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Minimising Energy-consumption of Yarn Winding in Ring Spinning

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ABSTRACT

Ring spinning has been and will continue to be an important spinning system for making staple spun yarns from different fibres in the textile industry. But high power consumption and low productivity are outstanding problems of the ring spinning. Based on the analysis of power distribution during yarn winding in ring spinning with the principles of dynamics and aerodynamics, the models about the ratio of energy-consumption to yarn-production for a full yarn package are established. The spindle-speed, yarn-count and package-diameter are three key parameters to decrease energy-consumption and/or increase yarn-production during yarn winding in ring spinning. The effects of single-variable and multi-variables of these key parameters are discussed through case study. Suggestions for minimising energy-consumption during yarn winding in ring spinning are given.
1 Introduction

Because of the careful fibre control during the spinning process, ring spun yarns have a very high quality. The quality of ring spun yarns has been used as a benchmark against which the quality of yarns produced on other spinning systems is judged [7]. Therefore, ring spinning has been the dominant system of manufacturing high quality yarns for apparel applications. In recent years, leading European textile machinery manufacturers, such as Rieter (Switzerland) and Suessen (Germany), have invested heavily in further developing the ring spinning system to improve the quality of yarns.

Since twist is inserted into the tiny strand of fibres by the rotation of the relatively massive yarn package, the power consumption in ring spinning is much higher than that in other spinning systems for per unit yarn-production. In other words, high power consumption and/or low productivity are two outstanding problems of ring spinning. In addition, the newly formed yarn is under considerable tension during the spinning process and the need for reducing yarn breakage (or ends-down) is a key reason for the low productivity of ring spinning, particularly for spinning the high-demand fine yarns. This adds significantly to the cost of yarn-production and makes yarns produced on the ring spinning system very expensive, compared to yarns of lesser quality produced on the rotor and vortex systems.

Many studies have been carried out to address the issues of high power consumption and low productivity in ring spinning. Barr and Catling (1965) described power requirements in ring spinning [1]. Chang et al. examined the effect of yarn hairiness on power consumption during high speed rotation of a ring spun yarn package [4]. Clark et al. (1998) analysed and confirmed the effects of air-drag [5], Bracewell and Greenhalgh (1953) explored the effects of
traveller friction and yarn friction [3]. These effects make a contribution to the power consumption in ring spinning. But little has been reported in the literature on how to minimize the ratio of energy-consumption to yarn-production of yarn winding in ring spinning.

In this study, we will estimate yarn-production and analyze the distribution of power requirements using the principles of dynamics/aerodynamics during yarn winding in ring spinning. We will investigate the key parameters which affect energy-consumption and/or yarn-production, and show how the ratio of energy to production for winding a full yarn package can be calculated. Finally, we will discuss the effects of spindle-speed, yarn-count and package-diameter on the energy to production ratio.

We make the following assumptions in this paper (a) the yarn package is wound with the cop-build method in ring spinning; (b) the profiles of both the top and bottom conical ends are straight/linear; (c) the upper and lower chases have the same angle of \( \beta \) \( (0^\circ < \beta < 90^\circ) \); and (d) we ignore the effects of yarn hairiness and the skin friction drag caused by the exposed surface of the tube in a bobbin because the surface of a tube (empty bobbin) is quite smooth comparing to the surface of a yarn package.
2 Yarn-production of a full package

2.1 Yarn-production

Yarn-production is related to yarn linear density or count, which is usually expressed in tex (N) – mass in grams per kilometre of the yarn. During ring spinning, the yarn-count is pre-determined. So the amount of yarn produced within a given time [8] is:

\[ m_y(t) = N \nu_w t \quad (0 \leq t \leq T_p) \]  

(1)

where \( m_y(t) \) [mg] is the mass of the yarn wound onto a bobbin at time \( t \) [s], and \( N \) [tex] is yarn-count, \( \nu_w \) [m/s] is linear winding-on velocity (front delivery velocity) and \( T_p \) [s] is the total time taken to wind a full yarn package.

