumatic and mechanical compacting based on the condensing principle [13]. Recently, the dominant type is the pneumatic compact spinning systems [14, 15] and it is mainly classified into perforated drum and lattice apron compact spinning systems [16, 17].

Compact spinning with lattice apron is the most widely used pneumatic compact spinning system, and it has three-line compact spinning (TLCS) and four-line compact spinning (FLCS) [4, 16]. The condensing zone’s flow field pattern plays an essential role in the pneumatic compact spinning, which directly affects the qualities of yarn [18]. Therefore, the flow field investigations in the condensing zone of pneumatic compact spinning have received more attention recently [19]. Recent research on the condensing zone in pneumatic compact spinning use computational fluid dynamics (CFD) [20]. CFD is one of the powerful methods to investigate flow field-based problems [1, 21, 22] because of its ability to investigate theoretical phenomena of fluid flow based on the physical model [23–25].

Employing the self-designed MATLAB procedure, Dou et al. [26] obtained the motion trajectory of cotton fiber in the flow zone and the compact effect of fiber strands due to the airflow. Zhang et al. [27] have used CFD to build a model for compact spinning with an inspiratory groove for cotton using numerical investigation calculations and characterized the flow state in the compact zone.

In this article, we investigate the condensing zone of compact spinning systems with lattice apron and the effects of different negative air pressure on fiber condensing as well as the mechanical properties of yarn. In the next sections, numerical simulation steps, model setup, simulation data, and analysis are presented. A comprehensive conclusion is then drawn based on the results.

2. Numerical simulations

2.1. Three-dimensional physical models for the condensing zone

Figure 1 represents the side view of the condensing zone of the compact spinning system with a lattice apron. The 3D flow field’s numerical simulations in the condensing zones of three different negative air pressure will be studied. The physical parameters of the model are shown in Figure 2.

Keywords:
Compact spinning, lattice apron, airflow, negative pressure, numerical simulation
In these models, the fiber strand's output direction is defined as the negative direction of the x-axis. In contrast, the transverse condensing direction of the fiber strand is defined as y-axis, whereas the width of the fiber strand is defined as z-axis. The midpoint of the lower end of the suction groove is taken as the origin. The fiber strand was ignored because, theoretically, the fiber strand volume is smaller than the condensing zone.

2.2. Boundary conditions

The flow field in the condensing zone is assumed as incompressible and the turbulence model adopted is the standard k-epsilon two-equation model. As shown in Figure 2, there are three pressure inlet points that are assigned the static pressure values equal to the atmospheric pressure (101,325 Pa). The collecting pipe is connected to the centrifugal fan, and the air inside the collecting pipe is sucked from one side of the pipe; therefore, the side is set as a pressure outlet boundary, that is, −1,000 pa, −2,000 pa, and −3,000 pa (see Figure 2) concurrently.

2.3. Porous jump boundary condition

To simulate the effect of the lattice apron on the airflow characteristics, the plane covered by the grid circle is set to a porous jump boundary (see Figure 2). The pressure changes (Δp) above and below the plane can be defined by Darcy’s law and an inertia term:

\[
\Delta p = -\left(\frac{\mu}{\alpha} + C_2 \frac{v^2}{2} \rho \Delta m\right)
\]

In the above formula, \(\mu\) is the laminar viscosity, \(\alpha\) is the permeability, \(C_2\) is the pressure jump coefficient, \(v\) is the normal velocity, and \(\Delta m\) is the plane thickness. The effect of grid circles of different thicknesses and porosity on the airflow can be simulated by setting the permeability and the thickness of the porous plane. According to the grid circle’s actual state, the permeability and the thickness of the porous plane are set at \(10^{-7}\) and 0.09 mm, respectively.

2.4. Solid wall boundary condition

The other faces of the calculation area are solid walls. The condition of the nonslip boundary is observed on the solid wall, which means that the velocity on the wall is zero. The solvers were implemented with a single-precision implicit split operator, and thereby the coupling problem between pressure and velocity was resolved. SIMPLEC algorithm is used, and grid spacing 0.5 mm and convergence precision \(10^{-4}\) are set to reduce the error to acceptable levels.

3. Numerical simulation results with different negative air pressure

In this section, the effects of three different negative pressures on flow velocity were simulated. Figures 3 and 4 indicate that by varying the negative pressure from -1,000 pa to -2,000 pa and -3,000 pa, the airflow velocity will increase from 37.32 m/s to 53.97 m/s and 67.54 m/s, respectively.

Figure 3 shows the streamline diagram of flow velocity in the X–Z section when Y is equal to zero (along the x-axis) with the velocity vector colored according to velocity magnitude in m/s. The results from Figure 3 reveal that the whole area of air suction slot is covered by the flow field and this is attributable to the significant rise of negative pressure effective.

Table 1. The Geometrical parameters of the condensing zone

| Front top roller diameter (mm) | Output top roller diameter (mm) | Length of suction slot (mm) | Width of suction slot (mm) |
|-------------------------------|--------------------------------|-----------------------------|---------------------------|
| 28                            | 40                             | 20                          | 1.5                       |

Figure 1. The side view of the condensing zone of the compact spinning system with lattice apron.

