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The Effect of Yarn Hairiness on Energy Consumption in Rotating a Ring-spun Yarn Package

Lingli Chang, Zheng-Xue Tang and Xungai Wang

School of Engineering and Technology, Deakin University
Geelong, Victoria 3217, Australia

ABSTRACT

The effect of yarn hairiness on the energy consumption in rotating a ring-spun yarn package has been investigated theoretically and experimentally in this paper. A theoretical model has been developed to calculate the energy required in rotating hair fibers, based on the hair length and number, as well as the package speed and size. A single spindle test rig was employed to verify the theoretical prediction. The experimental results confirm the theoretical prediction that the package power increases with the increase in yarn hairiness level and spindle speed.

1 Corresponding author – Email: xwang@deakin.edu.au
1. INTRODUCTION

In recent years, considerable research has gone into the development of the theory of ring spinning [5-12, 16, 17] and the studies of yarn hairiness [1-3, 15, 18-26]. While ring spinning has been a very important technology for staple yarns, it is also known for its high power consumption and low productivity. It is conceivable that the power consumption in ring spinning will be exacerbated by any increase in the hairiness level of yarns during the spinning process, because of the likely increase in the air drag associated with rotating a hairy yarn and yarn package.

In the only reported trial we can find from literature [14], the power to rotate one frame package of continuous-filament yarn was recorded; the package was then wrapped manually with one layer of heavy-count woollen yarn, and the power required was five times the initial result. This highlights the importance of yarn hairiness in energy consumption during ring spinning. But no one has yet attempted to quantify the effect of yarn hairiness on the power consumption in ring spinning.

In a normal ring spinning process, the total power consumption will include the power required to overcome friction between moving machine parts, to rotate the yarn package and the yarn balloon etc [4]. In this paper, we consider the simple case of power consumption in rotating a single yarn package. We developed a power model to calculate the increase in power consumption due to an increase in the hairiness of yarns on the package. We also conducted experiments to verify the power model.

2. THEORETICAL

2.1 Background

Wang studied the drag force acting on the hair of a traversing yarn [19]. For a yarn with a single horizontal hair of length \( L \) and travelling vertically at a speed \( V \) (in steady air), the drag force \( F \) acting on the hair owing to air-resistance can be calculated using the following formula [13]:
\[ F = \frac{1}{2} C_D \rho A V^2 \]  

... (1)

where \( \rho \) is air density, \( A \) is the projected fronted area, \( V \) is hair velocity, and \( C_D \) is the drag coefficient which relates to the Reynolds number:

\[ R_e = \frac{V d_f}{\mu / \rho} \]  

... (2)

where \( d_f \) is the hair diameter and \( \mu \) is the air viscosity.

2.2 A model of power required in overcoming air drag on hairs

To simplify the calculation, we assume that hair fibers are straight and have the same fiber diameter. Figure 1(a) shows a yarn package with a single hair of length \( L \) and of diameter \( d_f \). The package rotates clockwise about axis \( z \), as in a normal ring-spinning situation. The drag force acting on \( dx \) of the hair owing to air-resistance can be evaluated according to Equation (1):

\[ \Delta F = \frac{1}{2} C_D \rho \bullet \Delta A \bullet \Delta V^2 \]  

... (3)

where \( \Delta A \) is the projected frontal area of \( dx \), i.e., \( \Delta A = d_f dx \), and \( \Delta V \) is the hair velocity of \( dx \), i.e., \( \Delta V = x \omega \). So,

\[ \Delta F = \frac{1}{2} C_D \rho d_f \omega^2 x^2 dx \]  

... (4)

Because the work done by the air drag acting on the hair is equal to the drag force times the displacement of the hair and power is the work done during 1 second of time, the power required to overcome the drag = drag force \( \times \) hair velocity when hair velocity is measured in m/s. Hence, the power required of rotating \( dx \) is:

\[ \Delta P = \frac{1}{2} C_D \rho d_f \omega^3 x^3 dx \]  

... (5)
Therefore, we can calculate the power required to overcome the resistance of the whole hair (the work done by the drag force of the whole hair during 1 second) by integrating equation (5) over the interval \( r_p \leq x \leq r_p + L \):

\[
P = \frac{1}{2} C_D \rho df \omega^3 \int_{r_p}^{r_p+L} \alpha^3 dx
\]

or,

\[
P = \frac{1}{8} C_D \rho df \omega^3 \left(4r_p^3L + 6r_p^2L^2 + 4r_pL^3 + L^4\right) \quad \ldots(6)
\]

where \( C_D \) is the drag coefficient [dimensionless], \( \rho \) is air density [kg\(\cdot\)m\(^{-3}\)], \( df \) is hair diameter [m], \( \omega \) is the angular speed of spindle [s\(^{-1}\)], \( L \) is the length of hair [m] and \( r_p \) is the maximum winding diameter of yarn package [m].

