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RECENT STUDIES ON YARN TENSION AND ENERGY CONSUMPTION IN RING SPINNING

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ABSTRACT

High energy consumption remains a key challenge for the widely used ring spinning system. Tackling this challenge requires a full understanding of the various factors that contribute to yarn tension and energy consumption during ring spinning. In this paper, we report our recent experimental and theoretical research on air drag, yarn tension and energy consumption in ring spinning. A specially constructed rig was used to simulate the ring spinning process; and yarn tension at the guide-eye was measured for different yarns under different conditions. The effect of yarn hairiness on the air drag acting on a rotating yarn package and on a ballooning yarn was examined. Models of the power requirements for overcoming the air drag, increasing the kinetic energy of the yarn package (bobbin and wound yarn) and overcoming the yarn wind-on tension were developed. The ratio of energy-consumption to yarn-production over a full yarn package was discussed. A program to simulate yarn winding in ring spinning was implemented, which can generate the balloon shape and predict yarn tension under a given spinning condition. The simulation results were verified with experimental results obtained from spinning cotton and wool yarns.

Key words: Ring spinning; yarn tension; energy consumption; yarn balloon; air drag; modelling

1. INTRODUCTION

The two outstanding challenges for ring spinning are high power consumption and low productivity. The low spinning efficiency is due to the relatively high yarn tension during ring spinning, which increases the chance of yarn breakage. The high power consumption is caused by high air drag from the ballooning yarn (Fraser, 1993a) and yarn hairiness (Chang, et al., 2003), which also generates high yarn tension during ring spinning.

According to the theory of fluid mechanics (John and Haberman, 1988), the air drag on a body is due to the sum of pressure drag and skin friction drag. In many cases, one or the other of these two drags is predominant. In ring spinning, air drag on the rotating yarn package is mainly due to skin friction drag on the package surface, while pressure drag is the dominant one on the ballooning yarn. Understanding the various factors that contribute to air drag is important in the optimization of the ring spinning process.

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1 Based on a paper presented at the 84th World Conference of the Textile Institute, Raleigh, March 2005
In this paper, we will report our recent experimental and theoretical research into air drag, yarn tension and energy consumption in ring spinning.

2. EXPERIMENTAL

2.1 Yarn Samples and Their Hairiness Indexes

We used various singed and un-singed cotton and wool yarns in the experiments. We measured the hairiness index of un-singed yarns on an Uster Tester 4 under standard conditions and at a speed of 400 m/min. Table I lists the hairiness results, which we will use for further analyses in the following sections.

<table>
<thead>
<tr>
<th>Yarn type</th>
<th>Cotton</th>
<th>Cotton</th>
<th>Wool</th>
<th>Wool</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yarn count (tex)</td>
<td>38.0</td>
<td>50.4</td>
<td>70.1</td>
<td>103.0</td>
</tr>
<tr>
<td>Hairiness index (H)</td>
<td>8.1</td>
<td>8.1</td>
<td>12.0</td>
<td>13.0</td>
</tr>
</tbody>
</table>

We used a yarn and the roving build method to wind a yarn package with one layer and removed the hairiness on the package surface by singeing. Then we obtained the singed yarn by unwinding the yarn from the package.

2.2 Power Consumption for Rotating Yarn Packages

We used a single spindle experimental rig (see Figure 3 in Chang, et al. (2003)) to measure the level of power consumption during the rotation of a single yarn package. We used the cotton or wool yarn of a given count and the roving build method to wind different yarn packages with the appropriate number of layers, which was determined by the requested package diameter and yarn count. We removed the hairiness on the surface of some packages via singeing. For each of the packages, we took the diameter measurements at two ends and in the middle, and used their average as the diameter of the package. All packages had the same height \( h_0 \) of 0.245 m. We tested each of the packages twice at spindle speeds ranging from 2,000 rpm (i.e. 33 rps) to 16,000 rpm (i.e. 267 rps), in steps of 2000 rpm. For each of the packages at different spindle speeds, we took the average values of the current and voltage readings from the test device and used these readings to calculate the power consumption at a given spindle speed (Tang, et al., 2004b, 2005a).

2.3 Tension in a Ballooning Yarn

We measured tension in the singed and un-singed yarns using a specially constructed rig (see Figure 2 in Tang, et al. (2004e)), which can rotate a yarn at high speeds without inserting any real twist into the yarn.