Figure 2. The 3D physical model for the condensing zone of a compact spinning system with a lattice apron.
4. The effect of different negative air pressure on flow velocity

In this section, numerical simulation of the flow velocity along the motion trajectory of the fiber strand in the condensing zone was studied. In the condensing zone, there are three kinds of forces acting on the fibers generally. First, the transverse condensing force on the $y$-axis direction: under this force the width of the fiber strand is reduced and the spinning triangle is decreased. Second, the output force on the $x$-axis direction: under this force the fibers strands can be straightened and the condensing effect is improved. Third, the assisted condensing force on the $z$-axis direction: under this force the fiber strands are made to cling to the outer surface of lattice apron, the strand structure is kept stable, and there is an improvement in fiber-condensing effect. The effects of output force on the $x$-axis direction produced by the airflow can be ignored towing to the fact that the fiber strand was mainly affected by the drafting force on the $x$-axis direction. For the convenience of the subsequent comparative analysis, a straight line located in the middle condensing zone is defined, which is parallel to the $y$-axis ($X = 10$ mm, $Z = 1.2$ mm).
5.1. Yarn spinning and testing

After spinning, all the yarn samples were kept in the lab for at least 48 h under standard conditions, namely, 20 ± 2°C and 65 ± 2% relative humidity (RH). To study the effect of different negative pressure, yarn properties such as the yarn evenness (CV), hairiness index, and breaking strength were measured. The yarn hairiness was measured 10 times for each yarn bobbin using a YG172A hairiness tester under 30 m/min speed, and the average value of the 10 tested results was taken as the hairiness of any particular single bobbin yarn. The average

4.1. Flow velocity component on the y-axis direction

The diagram of flow velocity component on y-axis direction is shown in Figure 5. It shows the flow velocity is positive in the left side of the fiber strand, whereas the same is negative in the right side in the whole condensing zone. The flow velocity on the y-axis direction denotes the transverse condensing direction of the fiber strand, which indicates the need for reducing the fiber strand width and decreasing the spinning triangle. Further, with increasing negative pressure, the transverse condensing force is beneficial for reducing fiber width. Consequently, the flow velocity component possibly is beneficial for increasing strength and eliminating hairiness.

4.2. Flow velocity component on the z-axis direction

The flow velocity component on the z-axis and the positive value of flow velocity describe the movement of the fiber strand away from the outer surface of lattice apron and the negative value describes the fiber strand that is clung to the outer surface of lattice apron.

The diagram of flow velocity component on z-axis direction is shown in Figure 6. The value of flow velocity component on the z-axis is negative. However, with increasing negative pressure, the negative value of flow velocity is highly increased.

5. Experimental

The spinning experiments were carried out using DHU X01 multifunction digital spinning machine whose condensing device had three-rollers lattice negative-pressure type. To verify the results obtained from the simulation discussed above, the three different yarn counts used were spun 29.2 tex, 19.6 tex, and 14.6 tex at different negative air pressures. The yarn count range was selected to cover the common of the yarn produced. The cotton fiber properties and the details of the spinning parameters are shown in Tables 2 and 3, respectively. A cotton roving of 600 tex was used.

![Figure 5. The diagram of flow velocity component on y-axis direction.](image)

![Figure 6. The diagram of flow velocity component on z-axis direction.](image)

| Fiber properties          | Values ± SD% |
|---------------------------|--------------|
| Micronaire                | 4.33 ± 0.09  |
| Maturity index            | 0.86 ± 0.03  |
| Average length (mm)       | 31.4706 ± 1.2192 |
| Upper half length (mm)    | 35.6108 ± 0.762 |
| Uniformity index          | 88.3 ± 1.7   |
| Short fiber index         | 7.8 ± 0.4    |
| Strength (cN/tex)         | 49.5 ± 3.1   |
| Elongation (%)            | 6.6 ± 0.2    |
| Moisture (%)              | 12.0 ± 0.2   |
| Reflectance (Rd)          | 81.7 ± 0.4   |
| Yellowness (+b)           | 17.2 ± 0.3   |

| Spinning process parameters |  |
|-----------------------------|--|
| Linear density (tex)        |  |
| Spindle speed (rpm)         |  |
| Twist (per meter)           |  |
| 29.2                         | 10,000 | 630   |
| 19.6                         | 10,000 | 730   |
| 14.6                         | 10,000 | 830   |
When the negative pressure was increased, the total velocity of airflow is increased as well. Accordingly, decreasing the transfer of border fibers and the fibers’ distribution in the yarn body became more uniform and advantageous for enhancing CV.

6. Conclusions

To summarize, we have established the 3D physical model of the condensing zone by implementing numerical simulations based on a standard k-epsilon model. The numerical simulations of the 3D flow field in the condensing zone for compact spinning systems with lattice apron and the effects of different negative pressures on fiber condensing were extensively evaluated. The results reveal that the airflow field helps to achieve convergence of the fiber bundle in compact spinning systems with lattice apron. The optimization of the airflow field resulted in significant increase in yarn mechanical properties.

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