Assuming there are \( n \) such hair fibers on the package surface, we can classify these \( n \) hairs into \( m \) groups based on their hair length distribution: group 1 with \( n_1 \) hairs of length \( L_1 \), group 2 with \( n_2 \) hairs of length \( L_2 \)… and group \( m \) with \( n_m \) hairs of length \( L_m \) (where \( n_1 + n_2 + \ldots + n_m = n \)). The total power required to overcome the resistance of these \( n \) hairs will be:

\[
P = \frac{1}{8} C_D \rho df \omega^3 \sum_{i=1}^{m} n_i \left(4r_p^3L_i + 6r_p^2L_i^2 + 4r_pL_i^3 + L_i^4\right) \quad \ldots(7)
\]

Under a given testing environment, air viscosity (\( \mu \)) and air density (\( \rho \)) are constants. Once the fiber materials for the yarn are selected, the hair diameter (\( df \)) is also constant. From Equation (2), Reynolds number (\( Re \)) is proportional to hair velocity (\( V \)). In other words, Reynolds number (\( Re \)) is proportional to spindle speed. As drag coefficient (\( C_D \)) decreases when Reynolds number (\( Re \)) increases for \( 10^1 \leq Re \leq 10^3 \) [13], the increase of spindle speed leads to the decrease of drag coefficient. But Equation (7) shows that the effect of angular velocity (\( \omega \)) on power requirement (\( P \)) is much greater than that of drag coefficient (\( C_D \)). So we would expect higher power
level at a higher spindle speed according to Equation (7). Equation (7) also suggests that the effect of hair length \( (L_i) \) on power requirement is quite large, followed by the package radius \( (r_p) \) and then the hair number \( (n_i) \).

### 2.3 Effect of hair angle on power consumption

If the hair is not perpendicular to the surface of a yarn package as indicated in Figure 2a, the projected length of the hair will be \( L \sin \phi \). In this case, the power required to overcome the resistance of hairs can be estimated using \( L \sin \phi \) instead of \( L \) in Equation (7). But when a yarn package is rotating at a high speed, the hair fibers may stay perpendicular to the package surface due to the centrifugal force acting on the hair fibers. We can also consider another case, shown in Figure 2(b), in a similar way. This situation would arise due to the action of the air drag and the flexibility of hair fibers. This will then decrease the \( L \) value, and consequently we expect the measured power level of the hairs to be less than the calculated power value of the hairs. The actual power required to overcome the resistance of \( n \) hairs (Equation 7) will be:

\[
P = \frac{1}{8} C_D \rho d_f \omega^3 \sum_{i=1}^{m} n_i (4r_p^3 L_i \sin \theta + 6r_p^2 L_i^2 \sin^2 \theta + 4r_p L_i^3 \sin^3 \theta + L_i^4 \sin^4 \theta)
\]  

...(8)

When \( \theta = 90^\circ \), \( \sin \theta = 1 \), the power level has maximum value, ie:

\[
P_{\text{max}} = \frac{1}{8} C_D \rho d_f \omega^3 \sum_{i=1}^{m} n_i (4r_p^3 L_i + 6r_p^2 L_i^2 + 4r_p L_i^3 + L_i^4)
\]  

...(9)

Thus the actual power level \( (P) \) of hairs would be \( P \leq P_{\text{max}} \).