The end of the yarn which passes through a guide-eye was attached to the tension sensor and another end was fixed on a rotating eyelet. When the eyelet starts rotating, the yarn between the guide-eye and eyelet formed a balloon and generated tension in the yarn.
The tension signal at the guide-eye was digitized by the computer data acquisition system.

For yarn tension measurement, we ‘spun’ the yarns at different ‘twisting’ speeds on the rig, with the balloon height varying from 120 mm to 360 mm. We measured the yarn rotating speed (i.e. spindle speed) with a digital tachometer during the tests, and used a digital camera with video capability to capture the balloon shape.

### 3. THEORETICAL

#### 3.1 A Geometrical Model of a Bobbin with Full Yarn Package

A geometrical model of a yarn package is required for subsequent calculations of energy consumption during the package build-up. Based on the cop build method in a ring spinning system, we built up a model of a bobbin with a full yarn package, as shown in Figure 1, where we considered the profiles of both the top and bottom conical ends to be straight/linear, the upper and lower chases have the same angle of $\beta (0^\circ < \beta < 90^\circ)$, and the yarn region of a full yarn package consists of a main part and a base part.

![Figure 1. (a) A model of a bobbin with a full yarn package, and (b) A part of the lateral section of a winding on a yarn package using the cop build method (Tang, et al., 2004a).](image)

Let $d_0 \, [\text{m}]$ be the diameter of the empty bobbin, $d \, [\text{m}]$ the maximum diameter of the full yarn package; let $L_b$ be the number of complete layers, $C_1$ the number of yarn coils in first complete main (up) winding layer and $L_i$ the yarn length of the $i$th complete layer ($i = 1 \rightarrow L_b$) in the base part; let $L_y$ be the number of complete layers, $C_m$ the number of yarn coils in each main (up) winding layer and $L_m$ the yarn length of each complete layer in the main part; and let $N \, [\text{tex}]$ be yarn count, $D \, [\text{g/cm}^3]$ fibre density, $v_w \, [\text{m/s}]$
linear winding-on speed (i.e., front roller delivery speed) and \( T_p \) [s] the total time taken to wind a full yarn package. Then

\[
L_m = 1.5(d - d_y)\pi C_m - \frac{1.5(d - d_y - 2d_y)\pi}{C_m - 1} \sum_{i=1}^{C_m}(i - 1)
\]

\[
L_i = 1.5 \left( d_0 + d_y \right) \pi C_1 + (i - 1) \times \frac{L_m - 1.5(d_0 + d_y)\pi C_i}{L_p - 1} \quad (i = 1 \rightarrow L_b)
\]

\[
T_p = \left[ \left( \sum_{i=1}^{L_b} L_i + L_m \times L_p \right)/\omega_w \right]
\]

where \( C_m = \left[ \frac{d_p - d_0}{2d_y \sin \beta} \right], L_y = \left[ \frac{h_m \sin \beta}{2d_y} \right], d_y \) [m] is yarn diameter, which can be calculated (Booth, 1975) by

\[
d_y = 4.44 \times 10^{-5} \sqrt{\frac{N}{D}}
\]

The more detailed derivations for \( C_m, L_y, L_i, L_m, \) and \( T_p \) can be found in Tang et al. (2004a). The power distribution during the yarn package build-up will be discussed based on a case study in section 7.5.

### 3.2 Modelling Skin Friction Coefficient on a Rotating Yarn Package Surface

For a full yarn package, the surface area of the main part (with the maximum package diameter) is about 90% of the package surface. When the diameter of main part of a rotating yarn package is \( d \) [m] and the height of the full yarn package is \( h_0 \) [m], then the yarn package can be considered to be a cylinder having diameter \( d \) and height \( h_0 \) and the skin friction coefficient on the package surface, \( C_f \) [scalar], can be expressed as

\[
C_f = \frac{2P_f}{\rho(d\pi)^3 h_0 V^3}
\]

where \( V \) [rps] is a given full spindle speed, \( \rho \) is air density and \( P_f \) [W] is the power required to overcome skin friction drag on the package surface (which can be measured during experiments) (Tang, et al., 2004b).

