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Theoretical Profile of Ring-Spun Slub Yarn and its Experimental Validation

Abstract
A mathematical model for the yarn count of ring-spun slub yarn was established to predict the yarn profile based on process parameters such as the fibre length, the velocities of rollers and the time of over-feeding. The theoretical study shows that the slub length depends mostly on the process parameters above. The actual slub length is a fibre length greater than the slub length designed, and the actual length of basic yarn is a fibre length less than the length of basic yarn designed. The validity of the model was then verified using four sets of experiments. The experimental results agreed well with the model predictions and showed that the present model had high prediction accuracy, which may aid in the design and production of a desired slub yarn with controlling spinning parameters.

Key words: *slub yarn, mathematical model, slub profile, slub length, basic yarn length.*

Introduction

Fancy yarns, because of their abundance of special aesthetic and structural effects of the textile materials in which they are used, have attracted much interest in recent years [1 - 3]. These yarns give decorativeness, improve the appearance of a garment and change the end-use properties of a fabric [4 - 6].

Slub yarn, as one of the fancy yarns, is now increasingly used for almost all kinds of textile products, such as denim garments, shirts and upholstery, due to its unique style and bamboo-like profile [7 - 9]. To date, a variety of methods are available for producing slub yarns, like ring-spun slub yarns and rotor-spun slub yarns. In these methods, ring spinning is the earliest and also the most common processing technology in slub yarn production at the present time. A well-known method in this process is to modify the ring spinning frame in such a way that the intermittent acceleration of the drafting rollers causes constantly varying degrees of draft to be applied [10]. In earlier research on slub yarn, Testore and Minero [11] proposed and discussed a classification and standardisation for the determination of the fundamental parameters that characterise slub-type fancy yarns. Grabowska [12] studied and characterised the basic parameters describing the structure and tensile properties of slub fancy yarn produced on a ring-twisting frame. Wang and Huang [13] discussed and analysed the parameters of rotor spun slub yarns in detail. Recently Lu, Gao and Wang [14] established a mathematical model based on the bar torsion model to describe twist distribution in slub yarn. Liu et al. [15] presented an analytical method of determining slub yarn geometrical parameters based on a 2D visualisation image of a slub yarn. However, there is still a lack of adequate understanding of this process, especially the relationship between process parameters and the profile of slub yarn in the spinning process. For example, the actual slub length of slub yarn is not exactly equal to the length designed in actual yarn production.

In this work, the intermittent acceleration of the drafting rollers by controlling stepper motors in ring spinning, causing constantly varying degrees of draft to form randomly distributed slubs (thick places) in the yarn, was adopted to experimentally and theoretically study the relationship between the yarn count and some important process parameters such as the fibre length, roller velocity, running time.

Mathematical model

In this study, slub yarn was produced by changing the speeds of the back-mid rollers while the front roller ran with a constant speed to deliver the sliver at a constant rate, which caused a variation in the resultant yarn fineness. Slub yarns were considered using the overfeeding of the back-mid roller method in the 3-over-3 apron drafting system. After initial stretching and drafting between the back rollers and middle rollers, the sliver was fed into the drafting zone (middle and front rollers). The speed of back-mid rollers varied with an intermittent acceleration, which was equivalent to additional fibre feeding into the drafting zone, allowing the production of slub yarns.

Generally the characteristics of slub yarn depend mainly upon how and where the fibres in the sliver are accelerated and overfed, hence the speed, acceleration time, deceleration time and highest speed time of the accelerated rollers are of crucial importance.

In order to simplify the problem, we can make some assumptions:

a) The drawing process is ideal for slub yarn production, *i.e.,* a part of fibres, whose headend, which is defined as the leading end of the fibre while moving, arrive at the front roller nip in a ring frame, are then gripped and move immediately at a linear speed of the front roller, while any other fibres in the drawing zone keep their original speed of back-mid rollers. There are no floating fibres during drafting.

b) All the fibres have the same fibre length (l) and fibre fineness (N_{tf}).

