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# Skin Friction Coefficient on Yarn Package Surface in Ring Spinning

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## Abstract

The skin friction coefficient on the surface of a rotating yarn package affects the power required to drive the yarn package. This paper examines the relationship between the skin friction coefficient on the package surface and the diameter and rotating speed of the package, based on the fundamentals of aerodynamics and the experimental results of power consumption. The skin friction coefficients on the surfaces of airplane, car top and yarn package have been discussed. The results indicate that the skin friction coefficient on the package surface without hairiness depends on the package diameter and spindle speed only. The skin friction coefficient on the yarn package surface is about 3-times of that on the top surface of a car, and is about 20-times of that on an airplane surface. The power consumed on overcoming skin friction drag is more than that consumed on driving spindle if spindle speed is very slow. However the situation is reversed when spindle speed is fast.

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# 1 Introduction

Air drag plays a special role during yarn processing. Without it, neither up-twisting nor winding-up would be possible [2]. However, the drag increases energy consumption in ring spinning. Reducing power consumed on air drag during yarn winding is one of the critical problems for increasing productivity. It is therefore very important to predict and then control the drag in ring spinning.

One of present authors investigated the characteristics of air drag on the ring spinning balloon [4, 6–9], such as air drag magnitude and its effects on balloon shape, the relationship between the air drag and yarn tension in balloon, and so on. But no research of air drag on the surface of a rotating yarn package has been reported in the literature.

Air drag on any aerodynamic body is composed of pressure drag and skin friction drag [1]. The drag on the surface of a rotating yarn package is mainly caused by skin friction because there are same pressure environments around the package. Many researchers [3, 5, 10–12, 14, 15, 17, 18, 20] have made their contribution to the measurement and reduction of the skin friction drag in different fields, such as aircraft and ships. There are some formulae for calculating skin friction drag for linear motion [1, 19], but they are difficult to apply to a rotating yarn package because the package's profile varies with winding-on time in ring spinning. So we will concentrate on the skin friction coefficient on the surface of a rotating yarn package in our present study.

There exists a model for the skin friction coefficient on the surface of an object (such as an aircraft) for linear motion, in which the skin friction coefficient relies on flow velocity and, in general, the velocity is very high. For example, an airplane may cruise at a velocity of 220 meter per second (492 miles per hour) at an altitude of 10058 m (i.e., 33,000 ft). In contrast, the linear velocity at the surface of a rotating yarn package is much smaller. So the model for high velocity object may not be suitable for the rotating package problem.

In the present paper, we will develop a model of skin friction coefficient on the surface of a rotating yarn package based on the experimental data and the principles of dynamics and aerodynamics.

## 2 Theoretical

### 2.1 Incompressible and laminar flow

In aerodynamics, the Mach number ($M$) is defined as the ratio of the flow velocity to the speed of sound. When Mach number is less than 0.3, it is always safe to assume air density $\rho$ to be a constant, so the flow can be considered to be incompressible.

In commercial ring spinning, the maximum surface velocity of a yarn package is usually much lower than 70 m/s. At standard sea level conditions, the speed of sound is $a_\infty$ = 3.402×10$^2$ m/s [1], which will give a Mach number of less than 0.2 in the case of a rotating yarn package. So the flow around the rotating package can be considered to be incompressible. In addition, the airflow near the package surface is a laminar flow.

## 2.2 Effects of package diameter and spindle speed

For incompressible and laminar flow, there is a relationship between skin friction coefficient ($C_f$) and Reynolds number ($Re$) [1] as below:

$$C_f = \frac{1.328}{\sqrt{Re}} \tag{1}$$

and the value of Reynolds number ($Re$) for flow over a circular-cylinder having diameter of $d$ [m] can be obtained by:

$$Re = \frac{\rho \upsilon d}{\mu} \tag{2}$$

where $\rho$ [kg/m$^3$] is air density, $\upsilon$ [m/s] is linear velocity, $\mu$ [kg/m•s] is air viscosity.

Now we apply Equations (1) and (2) in ring spinning system. At a point on the package surface with diameter $d$,

$$C_f = \frac{1.328}{d\sqrt{V}}\sqrt{\frac{\mu}{\rho\pi}} \tag{3}$$

In Equation (3), $\sqrt{\frac{\mu}{\rho\pi}}$ is a constant in the environment of ring spinning. Therefore, skin friction coefficient $C_f$ on the package surface is inversely proportional to the diameter $d$ and the square root of the full spindle speed $V$. Furthermore, the product of skin friction coefficient, $C_f$, on the package surface and the diameter, $d$, of the package is a constant at any given spindle speed $V$ (> 0) during yarn winding in ring spinning.