In particular, for an empty bobbin diameter \( d_0 = 0.025 \) m, the skin friction coefficient \( C_f \) on a rotating yarn package surface without hairiness depends on the full spindle speed \( V \) and the package diameter \( d \):

\[
C_f = \frac{0.025}{d} a V^b
\]

where \( a \) and \( b \) are constants which can be determined from experiments: \( a = 148030 \) and \( b = -2.575 \) for the cotton yarn (Tang, et al., 2004b).

We modified Equation (6) into a general model for skin friction coefficient on the surface of a rotating yarn package:

\[
C_f = \frac{0.025}{d} \left( a V^b + a_1 H V^{b_1} \right)
\]

where \( H \) [scalar] is yarn hairiness index which can be measured, constants \( a \) and \( b \) are the same as the ones in Equation (6), and constants \( a_1 = 384128 \) and \( b_1 = -3.4316 \) for the cotton yarn (Tang, et al., 2005a).
Furthermore, a new model which can more accurately predict the skin friction coefficient on the surface of a rotating wool yarn package has been developed and is shown below:

\[
C_f = \frac{0.025}{d} \left( aV^b + 1.4a_iHV^{b_i} \right) \tag{7a}
\]

where constants \( a, b, a_i \) and \( b_i \) are the same as ones in Equation (7), respectively.

### 3.3 Simulating Yarn Winding in Ring Spinning

We consider a balloon curve that rotates at a constant angular velocity \( \omega \) (clockwise rotation, from the top down) during ring spinning, as shown in Figure 2. Let \( e_r, e_\theta, k \) be unit based vectors of a cylindrical coordinate system, a material point \( P \) on a rotating yarn has the coordinates \((r, \theta, z)\). The distance measured along the yarn from the guide-eye \( O \) to the point \( P \) is \( s \). If the balloon shapes are considered to be stationary when viewed from the rotating reference frame, the position vector of \( P \) can be expressed as \( R(s) = re_r + zk \). Following the work of Fraser (1993a), we can obtain a stationary-balloon system for the yarn element at \( P \) in normalized form:

\[
k \times (k \times R) = (TR')' - \frac{p_0}{16}[p_n]v_n
\]

\[
v_n = R' \times ((k \times R) \times R')
\]

\[
R' \bullet R' = 1
\]

with initial and boundary conditions:

\[
R(0) = 0
\]

\[
R(s_i) = e_r + h k
\]

where \( T(s) \) is the normalized tension in the yarn at \( P \), \( p_0 \) is the normalized air-drag coefficient on ballooning yarn, \( h \) is normalized balloon height and \( s_i \) is normalized yarn-length in balloon.

We implemented a program on the above system (8) using MATLAB language with grid search method to find out a pair of numbers \((T(0), r'(0))\), where \( T(0) \) is tension and \( r'(0) \) is balloon radius’ tangent at guide-eye, so that the corresponding solution makes the approximate error function \( E = |r(s)|_{s=s_i} - 1| + |z(s)|_{s=s_i} - h| \) have the minimum value on the domains of \( T(0) \) and \( r'(0) \). Then \( T(0) \) will be the desired tension (Tang, et al., 2004d).

We simulated the balloon shape and the tension at guide-eye against yarn-length in balloon for different normalized air drag coefficient \((p_0)\) using the above program because the normalized air drag coefficient on ballooning yarn is a unique parameter in the system (8).
Figure 2. The cylindrical coordinates of a material point $P$ on a rotating yarn are $r$, $\theta$, and $z$ (Tang, et al., 2004d).

4. THE VERIFICATION OF THE SIMULATIONS

4.1 Balloon Shape

Figure 3 shows the balloon shapes of ballooning yarn with normalized air drag coefficient $p_0 = 3.3$ for different yarn lengths in balloon from simulations (Further information on air drag is provided in Section 5). Figure 4 displays the balloon shapes which were captured from simulated spinning experiments of pure wool 70.1 tex two-fold yarn.

Figures 3 and 4 indicate that the experimental results confirmed simulation results very well. Since yarn-length in balloon and balloon loop(s) are two of the outputs from simulation, we can estimate yarn-length in balloon and the number of balloon loops in ring spinning based on the simulation results (Tang, et al., 2004d).

Figure 3. Balloon shapes from simulations: normalized yarn-length in balloon (a) $s_l = 10.3$, (b) $s_l = 11.0$, (c) $s_l = 12.0$, (d) $s_l = 13.5$, and (e) $s_l = 16.5$ (Tang, et al., 2004d).
Figure 4. Balloon shapes from the experiments with a pure wool 70.1 tex two-fold yarn (Tang, et al., 2004d).