2.2 Spindle-speed and winding-on velocity

The spindle rotation is on full speed over 99% of yarn packaging time. The spindle-speed \( V(t) \) can be considered to be at full speed \( V_0 \) when yarn is wound onto a bobbin. Thus

\[ V(t) \approx V_0 \quad (0 \leq t \leq T_p). \]  

(2)

The linear winding-on velocity \( \nu_w \) [m/s] is proportional to the full spindle-speed \( V_0 \) [rps], since the twist level in the yarn is pre-determined before spinning. Let \( \nu_w = k_1 V_0 \), from Equation (1)

\[ m_y(t) \approx k_1 V_0 N t \quad (0 \leq t \leq T_p). \]  

(3)

Furthermore, the yarn-production on a full yarn package will become

\[ m_y = k_1 V_0 N T_p. \]  

(4)
3 Energy-consumption

We are mainly considering power requirements for overcoming skin friction drag, yarn wind-on tension and storing kinetic energy onto rotating bobbin during yarn winding in ring spinning. Based on our previous work [8], the energy consumed on skin friction drag and yarn wind-on tension is over 99%. The power requirements for overcoming the skin friction drag on the surface of a rotating yarn package and for overcoming the yarn wind-on tension, respectively,

\[
P_f(t) = \frac{1}{2} \rho (\pi d_p V(t))^3 S_p(t) C_f \quad (0 \leq t \leq T_p) \tag{5}
\]

\[
P_r(t) = 2\pi F(t)V(t)r_p(t) \quad (0 \leq t \leq T_p) \tag{6}
\]

where \(\rho\) [kg/m\(^3\)] is a constant and is equal to 1.197, \(C_f\) [dimensionless] is the skin friction coefficient on the surface of the yarn package, \(d_p\) [m] is the maximum diameter of the yarn package, \(V(t)\) [rps (revolutions per second)] is spindle-speed, \(S_p(t)\) [m\(^2\)] is the surface-area of the yarn package, \(F(t)\) [N] is the yarn wind-on tension and \(r_p(t)\) [m] is the distance from the centre line of the rotating bobbin to the yarn wind-on point at time \(t\) [s].

3.1 Simplification of \(S_p(t)\)

After winding the first complete layer or yarn, the surface area of a yarn package is

\[
S_a = (d_0 + 4d_y)\pi \frac{d_p - d_0}{2} \cot \beta . \tag{7}
\]

The surface area of the full yarn package will be

\[
S_b = [h_0 - (d_p - d_0)\cot \beta]\pi d_p + \frac{d_p - d_0}{2\sin \beta} (d_0 + d_p + 2d_y)\pi . \tag{8}
\]

Yarn diameter \(d_y\) in the Equations (7) and (8) can be estimated [2] by
\[ d_y = k_2 \sqrt{N} \]  

(9)

where \( d_y \) [m] is yarn diameter, \( N \) [tex] is yarn-count, \( k_2 \) [(g/cm\(^3\))\(^{-0.5}\)] is a constant.

For ease of calculation, we assume that the surface area of a yarn package increases evenly from \( S_a \) to \( S_b \) throughout the yarn packaging process. Furthermore, since the time taken to wind the first complete layer is less than 0.6% of \( T_p \) (the time used to wind a full yarn package), then

\[ S_p(t) \approx \frac{S_b - S_a}{T_p} t \]  

(0 \leq t \leq T_p)  

(10)

where \( S_a \) and \( S_b \) are given by Equations (7) and (8).

### 3.2 Simplification of \( F(t) \) and \( r_p(t) \)

The yarn wind-on tension during winding of a cop layer is variation. For the sake of simplicity in this study, \( F(t) \) can be considered to be the maximum yarn wind-on tension [1, 6]:

\[ F(t) \approx 0.4 \] [Newton]  

(0 \leq t \leq T_p).  

(11)

While winding yarn with the cop-build, \( r_p(t) \) varies between \( d_o/2 \) and \( d_p/2 \) within every complete layer in the main part [8]. The time used to wind the main part is over 93% of the total time used to wind the full yarn package. Therefore, \( r_p(t) \) can be considered to vary between \( d_o/2 \) and \( d_p/2 \) throughout the yarn packaging process. Furthermore, the \( r_p(t) \) evenly varies from \( d_o/2 \) to \( d_p/2 \) during main (up) winding and from \( d_p/2 \) to \( d_o/2 \) during cross (down) winding, respectively. So, when calculating the energy consumed on yarn wind-on tension (i.e., integrating over the interval 0 \( \leq t \leq T_p \)) with Equation (6), we can use that
3.3 Estimation of energy-consumption for a full package