Let $d_0$ [m] be the minimum diameter of a yarn package (eg. a package with only one layer of yarn), $C_{f0}$ the skin friction coefficient on the surface of the package having diameter $d_0$, $C_f$ the skin friction coefficient on the surface of the package having diameter $d$ ($d \geq d_0$). For any given spindle speed $V$ (> 0), from Equation (3)

$$d_0 C_{f0} = d C_f$$

i.e.,

$$C_f = \frac{d_0}{d} C_{f0} \qquad (4)$$

From $d \geq d_0$, we have that $C_f \leq C_{f0}$. In particular, when $d_0$ is the minimum diameter of a bobbin with only one layer of yarn, we call $C_{f0}$ the maximum skin friction coefficient on the surface of the bobbin or yarn package. Equation (4) indicates that the skin friction coefficient at any point on the surface of a rotating yarn package is proportional to the maximum skin friction coefficient and is inversely proportional to the diameter at the point of the yarn package.

### 2.3 Formulation of the maximum skin friction coefficient of a yarn package

A yarn package, being a circular-cylinder with diameter of $d$, rotates at a given full spindle speed $V$, the total skin friction drag on the package surface can be obtained by [1],

$$D_f = \frac{1}{2} \rho (\pi d V)^2 S_p C_f \qquad (5)$$

and

$$P_f = \frac{1}{2}\rho(\pi dV)^3 S_p C_f \qquad (6)$$

where $P_f$ [W] is the power required to overcome skin friction drag $D_f$ [N], $C_f$ [dimensionless] is the skin friction coefficient, $V$ [rps] is full spindle speed, $d$ [m] is the diameter and $S_p$ [$m^2$] is the surface-area of the yarn package.

In the period of measuring power consumed on a rotating yarn package, one part of the power consumption is due to skin friction drag on the surface of the yarn package while the other part is due to driving the spindle (including power consumption by the electric motor, tape, gear, etc). Let $P_i$ be the total power which is consumed by a rotating yarn package having diameter of $d_i$, $P_{fi}$ the power consumption due to skin friction drag on the surface of a yarn package having diameter of $d_i$ ($i$ = 1, 2, and $d_1 < d_2$), $P_0$ the power consumed driving the spindle, thus

$$P_1 = P_0 + P_{f1} \qquad (7)$$

and

$$P_2 = P_0 + P_{f2} \qquad (8)$$

From Equations (4) and (6)–(8)

$$P_2 - P_1 = \frac{1}{2}\rho\pi^3 d_0 V^3 C_{f0}(d_2^2 S_2 - d_1^2 S_1) \qquad (9)$$

As the packages used in experiments are circular-cylinders with height of $h$, we have

$$C_{f0} = \frac{2(P_2 - P_1)}{\rho \pi^4 h d_0 V^3 (d_2^3 - d_1^3)} \qquad (10)$$

In Equation (10), $\rho$ and $\pi$ are constants, $d_0$, $d_1$, $d_2$, and $h$ can be measured before the experiment starts, spindle speed $V$ can be read from speed meter and powers $P_1$ and $P_2$ can be calculated based on the measured values of current and voltage during the experiments.

# 3 Experimental

## 3.1 The set-up

We used a single spindle experimental rig  to measure the level of power consumption during the rotation of a single yarn package. Figure 1 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] from (*D*) and voltage values [volt] from (*E*) at any given speed [rpm] which can be directly obtained from Tachometer (*F*) during package rotation.

### 3.2 Materials and testing methods

We used a 38 tex cotton yarn and the roving build method to wind two yarn packages. The packages have the same height $h$ of 0.245 m. After winding the packages with the 38 tex cotton yarn, we removed the hairiness on the package surface via singeing and measured the package diameters. For each of the two packages, we took the diameter measurements at two ends and in the middle, and used their average as the diameter of the package. The first yarn package has a diameter $d_1$ of 0.028 m and the second one has a diameter $d_2$ of 0.034 m.

We tested each of the two packages twice at spindle speeds ranging from 33 rps (2000 rpm) to 267 rps (16000 rpm), in steps of 33 rps (2000 rpm). For each of the packages at different spindle speeds, we took the average values of the current and voltage reading from the test device and used these readings to calculate the power consumption at a given spindle speed.