4.2 Curve of Tension at Guide-eye Against Yarn-length in Balloon

Figure 5 is a comparison of the curves of tension at guide-eye against yarn-length in balloon, where the experimental data came from simulated spinning experiments of 38 tex cotton single yarn and 50.4 tex cotton two-fold yarn and have been converted into normalized form, and the theoretical curves came from simulations with normalized air drag coefficient $p_0 = 5.0$ and $p_0 = 4.0$, which have been estimated by making a “best fit” between the theoretical and experimental turning points (Tang, et al., 2005b).

Figure 5 shows us that the air drag coefficient on ballooning yarn during ring spinning can be modelled. Furthermore, we can estimate the air drag force on the ballooning yarn, tension at guide-eye and the yarn tension in balloon for ring spinning.

Figure 5. Comparison of the curves of tension at guide-eye against yarn-length in balloon obtained from experiment and simulation (Tang, et al., 2005b).

5. AIR DRAG

5.1 Skin Friction Drag on a Rotating Yarn Package Surface
5.1.1 Calculating the Skin Friction Drag on the Package Surface

As mentioned in section 3.2, a rotating full yarn package can be considered to be a rotating cylinder. Therefore, when the package has a diameter of \( d \) [m] and a height of \( h_0 \) [m], the air drag \( F_p \) [N] on the package surface can be obtained (Anderson, 2001) by

\[
F_p = \rho (\pi d)^3 V^2 h_0 C_f
\]  

(9)

where \( V \) [rps] is a given full spindle speed, \( \rho = 1.197 \text{ kg/m}^3 \) and \( C_f \) [scalar] is the skin friction coefficient on the rotating surface.

![Graph](image)

Figure 6. Modeling of skin friction coefficient on a package surface for YPD (yarn package diameter) = 0.025 m and predicting for YPD = 0.045 m (Tang, et al., 2004b).

When \( d = 0.045 \) m, from Equation (6), the skin friction coefficient on the package surface can be given by

\[
C_f = 82239 V^{-2.575}
\]  

(10)

A curve of the skin friction coefficient corresponding to Equation (10) is shown in Figure 6. In particular, for a given full spindle speed of 200 rps (i.e., 12000 rpm), the skin friction coefficient on the package surface is about 0.098 (Tang, et al., 2004b).

5.1.2 The Effect of Yarn Hairiness on Skin Friction Drag on a Yarn Package Surface

We examined four yarn packages having the same diameter of 0.045 m and the same height of 0.245 m: two cotton yarn packages wound by the 38 tex cotton yarn and another two wool yarn packages wound by the 103 tex wool yarn, and the surfaces of one cotton package and one wool package were singed to remove the hairs. Using Equations (6), (7), (7a) and (9), we calculated the air drag for the singed and un-singed cotton and wool yarn packages rotating at different speeds (see Tables 5 and 6 in Ref. Tang, et al., 2005a). The results show that yarn hairiness has resulted in a 25% increase in air drag (average value) on the surface of a rotating cotton yarn package and 35% increase in air drag (average value) on the surface of a rotating wool yarn package.

5.2 Air Drag on a Ballooning Yarn

5.2.1 Modelling Air Drag Coefficient on a Ballooning Yarn
Figure 7 shows the comparisons of the curves of tension at guide-eye against yarn-length in balloon, where the experimental data came from simulated spinning experiments and have been converted into a normalized form, and the theoretical curve came from simulation with normalized air drag coefficients, which have been estimated by making a “best fit” between the theoretical and experimental turning points. The normalized air drag coefficient $p_0$ equals 5.0 for the natural 38 tex cotton yarn and $p_0$ equals 4.6 for singed 38 tex cotton yarn (Tang, et al., 2005a).