Substituting Equations (2) and (10), and \( C_f = \alpha d_0 V_0^b / d_p \) [9] into Equation (5), and then integrating over the interval \( 0 \leq t \leq T_p \), the energy consumed by overcoming skin friction drag on the package surface for winding a full yarn package in ring spinning can be represented as

\[
E_f = \frac{d_0}{4} \rho \pi^3 d_p^2 V_0^3 (S_b - S_a) a V_0^b T_p \tag{13}
\]

where \( a \) and \( b \) are constants which can be determined by experiments, \( S_a \) and \( S_b \) can be obtained from Equations (7)–(9):

\[
S_a = (d_0 + 4 k_2 \sqrt{N}) \pi \frac{d_p - d_0}{2} \cot \beta
\]

\[
S_b = [h_0 - (d_p - d_0) \cot \beta] \pi d_p + \frac{d_p - d_0}{2 \sin \beta} (d_0 + d_p + 2k_2 \sqrt{N}) \pi.
\]

Substituting Equations (2), (11) and (12) into Equation (6), the energy consumed in overcoming yarn wind-on tension for winding a full yarn package in ring spinning can be written as

\[
E_F = 3.53 \pi (d_0 + d_p) N V_0 T_p \times 10^{-3}. \tag{14}
\]
4. Model of the ratio of energy-consumption to yarn-production

4.1 Definition

During yarn winding in ring spinning, the energy-consumption consists of three parts: (I) one part is used to overcome the drag force caused by the skin friction between the package surface and air around the surface (this part is transferred into heat and then lost during package rotation); (II) the next part (which includes the energy required to overcome the air drag on the balloon, the yarn/traveller and traveller/ring friction) is used to overcome the yarn wind-on tension (this part is transferred into work while the yarn is wound onto the package); (III) the final part is converted into the kinetic energy of rotating package when the angular acceleration generates and/or the package mass increases (this part will be released to overcome the skin friction drag when the spindle-speed decreases). However, about 99% of the energy is consumed in overcoming the skin friction drag and yarn wind-on tension during package rotation [8]. Therefore the energy-consumption per unit yarn-production, $R$ [J/mg], can be defined as

$$R = \frac{E_f + E_F}{m_y}$$  \hspace{1cm} (15)

where $m_y$ [mg] is the mass of yarn on the package, $E_f$ [J] is the energy consumed in overcoming skin friction drag on the package surface, $E_F$ [J] is the energy consumed in overcoming the yarn wind-on tension for winding a full yarn package in ring spinning.
4.2 Mathematical model

Substituting Equations (4), (13) and (14) into Equation (15), we obtain a model for the ratio of energy-consumption to yarn-production during yarn winding in ring spinning [10]:

\[
R = \frac{3.53 \pi (d_0 + z) \times 10^{-3}}{k_1} + \frac{a d_0 \rho \pi^4 x^{2 \beta} z^2 (h_0 \sin \beta - (z - d_0) \cos \beta)}{4k_1 y \sin \beta} \\
+ \frac{ad_0 \rho \pi^4 x^{2 \beta} z^2 (d_0 + 2k_2 \sqrt{y + z})(z - d_0)}{8k_1 y \sin \beta} - \frac{ad_0 \rho \pi^4 x^{2 \beta} z^2 (d_0 + 4k_2 \sqrt{y})(z - d_0) \cos \beta}{8k_1 y \sin \beta}
\]

(16)

over the set

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

where \(R [\text{J/mg}]\) is the ratio of energy-consumption to yarn-production, \(x [\text{rps}]\) is full spindle-speed \((V_0)\), \(y [\text{tex}]\) is yarn-count \((N)\), \(z [\text{m}]\) is the maximum diameter of a yarn package \((d_p)\), \(d_0 [\text{m}]\) is the minimum diameter of the yarn package, \(h_0 [\text{m}]\) is the total height of the full yarn package, \(\beta [\text{o}]\) is the chase angle of the full package, \(\rho [\text{kg/m}^3]\) is air density and is equal to 1.197, \(k_1 [\text{m/rev}]\) 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.