## 4 Results and Discussion

### 4.1 The maximum skin friction coefficient $C_{f0}$

We collected the measured current and voltage values and worked out the power consumption corresponding to each of varying spindle speeds as shown in Table 1. Substituting $\rho = 1.197$ kg/m$^3$, $h = 0.245$m, $d_0 = 0.025$m, $d_1 = 0.028$m and $d_2 = 0.034$m into Equation (10), we obtain

$$C_{f0} = 161390(P_2 - P_1)/V^3 \qquad (11)$$

The maximum skin friction coefficients $C_{f0}$ at varying spindle speed are shown in the third column in Table 2. Furthermore, from (4), we can calculate skin friction coefficients $C_{f1}$ and $C_{f2}$ on the surface of the packages which have diameters $d_1$ of 0.028 m and $d_2$ of 0.034 m, respectively. The details are shown in Table 2.

Based on the data in the third column in Table 2, we can establish the following relationship between the maximum skin friction coefficient $C_{f0}$ (for $d_0$ = 0.025 m) and varying spindle speed $V$ (also see Figure 2):

$$C_{f0} = 148030V^{-2.575} \tag{12}$$

Table 1 Power consumption at varying spindle speed

| Package 1 | | | Package 2 | | |
|---|---|---|---|---|---|
| Spindle speed ($V$) | | Power 1 | Spindle speed ($V$) | | Power 2 |
| [rpm] | [rps] | [W] | [rpm] | [rps] | [W] |
| 2000 | 33 | 10.644 | 2000 | 33 | 14.996 |
| 4000 | 67 | 16.681 | 4000 | 67 | 22.164 |
| 6000 | 100 | 23.923 | 6000 | 100 | 30.400 |
| 8000 | 133 | 32.148 | 8000 | 133 | 39.500 |
| 10000 | 167 | 42.092 | 10000 | 167 | 50.250 |
| 12000 | 200 | 53.350 | 12000 | 200 | 62.278 |
| 14000 | 233 | 67.721 | 14000 | 233 | 77.328 |
| 16000 | 267 | 84.375 | 16000 | 267 | 94.607 |

Table 2 The skin friction coefficient at varying spindle speed for three diameters

| Spindle speed ($V$) | | $C_{f0}$ | $C_{f1}$ | $C_{f2}$ |
|---|---|---|---|---|
| [rpm] | [rps] | ($d_0$ = 0.025 m) | ($d_1$ = 0.028 m) | ($d_2$ = 0.034 m) |
| 2000 | 33 | 18.9640 | 16.9321 | 13.9441 |
| 4000 | 67 | 2.9865 | 2.6666 | 2.1960 |
| 6000 | 100 | 1.0453 | 0.9333 | 0.7686 |
| 8000 | 133 | 0.5006 | 0.4469 | 0.3681 |
| 10000 | 167 | 0.2844 | 0.2539 | 0.2091 |
| 12000 | 200 | 0.1801 | 0.1608 | 0.1324 |
| 14000 | 233 | 0.1220 | 0.1090 | 0.0897 |
| 16000 | 267 | 0.0871 | 0.0778 | 0.0640 |

### 4.2 General skin friction coefficient $C_f$

As described in the previous sections, let $d_0$ [m] be the minimum diameter of a yarn package, $C_{f0}$ the skin friction coefficient on the surface when the package has diameter of $d_0$, $C_f$ the skin friction coefficient on the surface when the package has diameter of $d$, $V$ a given full spindle speed, then $C_f$ is equal to $\frac{d_0}{d} C_{f0}$ and $C_{f0}$ approximates to $aV^b$, thus

$$C_f = \frac{d_0}{d} aV^b \tag{13}$$

where $a$ and $b$ are constants which can be determined from experiments: $a$ = 148030 and $b$ = –2.575 for $d_0$ = 0.025 in this study.

During yarn winding in ring spinning, the package profile varies with winding-on time and is not of a strictly cylindrical shape. For a full yarn package, the surface area of the main part (with the maximum package diameter) is about 90% of the yarn package surface. In order to simplify the calculation, the skin friction coefficient on the surface of the yarn package can be considered to be the skin friction coefficient on the surface of the main part of this yarn package. Let $d_p$ [m] be the maximum diameter of a yarn package, then the yarn package can be considered to be a cylinder having diameter $d_p$. Using Equation (13), we can predict skin friction coefficient on the surface of the package.

For example, if the maximum diameter $d_p$ is equal to 0.045 m during yarn winding in ring spinning, the skin friction coefficient on the surface of the package can be estimated by

$$C_{fp} = 82239V^{-2.575} \quad (14)$$

where $V$ [rps] is full spindle speed. A curve of the skin friction coefficient corresponding to Equation (14) is shown in Figure 2. In particular, for a given full spindle speed of 200 rps (i.e., 12000 rpm), the skin friction coefficient on package surface is about 0.098.