![Figure 7. Modelling air drag coefficients ($p_0$) on ballooning 38 tex cotton yarn at 5300 rpm: $p_0 = 5.0$ for natural yarn and $p_0 = 4.6$ for singed yarn (Tang, et al., 2005a).](image)

### 5.2.2 Calculating the Air Drag on a Ballooning Yarn

For simplicity, we assume that the air drag coefficient $\Delta C_D$ is constant along the whole length of the yarn in the balloon, and it takes on a value appropriate to the velocity of the yarn at the maximum balloon radius. So the quantity of air drag acting on the whole ballooning yarn can be estimated (Chang, et al., 2003) by

$$F_y \approx 2\pi \rho d_y s_i r_{\text{max}}^2 V^2 C_D$$

(11)

where $\rho = 1.197 \text{ kg/m}^3$, $d_y \text{ [m]}$ is yarn diameter, $s_i \text{ [m]}$ is yarn length in balloon, $r_{\text{max}} \text{ [m]}$ is the maximum radius of the balloon, $V \text{ [rps]}$ is spindle speed and $C_D \text{ [scalar]}$ is the air drag coefficient on the ballooning yarn, which can be obtained by

$$C_D = \frac{m}{8\rho a d} p_0$$

(12)

where $p_0 \text{ [scalar]}$ is the normalization form of air drag coefficient, $\rho = 1.197 \text{ kg/m}^3$, $d \text{ [m]}$ is yarn diameter, $a \text{ [m]}$ is ring radius and $m \text{ [kg/m]}$ is linear density of yarn (Fraser, 1993b).

### 5.2.3 The Effect of Yarn Hairiness on Air Drag on a Ballooning Yarn

Let $C_{Ds}$ and $F_{ys}$ be the air drag coefficient and air drag, respectively, on a ballooning yarn which has been singed; similarly, let $C_{Dn}$ and $F_{yn}$ be the respective air drag coefficient and air drag on a ballooning natural yarn. If we ignore the effects of hairiness on the diameter and mass of yarn in balloon, from Equation (11),
\[ F_{yn} = 2\pi \rho d_y s_y r_{\text{max}}^2 V^2 C_{Dn} \]  
(13)

and

\[ F_{ys} = 2\pi \rho d_y s_y r_{\text{max}}^2 V^2 C_{Ds} \]  
(14)

where \( \rho = 1.197 \text{ kg/m}^3 \), \( d_y \) [m] is yarn diameter, \( s_y \) [m] is yarn length in balloon, \( r_{\text{max}} \) [m] is the maximum radius of the balloon, \( V \) [rps] is spindle speed and \( C_D \) [scalar] is air drag coefficient on the ballooning yarn.

From Equations (12), (13) and (14), and \( p_{0n} = 5.0 \) and \( p_{0s} = 4.6 \) for the 38 tex cotton yarn, we have

\[
\frac{(F_{yn} - F_{ys})}{F_{ys}} = \frac{C_{Dn} - C_{Ds}}{C_{Ds}} = \frac{p_{0n} - p_{0s}}{p_{0s}} \approx 8.7 \%
\]  
(15)

Equation (15) shows that the hairiness on a ballooning cotton yarn increases the air drag by around 9%. This can be considered to be a skin friction drag increase due to hairiness when we ignore the effects of hairiness on the diameter and mass of yarn in balloon (Tang, et al., 2005a).

6. THE EFFECTS OF MAIN PARAMETERS ON YARN TENSION

6.1 The Influence of Yarn Type and Count

Figure 8 displays a comparison of pure wool 70.1 tex two-fold yarn, cotton 50.4 tex two-fold yarn and cotton 38 tex single yarn at the same rotating speed of 5300 rpm. When the yarn-length in balloon is 310 mm, the tensions at guide-eye are 33.95 cN, 24.13 cN and 17.45 cN for the two-fold wool yarn, two-fold cotton yarn and single cotton yarn, respectively. These results are expected because of the different yarn counts. Heavy yarns have a higher centrifugal force during rotation, which leads to higher yarn tension. In addition, the air drag is different for these yarns also. To isolate the yarn count effect, we expressed the yarn tension in terms of specific tension, i.e. the ratio of yarn tension over yarn-count. The specific tensions for the three different yarns are 0.484 cN/tex for pure wool two-fold yarn, 0.479 cN/tex for cotton two-fold yarn and 0.459 cN/tex for cotton single yarn. These differences in specific tension are due to the different air drags acting on the yarns. The two fold wool yarn has the highest hairiness index value (see Table I) and the largest yarn thickness, the air drag acting on this yarn is the largest, hence also the specific tension. The two cotton yarns have the same hairiness index values (see Table I), but the two-fold cotton yarn is heavier and has a larger ‘diameter’, hence its air drag and specific tension is slightly higher (Tang, et al., 2004e).
Figure 8. Yarn tension at the guide-eye against yarn-length in balloon at a rotating speed of 5300 rpm (solid lines: tension was measured as the yarn-length in balloon was decreased; broken lines: tension was measured as the yarn-length in balloon was increased) (Tang, et al., 2004e).