So, the power model developed in this section provides a useful tool to assess the relative impact of various parameters on the package energy consumption. It also allows us to calculate the power level of hairs if we know the number and length distribution of all the hairs on a package surface. We will verify this calculation method in the following section.
3. EXPERIMENTAL

3.1 The set-up

We used a simple experimental set-up to measure the power level during the rotation of a single yarn package. Figure 3 shows a photo and a schematic of the set-up we used. The set-up consists of the following key elements:

1. Spindle model \((A)\), driven by a tape from an electric motor \((B)\) (Voltage: 230/250 Volts; Frequency: 50 Hz; Current: 2.0 Amps)
2. A motor speed controller \((C)\) linked to the electric motor \((B)\)
3. An electric current meter \((D)\) and a voltage meter \((E)\), both linked to the motor speed controller \((C)\)
4. A separate tachometer \((F)\) to measure the actual spindle speed
5. A power source \((G)\) with an output voltage of 250V and output current of 10A.

We can read the current values [ampere] and voltage values [volt] directly from \((D)\) and \((E)\) to work out the power level during package rotation at a given spindle speed.

3.2 Materials and Method

(a). Quantitative Verification of the Theory

For simplicity, we used a polyester filament as model hairs. We used one empty bobbin (EP) and another empty bobbin with some model hairs (HP). The filament diameter is 92.8μm; the hair length is 50mm, 60mm, 70mm, and 80mm respectively; the hair number is 10, 12, 14, and 16 respectively; and the diameter of the bobbin is 27.5mm. We tested the power level for EP and HP at four spindle speeds, which are 7000rpm, 10000rpm, 13000rpm, and 16000rpm. We took 5 readings in each test and calculated the average power values of hairs as the measured results.

(b). Qualitative Verification of the Theory

We used two packages with worsted ring-spun wool yarns for the experiments. One package was an empty bobbin with one layer of normal yarn (NP), while the other
package was an empty bobbin with one layer of twice-wound yarn (WP). The yarn length of one layer is 40m in this experiment.

We tested the power level for NP and WP at four given spindle speeds, which are 7000rpm, 10000rpm, 13000rpm, and 16000rpm. We tested twice for every package conditions (NP and WP) at every spindle speed, and calculated the average values as the measured results. Then, we tested the yarn hairiness of four packages (two packages for NP and two packages for WP) on a Zweigle G565 Hairiness Meter, and calculated the average values of two packages as the yarn hairiness results of every package condition.

4. RESULTS AND DISCUSSION

4.1 Quantitative Verification of the Theory

We calculated the angular speed ($\omega$) and then the hair velocity ($V$, at the middle point of the hair) based on the spindle speeds, the radius of yarn package ($r_p$) = 13.8 mm, and the hair length (50mm, 60mm, 70mm, and 80mm respectively). Under standard testing conditions, air viscosity ($\mu$) = $18.22 \times 10^{-6}$ N s/m$^2$ and air density ($\rho$) = 1.197 kg/m$^3$ [13], so that we could calculate the Reynolds number ($Re$) using Equation (2). The drag coefficient ($C_D$) corresponding to the Reynolds number ($Re$) can be obtained from the established relationship between the drag coefficient and Reynolds number for long circular cylinder [13]. The results of angular speed ($\omega$), hair velocity ($V$), Reynolds number ($Re$) and drag coefficient ($C_D$) for four spindle speeds are shown in Table 1.
Table 1. Angular speed, hair velocity, Reynolds number, and Drag coefficient