### 4.3 Power consumed on overcoming the skin friction drag

In the above experiments, the power consumed on a rotating yarn package consists of the power to overcome the skin friction drag and the power to drive the spindle rotation. Using Equation (13), we can calculate the skin friction coefficient on the surface of package 1 and package 2 at varying spindle speeds, respectively. Then the power to overcome the skin friction drag on the surface of the packages can be calculated with Equation (6). Subtracting this power from the total power consumed on a rotating yarn package, we obtain the power consumed on driving the spindle. Some special values are shown in Figure 3.

### 4.4 Comparison of power consumed on overcoming skin friction drag and on driving the spindle

Figure 3 shows that for any given spindle speed, the power consumed on overcoming the skin friction drag on the surface of package 2 is higher than that on package 1. The difference is larger when spindle speed is faster.

When spindle speed is slow (such as 33 rps), the power consumed on overcoming the skin friction drag is more than that on driving the spindle; when spindle speed increases to 100 rps, the power consumed on driving spindle is more than that on overcoming the skin friction drag. As the spindle speed increases, the power consumption on driving the spindle increases much faster than the power consumption on overcoming the skin friction drag. However, the power consumed on driving a spindle as a proportion of the total power consumption for yarn winding during ring spinning may decrease if the electric motor drives multi-spindles.

### 4.5 Comparison of skin friction coefficient on the surface of plane, bus and yarn package

The average value of skin friction coefficient on an aircraft surface, in practice, is about 0.005 for good profiles [1, 16]. For the top surface of a car with a smooth body, the skin friction coefficient is 0.03 [19]. In general, based on the above calculation, the skin friction coefficient for the package surface (when a given full spindle speed is 200 rps or 12000 rpm and the package diameter is 0.045 m) is 0.098. This value is reasonable because: (1) the linear velocity on the package surface is about one eighth of aircraft velocity, and the slower the velocity, the higher the skin friction coefficient on the surface; (2) the surface of a yarn package is much rougher than the top surface of a car, and the rougher the surface, the higher the skin friction coefficient for the same linear velocity.

## 5 Conclusion

The experiments of testing the power consumed on a rotating yarn package were performed. It is found that the skin friction coefficient on the package surface without hairiness depends on the package diameter and spindle speed only. The skin friction coefficient on the yarn package surface is about 3-times of that on the top surface of a car, and is about 20-times of that on an airplane surface. The power consumed on overcoming skin friction drag is more than that consumed on driving spindle if spindle speed is very slow. However the situation is reversed when spindle speed is fast. While the experiments have been conducted on yarn packages with the hairs removed by singeing, the procedures reported in this paper can also be applied to normal yarn packages with a hairy surface. This will enable accurate estimation of the skin friction coefficient during ring spinning, which is required for the calculation of energy consumption in ring spinning.

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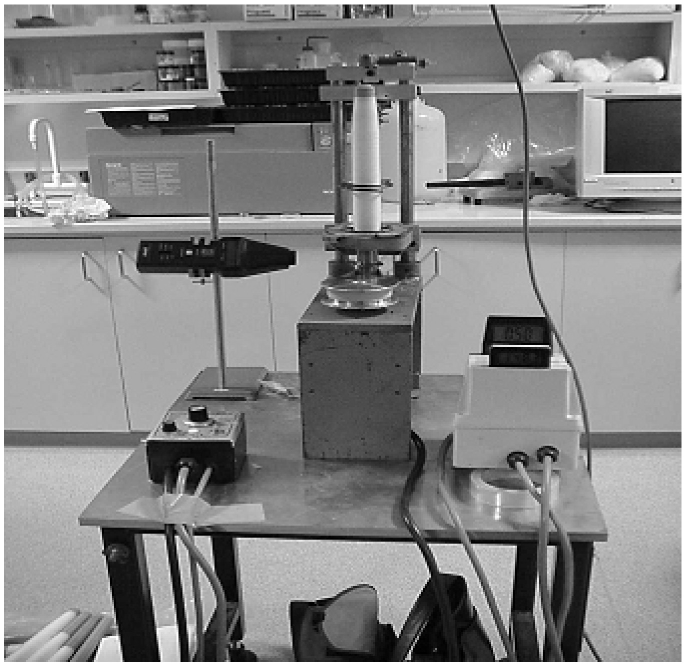
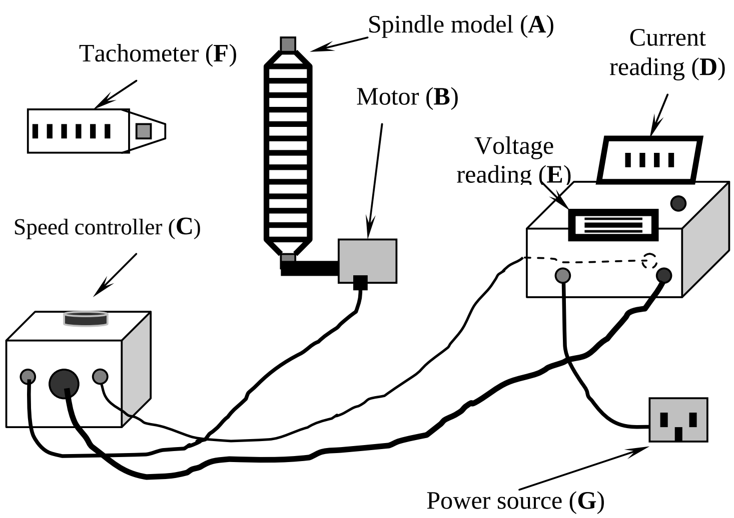