Figure 9. Yarn tension at the guide-eye against yarn length in balloon for varying rotating speeds (38 tex cotton single yarn, balloon height: 300 mm) (Tang, et al., 2004e).

6.2 The Influence of Spindle Speed

Figure 9 shows the tension curves for the single cotton yarn of 38 tex at different rotating speeds and a balloon height of 300 mm. When yarn-length in balloon is 310 mm, the tension levels at the guide-eye are 2.95 cN, 5.47 cN, 11.97 cN, 17.45 cN and 29.40 cN for the rotating speed of 2200 rpm, 3150 rpm, 4300 rpm, 5300 rpm and 6400 rpm, respectively.

The ratios of the maximum tension at guide-eye to rotating speed [cN/rpm] from Figure 9 are 0.0013, 0.0017, 0.0028, 0.0033 and 0.0046 for rotating speed of 2200 rpm, 3150 rpm, 4300 rpm, 5300 rpm and 6400 rpm, respectively. This means that the faster the spindle speed, the quicker the increase in yarn tension at the guide-eye, confirming that spindle speed is one of the main factors that affect spinning tension in ring spinning.

6.3 The Influence of Balloon Height
Figure 10 shows the effect of balloon heights on the tension for the two-fold cotton yarn of 50.4 tex at the same spinning speed of 3050 rpm. We measured yarn tension at the guide-eye for a given ratio of yarn-length in balloon over balloon-height \( (R_{lh} = 1.05) \). The yarn tension results are 4.27 cN, 4.20 cN, 4.91 cN, 6.34 cN, 6.11 cN, 7.43 cN, 7.78 cN, 9.88 cN, and 10.51 cN, when the ratio of balloon-height over ring-radius \( (R_h/r) \) is 4, 5, 6, 7, 8, 9, 10, 11 and 12, respectively. These results indicate that for a given rotating speed, the increase in yarn tension at guide-eye is proportional to the balloon-height. It suggests that decreasing the balloon-height is one of the methods that may reduce spinning tension in ring spinning (Tang, et al., 2004e).

![Figure 10. Yarn tension at the guide-eye against yarn-length in balloon with a rotating speed of 3050 rpm and varying balloon heights (Tang, et al., 2004e).](image)

7. ENERGY CONSUMPTION

7.1 A Model of the Ratio of Energy-consumption to Yarn-production

The ratio of energy-consumption to yarn-production during yarn winding in ring spinning can be formulated as (Tang, et al., 2003, 2004c):

\[
R = \frac{5\pi(d_0 + z) \times 10^3}{k_1} + \frac{ad_0\rho\pi^4x^2d^2z^2}{4k_1y\sin\beta - (z-d_0)\cos\beta} + \frac{ad_0\rho\pi^4x^2d^2z^2}{8k_1y\sin\beta - (z-d_0)\cos\beta}
\]

over the set

\[
S = \{(x, y, z): 350 > x > 50, 225 > y > 5, 0.065 > z > d_0\}
\]

where \( R \) [J/mg] is the ratio of energy-consumption to yarn-production, \( x \) [rps] is the full spindle-speed \( (V) \), \( y \) [tex] is yarn-count \( (N) \), \( z \) [m] is the maximum diameter of a yarn package \( (d_p) \), \( d_0 \) [m] is the minimum diameter of the yarn package, \( h_0 \) [m] is the total
height of the full yarn package, $\beta$ [°] is the chase angle of the full package, $\rho$ [kg/m$^3$] is air density and is equal to 1.197, $k_1$ [m/rev] is a constant which relates to winding-on velocity and full spindle-speed, $k_2$ [(g/cm$^3$)$^{0.5}$] is a constant which relates to yarn diameter and yarn-count, $a$ and $b$ are constants which can be determined from experiments.