<table>
<thead>
<tr>
<th></th>
<th>Spindle speed [rpm]</th>
<th>7000</th>
<th>10000</th>
<th>13000</th>
<th>16000</th>
</tr>
</thead>
<tbody>
<tr>
<td>Angular speed ($\omega$) [rad/s]</td>
<td></td>
<td>733</td>
<td>1047</td>
<td>1361</td>
<td>1675</td>
</tr>
<tr>
<td>Radius of yarn package (mm)</td>
<td></td>
<td>13.8</td>
<td>13.8</td>
<td>13.8</td>
<td>13.8</td>
</tr>
<tr>
<td>Average radius of hairs (mm)</td>
<td>hair length = 50mm</td>
<td>38.8</td>
<td>38.8</td>
<td>38.8</td>
<td>38.8</td>
</tr>
<tr>
<td></td>
<td>hair length = 60mm</td>
<td>43.8</td>
<td>43.8</td>
<td>43.8</td>
<td>43.8</td>
</tr>
<tr>
<td></td>
<td>hair length = 70mm</td>
<td>48.8</td>
<td>48.8</td>
<td>48.8</td>
<td>48.8</td>
</tr>
<tr>
<td></td>
<td>hair length = 80mm</td>
<td>53.8</td>
<td>53.8</td>
<td>53.8</td>
<td>53.8</td>
</tr>
<tr>
<td>Hair velocity ($V$) [m/s]</td>
<td>hair length = 50mm</td>
<td>28.44</td>
<td>40.62</td>
<td>52.81</td>
<td>64.99</td>
</tr>
<tr>
<td></td>
<td>hair length = 60mm</td>
<td>32.11</td>
<td>45.86</td>
<td>59.61</td>
<td>73.37</td>
</tr>
<tr>
<td></td>
<td>hair length = 70mm</td>
<td>35.77</td>
<td>51.09</td>
<td>66.42</td>
<td>81.74</td>
</tr>
<tr>
<td></td>
<td>hair length = 80mm</td>
<td>39.44</td>
<td>56.33</td>
<td>73.22</td>
<td>90.12</td>
</tr>
<tr>
<td>Reynolds number ($Re$)</td>
<td>hair length = 50mm</td>
<td>173.32</td>
<td>247.56</td>
<td>321.81</td>
<td>396.05</td>
</tr>
<tr>
<td></td>
<td>hair length = 60mm</td>
<td>195.65</td>
<td>279.46</td>
<td>363.28</td>
<td>447.09</td>
</tr>
<tr>
<td></td>
<td>hair length = 70mm</td>
<td>217.99</td>
<td>311.37</td>
<td>404.75</td>
<td>498.13</td>
</tr>
<tr>
<td></td>
<td>hair length = 80mm</td>
<td>240.32</td>
<td>343.27</td>
<td>446.22</td>
<td>549.17</td>
</tr>
<tr>
<td>Drag coefficient ($CD$)</td>
<td>hair length = 50mm</td>
<td>1.63</td>
<td>1.51</td>
<td>1.42</td>
<td>1.36</td>
</tr>
<tr>
<td></td>
<td>hair length = 60mm</td>
<td>1.58</td>
<td>1.47</td>
<td>1.39</td>
<td>1.33</td>
</tr>
<tr>
<td></td>
<td>hair length = 70mm</td>
<td>1.55</td>
<td>1.43</td>
<td>1.36</td>
<td>1.30</td>
</tr>
<tr>
<td></td>
<td>hair length = 80mm</td>
<td>1.52</td>
<td>1.40</td>
<td>1.33</td>
<td>1.27</td>
</tr>
</tbody>
</table>

The maximum power required to overcome the resistance of the hairs on HP was predicted by applying Equation (9) with $m = 1$ and $n = 10, 12, 14, \text{ and } 16$ respectively. The results are given in Table 2.
Table 2. The maximum power values (W) predicted from the theory

<table>
<thead>
<tr>
<th>hairs</th>
<th>Hair length (mm)</th>
<th>Spindle speed (rpm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>7000</td>
</tr>
<tr>
<td>16</td>
<td>50</td>
<td>2.36</td>
</tr>
<tr>
<td></td>
<td>60</td>
<td>4.10</td>
</tr>
<tr>
<td></td>
<td>70</td>
<td>6.68</td>
</tr>
<tr>
<td></td>
<td>80</td>
<td>10.29</td>
</tr>
<tr>
<td>14</td>
<td>80</td>
<td>9.00</td>
</tr>
<tr>
<td>12</td>
<td>80</td>
<td>7.72</td>
</tr>
<tr>
<td>10</td>
<td>80</td>
<td>6.43</td>
</tr>
</tbody>
</table>

Table 3 lists the measured actual power consumption results of hairs for different hair number, hair length, and spindle speed.

Table 3. The actual power values (W) measured during spindle rotation

<table>
<thead>
<tr>
<th>hairs</th>
<th>Hair length (mm)</th>
<th>Spindle speed (rpm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>7000</td>
</tr>
<tr>
<td>16</td>
<td>50</td>
<td>1.15</td>
</tr>
<tr>
<td></td>
<td>60</td>
<td>1.45</td>
</tr>
<tr>
<td></td>
<td>70</td>
<td>2.69</td>
</tr>
<tr>
<td></td>
<td>80</td>
<td>5.00</td>
</tr>
<tr>
<td>14</td>
<td>80</td>
<td>1.45</td>
</tr>
<tr>
<td>12</td>
<td>80</td>
<td>0.99</td>
</tr>
<tr>
<td>10</td>
<td>80</td>
<td>0.60</td>
</tr>
</tbody>
</table>