5. Discussion of main parameters

When \(d_0 = 0.025 \text{ m}, h_0 = 0.245 \text{ m}, \beta = 32^\circ, \rho = 1.197 \text{ kg/m}^3, k_1 = 0.002 \text{ m/rev}, k_2 = 3.6013 \times 10^{-5} (g/cm^3)^{-0.5}\) (the fibre density \(D = 1.52 \text{ g/cm}^3\) for the yarn which made of cotton), \(a = 148030\) and \(b = -2.575\) (obtained from experiments), then Equation (16) becomes

\[
R = 0.1386 + 5.5449z + (0.00064 x^{-0.575} y^{-0.5} z^2 - 0.0482 x^{-0.575} y^{-1} z^2 \\
- 0.0255 x^{-0.575} y^{-0.5} z^3 + 142.9175 x^{-0.575} y^{-1} z^3 - 354.2544 x^{-0.575} y^{-1} z^4) \times 10^5
\]

(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 \((V_0)\), \( y \) [tex] is yarn-count \((N)\), \( z \) [m] is the maximum diameter of a yarn package \((d_p)\).

### 5.1 Single-variable

**Spindle-speed \((V)\)**

For any given constant yarn-count and yarn package-diameter, from Equation (17), \( R \) is strictly monotone decreasing function with respect to spindle-speed. Figure 1 displays five curves which are corresponding to five data-pair of constant yarn-count and yarn package-diameter. When spindle-speed increases from 100 rps to 350 rps, the ratio of energy-consumption to yarn-production will decrease between 32.6% and 49.0%.

Figure 1 shows that, for any spindle-speed, the ratio of energy to production decreases noticeably when yarn-count from 10 tex to 38 tex, then to 120 tex for the same package-diameter (such as 0.045 m).

**Yarn-count \((N)\)**

For any given constant spindle-speed and yarn package-diameter, from Equation (17), \( R \) is strictly monotone decreasing function with respect to yarn-count. Figure 2 displays five curves which are corresponding to five data-pair of constant spindle-speed and yarn package-
When yarn-count increases from 38 tex to 225 tex, the ratio of energy-consumption to yarn-production will decrease between 56.0% and 71.1%.

Figure 2 shows that, for given spindle-speed and pre-designed package-diameter, the ratio of energy to production decreases rapidly when yarn-count from 5 tex increases to 30 tex, and then varies flatly when yarn-count increases continuously.

For any given constant spindle-speed and yarn-count, from Equation (17), \( R \) is strictly monotone increasing function with respect to yarn package-diameter. Figure 3 displays five curves which are corresponding to five data-pair of constant spindle-speed and yarn-count. When yarn package-diameter increase from 0.045 m to 0.065 m, the ratio of energy-consumption to yarn-production will increase between 77.3% and 182.7%.

Figure 3 shows that, when spindle-speed is slow and pre-designed yarn-count is small, the ratio of energy to production increases very quickly if package-diameter increases from 0.025 m into 0.065 m. Therefore, we may increase suitably spindle-speed for design of winding fine yarn.

### 5.2 Multi-variables

Since it takes time to replace the yarn bobbin and it consumes energy to re-start up during replacing the bobbin, the small diameter of yarn package is not necessary for considering. We
only consider that the diameter of a full yarn package is not less than 0.045 m. Furthermore, general speaking, in the most of practice time,

- Yarn-count is not less than 10 tex and is not greater than 120 tex, and
- Spindle-speed is greater than 100 rps (6000 rpm) and less than 250 rps (15000 rpm).

Next, we are mainly discussing objective function

\[
R = 0.1386 + 5.5449z + (0.00064 x^{-0.575} y^{-0.5} z^2 - 0.0482 y^{-0.575} y^{-1} z^2
- 0.0255 x^{-0.575} y^{-0.5} z^3 + 142.9175 x^{-0.575} y^{-1} z^3 - 354.2544 x^{-0.575} y^{-1} z^4) \times 10^5
\]  

over the set

\[S' = \{(x, y, z): 250 \geq x \geq 100, 120 \geq y \geq 20, 0.065 \geq z \geq 0.045\}.\]

**Yarn-count (N) and package-diameter (d_p)**

If the spindle-speed in ring spinning is given as 167 rps (i.e., \(x = 167\)), then Equation (18) becomes

\[
R_1 = 0.1386 + 5.5449z + 3.3738 y^{-0.5} z^2 - 254.0885 y^{-1} z^2
- 134.4244 y^{-0.5} z^3 + 753396.2249 y^{-1} z^3 - 1867468.4880 y^{-1} z^4
\]

over the set

\[S_1 = \{(y, z): 120 \geq y \geq 10, 0.065 \geq z \geq 0.045\}.\]

Figure 4 shows that the ratio of energy-consumption to yarn-production for a full package is about 3 J/mg for most of the area in \(S_1 = \{(y, z): 120 \geq y \geq 10, 0.065 \geq z \geq 0.045\}\) when a full spindle-speed is given as 167 rps during yarn winding in ring spinning. In particular, \(R\) will
get the minimum value 0.8916 J/mg at point spindle-speed = 167 rps, yarn-count = 120 tex and package-diameter = 0.045 m.