(*a*)




(*b*)

Figure 1 The experimental set-up for measuring power consumption during the rotation of a single yarn package: (*a*) General view and (*b*) Diagram.

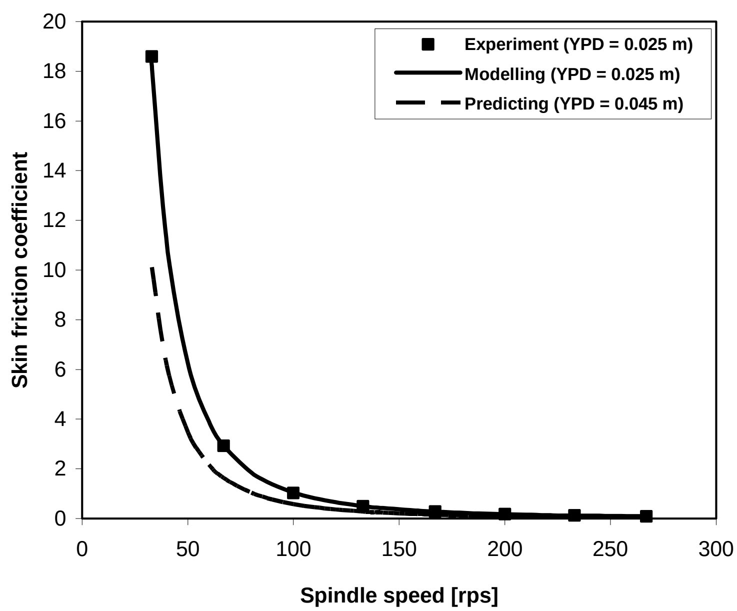



Figure 2 Modeling of skin friction coefficient on a package surface for YPD (yarn package diameter) = 0.025 m and predicting for YPD = 0.045 m.

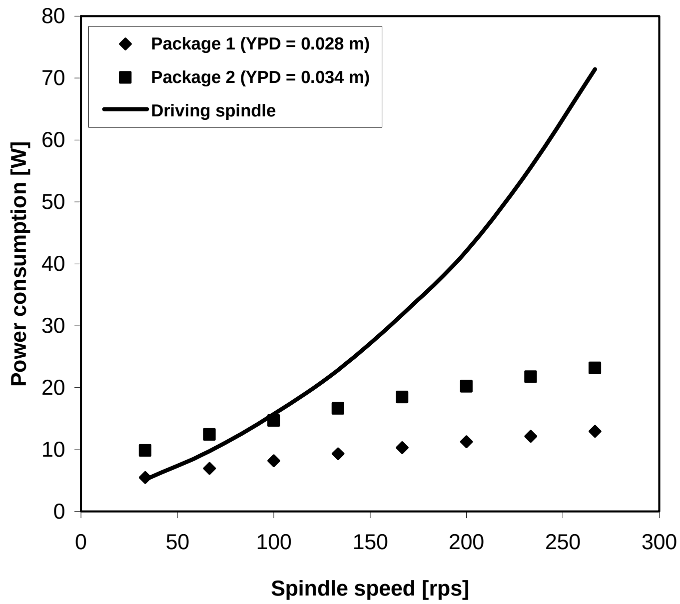



Figure 3 Comparison of powers consumed on overcoming skin friction drag and driving spindle during yarn winding.