Tables 2 and 3 show that the theoretical maximum power values are greater than the experimental results except for the marked one in table 3. This may be due to the hair angle effect as we have discussed earlier. We took three photos to verify this effect (Figure 4). Figure 4a shows the hairs in a static condition before the test. Figure 4b
shows the position of hairs when the spindle was running at 7000rpm. Figure 4c gives a photo of the hairs taken from above the spindle when the spindle was running at 7000rpm in an anti-clockwise direction. It is obvious from these photos that the hair fibers stay perpendicular to the package surface due to the centrifugal force acting on the hair fibers at high spindle speed (Figure 4b), and that the hair fibers curve around (Figure 4c) the yarn package surface due to the different air drag forces acting along the length of each hair. The curved hair configuration will reduce the energy required to rotate the hairs at high speed.

4.2 Qualitative Verification of the Theory

Table 4 lists the average hair number of 40m length of yarn in different length groups, where N1 represents the number of hairs greater than or equals to 1mm but less than 2mm, N2 represents the number of hairs greater than or equals to 2mm but less than 3mm etc [27].

Table 4. The number of the yarn hairiness for different length group in 40m length yarn

<table>
<thead>
<tr>
<th>Package</th>
<th>N1</th>
<th>N2</th>
<th>N3</th>
<th>N4</th>
<th>N6</th>
<th>N8</th>
<th>N10</th>
<th>N12</th>
<th>N15</th>
</tr>
</thead>
<tbody>
<tr>
<td>NP</td>
<td>2581</td>
<td>873</td>
<td>431</td>
<td>300</td>
<td>89</td>
<td>40</td>
<td>19</td>
<td>5</td>
<td>0</td>
</tr>
<tr>
<td>WP</td>
<td>3817</td>
<td>1364</td>
<td>684</td>
<td>597</td>
<td>206</td>
<td>105</td>
<td>54</td>
<td>23</td>
<td>2</td>
</tr>
</tbody>
</table>

Table 5 gives the power level of normal yarn package (NP) and hairy yarn package (WP) under four different spindle speed levels.

Table 5. The power level (W) of NP and WP

<table>
<thead>
<tr>
<th>Package</th>
<th>Spindle speed (rpm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>7000</td>
</tr>
<tr>
<td>NP</td>
<td>37.45</td>
</tr>
<tr>
<td>WP</td>
<td>38.64</td>
</tr>
</tbody>
</table>
We analysed the results in Table 5 statistically with a paired *t*-test for the mean values. The difference in mean power values of the normal yarn package (NP) and the power level of the hairy yarn package (WP) is significant at the 5% level. This indicates that the increase in yarn hairiness has caused a statistically significant increase in the package power consumption. In reality, the effect of yarn hairiness may be much greater than that indicated in table 5, because of the large diameter of a full yarn package and the longer length of yarn on the package surface. Another result from Table 5 is that the power level increases with the spindle speed increase as expected. These results have confirmed, qualitatively, the importance of yarn hairiness on power consumption in ring spinning.

5. **CONCLUSION**

This study has examined the effect of yarn hairiness on power consumption in rotating a ring-spun yarn package. A model of predicting power required to overcome the air-resistance caused by rotating hairs during ring spinning has been established. The model highlights the importance of hair length, spindle speed, package size, and the number of hairs in determining the power consumption in rotating a ring-spun yarn package. The theoretical work has been verified experimentally, with the help of a single spindle ring spinning test rig. The implication of this research is that reducing yarn hairiness will help reduce the power consumption in ring spinning. Further research is still needed to develop a full power consumption model for the whole ring spinning process, taking into consideration of all spinning and yarn related parameters.

6. **ACKNOWLEDGMENTS**

We would like to thank Dr Niall Finn at CSIRO and Mr. Chris Hurren at Deakin University for assisting with the experimental work.
REFERENCES

Figure 1. Model of a yarn package with a hair rotating clockwise about package centre (z)
Figure 2. Model of a hair inclining towards yarn package surface
Figure 3. The experimental set-up for energy consumption measurement: (a) General view, and (b) Schematic
Figure 4. Photos of hairs – (a) Static case, (b) Dynamic case, and (C) Viewed from top