However, the ratio is very high if yarn-count is less than 30 tex and yarn package-diameter is greater than 0.055 m. For example, \( R \) will get the maximum value 17.7411 J/mg at point spindle-speed = 167 rps, yarn-count = 10 tex and package-diameter = 0.065 m.

**Spindle-speed (V) and Yarn package-diameter \( (d_p) \)**

If the yarn-count in ring spinning is given as 38 tex (i.e., \( y = 38 \)), then Equation (18) becomes

\[
R_2 = 0.1386 + 5.5449z - 116.4599 x^{-0.575}z^2 + 375685.0196 x^{-0.575}z^3 - 932248.4211 x^{-0.575}z^4
\]

over the set

\[
S_2 = \{(x, z): 250 \geq x \geq 100, 0.065 \geq z \geq 0.045\}.
\]

Figure 5 shows that the ratio of energy-consumption to yarn-production for a full package is about 3 J/mg for most of the area in \( S_2 = \{(x, z): 250 \geq x \geq 100, 0.065 \geq z \geq 0.045\} \) when a yarn-count is selected as 38 tex during yarn winding in ring spinning. In particular, \( R \) will get the minimum value 1.6495 J/mg at point spindle-speed = 250 rps, yarn-count = 38 tex and package-diameter = 0.045 m.

However, the ratio is very high if spindle-speed is less 120 rps and yarn package-diameter is greater than 0.05 m. For example, \( R \) will get the maximum value 6.5901 J/mg at point spindle-speed = 100 rps, yarn-count = 38 tex and package-diameter = 0.065 m.
Spindle-speed \((V)\) and yarn-count \((N)\)

If the yarn package-diameter in ring spinning is given as 0.045 m (i.e., \(x_3 = 0.045\)), then Equation (18) becomes

\[
R_3 = 0.3881 - 0.1028 x^{-0.575} y^{-0.5} + 1147.3088 x^{-0.575} y^{-1}
\]

over the set

\[
S_3 = \{(x, y) : 250 \geq x \geq 100, \ 120 \geq y \geq 10\}.
\]

Figure 6 shows that the ratio of energy-consumption to yarn-production for a full package is about 1.5 J/mg for most of the area in \(S_3 = \{(x, y) : 250 \geq x \geq 100, \ 120 \geq y \geq 10\}\) when yarn package-diameter is selected as 0.045 m during yarn winding in ring spinning. In particular, \(R\) will get the minimum value 0.7874 J/mg at point spindle-speed = 250 rps, yarn-count = 120 tex and package-diameter = 0.045 m.

However, the ratio is very high if spindle-speed is less 120 rps and yarn-count is less than 20 tex. For example, \(R\) will get the maximum value 8.5081 J/mg at point spindle-speed = 100 rps, yarn-count = 10 tex and package-diameter = 0.045 m.
6. Conclusion

Models for predicting the ratio of energy-consumption to yarn-production for a full package during yarn winding in ring spinning are established. The effects of single-variable and multi-variables of three key parameters (such as spindle-speed, yarn-count and package-diameter) are discussed during yarn winding, respectively. It is found 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.

It should be noted that in this study, the time used to replace the yarn bobbin and the energy consumed on replacing the bobbin (re-start up, etc.) are not considered.

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Literature Cited


Figure 1 Ratio of energy-consumption to yarn-production for given yarn-count (N) and package-diameter (dp).
Figure 2  Ratio of energy-consumption to yarn-production for given spindle-speed (V) and package-diameter (dp).
Figure 3  Ratio of energy-consumption to yarn-production for given spindle-speed (V) and yarn-count (N).
Figure 4. Ratio of energy-consumption to yarn-production for a full package during yarn winding in ring spinning when spindle-speed is constant (167 rps).
Figure 5. Ratio of energy-consumption to yarn-production for a full package during yarn winding in ring spinning when yarn-count is constant (38 tex).
Figure 6. Ratio of energy-consumption to yarn-production for a full package during yarn winding in ring spinning when package-diameter is constant (0.045 m).