Under the following conditions: $d_0 = 0.025$ m, $h_0 = 0.245$ m, $\beta = 32$°, $\rho = 1.197$ kg/m$^3$, $k_1 = 0.002$ m/rev, $k_2 = 3.6013\times10^{-5}$ (g/cm$^3$)$^{0.5}$ (the fibre density $D = 1.52$ g/cm$^3$ for the yarn which made of cotton), $a = 148030$ and $b = -2.575$ (obtained from experiments), then Equation (16) becomes

$$R = 0.1964 + 7.8540z + (0.00064 x^{-0.575} y^{-0.5} z^2 - 0.0482 x^{-0.575} y^{-1} z^2 - 0.0255 x^{-0.575} y^{-0.5} z^3 + 142.9175 x^{-0.575} y^{-1} z^3 - 354.2544 x^{-0.575} y^{-1} z^4) \times 10^5$$ (17)

over the set

$$S = \{(x, y, z) : 350 > x > 50, 225 > y > 5, 0.065 > z > 0.025\}$$

where $R$ [J/mg] is the ratio of energy-consumption to yarn-production, $x$ [rps] is full spindle-speed ($V$), $y$ [tex] is yarn-count ($N$), $z$ [m] is the maximum diameter of a yarn package ($d_p$).

### 7.2 The Influence of Spindle-speed ($V$)

For any given yarn-count and yarn package-diameter, from Equation (17), $R$ is strictly a monotone decreasing function with respect to spindle-speed. Figure 11 shows five curves corresponding to five data-pairs of constant yarn-count and yarn package-diameter. It is obvious that the ratio of energy-consumption to yarn-production decreases as spindle speed increases. While increased spindle speed can help reduce energy consumption per unit yarn production, it is worth noting that in practice, spindle speed is constrained by ring/traveller friction and the need to reduce ends-down during spinning.

![Figure 11. Ratio of energy-consumption to yarn-production for given yarn-count ($N$) and package-diameter ($d_p$) (Tang, et al., 2004c).](image)

### 7.3 The Influence of Yarn-count ($N$)
For any given spindle-speed and yarn package-diameter, from Equation (17), $R$ is a strictly monotone decreasing function with respect to yarn-count. Figure 12 shows five curves corresponding to five data-pairs of constant spindle-speed and yarn package-diameter. Under all conditions, the ratio of energy-consumption to yarn-production decreases as yarn count (tex) increases. In other words, the unit energy consumption is much higher when producing finer yarns. This is particularly obvious at the fine end of the yarn count. As the yarn count increases further, the difference in per unit energy consumption tends to taper off (See Figure 12). The increased energy consumption in producing finer yarns also contributes to the higher cost of fine yarns.

![Figure 12. Ratio of energy-consumption to yarn-production for given spindle-speed ($V$) and package-diameter ($d_p$) (Tang, et al., 2004c).](image)

**7.4 The Influence of Yarn Package-diameter ($d_p$)**

For any given spindle-speed and yarn-count, from Equation (17), $R$ is a strictly monotone increasing function with respect to yarn package-diameter. Figure 13 shows five curves corresponding to five data-pairs of constant spindle-speed and yarn-count. We can see from Figure 13 that spinning very fine yarns onto a large yarn package consumes the most amount of energy. This also explains why very small yarn packages are often used in the industry for spinning very fine yarns.
Figure 13. Ratio of energy-consumption to yarn-production for given spindle-speed ($V$) and yarn-count ($N$) (Tang, et al., 2004c).

7.5 A Comparison of Power Distribution while Winding a Yarn Package

Supposing the diameter of an empty bobbin $d_0$ is 0.025 m, the maximum diameter of a full package (including bobbin and wound yarn) $d_p$ is 0.045 m, the total height of a full package $h_0$ is 0.245 m and the upper/lower chase angle in the cop of a full yarn package $\beta$ is 32°. If the yarn to be wound is made of cotton fibre with density $D = 1.52$ g/cm$^3$ (Rae and Bruce, 1973) and the linear-winding on speed (i.e., front roller delivery speed) $\nu_w$ is 0.3 m/s, then the data in Table II can be obtained from Equations (1) – (4).

Table II. Yarn diameter, layer number, yarn length and time spent winding a package

<table>
<thead>
<tr>
<th>Yarn count ($N$) [tex]</th>
<th>10</th>
<th>25</th>
<th>38</th>
<th>45</th>
<th>60</th>
<th>70</th>
<th>80</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diameter ($d_p$) [×10$^{-4}$ m]</td>
<td>1.14</td>
<td>1.80</td>
<td>2.22</td>
<td>2.42</td>
<td>2.79</td>
<td>3.01</td>
<td>3.22</td>
</tr>
<tr>
<td>Layer number of a yarn package</td>
<td>538</td>
<td>340</td>
<td>276</td>
<td>253</td>
<td>219</td>
<td>203</td>
<td>190</td>
</tr>
<tr>
<td>Total length of yarn [m]</td>
<td>14412</td>
<td>5742</td>
<td>3809</td>
<td>3205</td>
<td>2384</td>
<td>2044</td>
<td>1789</td>
</tr>
<tr>
<td>Time taken to wind a full yarn package ($T_p$) [second]</td>
<td>43236</td>
<td>17224</td>
<td>11427</td>
<td>9613</td>
<td>7151</td>
<td>6133</td>
<td>5369</td>
</tr>
</tbody>
</table>

Furthermore, the power requirements for yarn packaging in ring spinning a cotton yarn of 38 tex at full spindle speed of 167 rps is shown in Figure 14. While winding a yarn package in the initial stage, as illustrated in Figure 14(a), most power will be consumed by the yarn wind-on tension, followed by the skin friction drag, then increasing package mass. However, after the initial winding stage, the power required for overcoming the skin friction drag becomes dominant, as shown in Figure 14(b). The power requirement for increasing yarn package mass is “very small”; the reason may be that the variation of package mass is quite slow. In contrast, the power requirement for the initial acceleration is “very large” because the acceleration of bobbin rotation is very fast.

Figure 14. Comparison of power requirements for skin friction drag, kinetic energy and yarn wind-on tension during yarn packaging (a) initial range, and (b) first 3600 seconds (Tang, et al., 2004a).
8. CONCLUSION

A geometrical model of a bobbin with a full yarn package has been developed. The power requirements for a yarn package process are addressed. It is found that the power required to overcome skin friction drag is over 74% (on average) and that required to overcome yarn wind-on tension is about 25% (on average). The power consumed by the stored kinetic energy into a rotating yarn package can be neglected because it is less than 1% (on average). However the power required at the spinning start-up is also quite high (about 14%), due to the rapid package acceleration over a short period of time.

The skin friction coefficient on the package surface without hairiness depends on the package diameter and spindle speed only. Models for predicting skin friction coefficient on the surface of rotating cotton and wool yarn packages have been developed. The effects of yarn hairiness on air drag on the surface of a rotating yarn package and on a ballooning yarn were examined. The results indicate that the effect of yarn hairiness on the skin friction coefficient on the surface of a rotating yarn package is inversely proportional to spindle speed; and the air drag on a ballooning yarn and the average air drag on the surface of a rotating yarn package both increase with an increase in yarn hairiness. These results highlight the significance of yarn hairiness in ring spinning. Realistic models of ring spinning should incorporate the effect of yarn hairiness on air drag acting on the rotating package surface as well on the ballooning yarn.

Yarn tension at the guide-eye was measured for different yarns under different conditions. The results indicate that yarn tension experiences a sudden drop when the rotating yarn balloon collapses from a single loop to a double loop. Similarly, the tension undergoes an obvious change when the balloon loops change between double and triple, but the tension change is small when the balloon loops change between triple and quadruple, or between quadruple and above. Yarn hairiness and thickness, through their effects on air drag acting on the yarn, affect the measured yarn tension. The effect of yarn rotating speed on yarn tension is very significant. In addition, yarn tension increases when the ratio of balloon height to ring-radius increases, in particular, when the ratio is greater than 10.

Models for predicting the ratio of energy-consumption to yarn-production for a full package during yarn winding in ring spinning are established. The results indicate that the ratio of energy-consumption to yarn-production is proportional to yarn package-diameter, but is inversely proportional to spindle-speed and yarn-count. Overall, the effect of yarn-count is greater than that of spindle-speed and package-diameter during yarn winding in ring spinning.

The results in the present paper show that yarn winding behaviour in ring spinning can be simulated accurately. These simulations provide an important tool to investigate the effects of rotating speed, balloon height and yarn count on air drag force on a ballooning yarn and yarn tension in ring spinning. This will facilitate further research into the reduction of yarn breakage and power consumption in ring spinning.

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REFERENCES