c) The fineness of the sliver (N_{tc}) and distribution density of fibre headends in the sliver (m_c) are constant. Thus the number of fibres (n_c) in a cross-section of sliver and the distribution density (m_c) of fibre headends in a sliver can be expressed as

$$n_c = \frac{N_{tc}}{N_{tf}} \tag{1}$$

$$m_c = \frac{n_c}{l} = \frac{N_{tc}/N_{tf}}{l} = \frac{N_{tc}}{N_{tf} \times l} \tag{2}$$

If we consider the front roller nip as the ordinate origin and take the traveling direction of the yarn as the X axis towards the right as positive, the distribution density (m_x) of fibre headends in the yarn at a random position x along the X axis can be expressed as

$$m_x = \frac{m_c \times V_2(x)}{V_1} \tag{3}$$

where V_1 is the linear velocity of the front roller, and $V_2(x)$ is the instantaneous velocity of the back-mid roller when the random position yarn moves through the front roller nip.

The number of fibres in the cross-section of yarn at a random position x can be written in the form of ***Equation 4***.

$$\begin{aligned} n_x(x) &= \int_x^{x+l} m_x dx = \int_x^{x+l} \frac{m_c \times V_2}{V_1} dx = \\ &= \frac{N_{tc}}{N_{tf} \times l \times V_1} \int_x^{x+l} V_2 dx \end{aligned} \tag{4}$$

where $n_x(x)$ is the number of fibres at a random position x in the X axis.

Thus the yarn fineness can be expressed as

$$N_{tx}(x) = n_x(x) \times N_{tf} = \frac{N_{tc}}{l \times V_1} \int_x^{x+l} V_2 dx \tag{5}$$

As described above, N_{tc}, l, V_1 are constant and we can let $N_{tc}/lV_1 = A$. Thus the above equation can be simplified as

$$N_{tx}(x) = A \int_x^{x+l} V_2 dx \tag{6}$$

Thus the average linear density of slub yarn between positions x and $x + \Delta l$ can be written in the form of ***Equation 7***,

$$\begin{aligned} \overline{N_{tx}} &= \frac{1}{\Delta l} \int_x^{x+\Delta l} N_{tx}(x) dx = \\ &= \frac{N_{tc}}{\Delta l \times l \times V_1} \int_x^{x+\Delta l} \int_x^{x+l} V_2 dx^2 = \\ &= \frac{A}{\Delta l} \int_x^{x+\Delta l} \int_x^{x+l} V_2 dx^2 \end{aligned} \tag{7}$$

where the value of Δl is very small.

During the formation of slub yarn, the overfeeding of fibres, which can be caused by an acceleration of the back-mid rollers, which passes additional fibres to the drawing zone, will generally affect the size of the resulting slub. Generally the more the overfeeding fibres to the drawing zone, the greater the slub. The size and profile of the slub will also vary with a number of other variables, such as the linear velocities of the drawing rollers, the acceleration time, deceleration time and running time at the highest speed of the back-mid rollers. All of these may be varied to produce a finished yarn with the qualities desired. We assume that the linear velocity of the back-mid rollers are V_{21} and V_{22}, respectively, at the lowest and highest constant speed during the running time of t_1 and t_{22}, respectively. The acceleration time of the back-mid rollers from the lowest constant speed (V_{21}) to the highest constant speed (V_{22}) is t_{21}, and the deceleration time from V_{22} to V_{21} is t_{23}, as shown in ***Figure 1.a***. Here we define the whole time of slub spinning as

$$t_2 = t_{21} + t_{22} + t_{23}.$$

According to the spinning principle of slub yarn, some basic conditions such as

$$t_1 V_1 \geq l,\ t_{21} V_1 < l,\ t_{23} V_1 < l,\ V_{21} < V_{22}$$
$$\text{and } V_{22} < V_1.$$

are almost always true.

$$V_2(x) = \begin{cases} V_{21} & (0 \leq x < t_1 V_1) \\ V_{21} + \dfrac{V_{22} - V_{21}}{t_{21} V_1}(x - t_1 V_1) & (t_1 V_1 \leq x < t_1 V_1 + t_{21} V_1) \\ V_{22} & (t_1 V_1 + t_{21} V_1 \leq x < t_1 V_1 + t_{21} V_1 + t_{22} V_1) \\ V_{21} + \dfrac{V_{22} - V_{21}}{t_{23} V_1}(t_1 V_1 + t_2 V_1 - x) & (t_1 V_1 + t_{21} V_1 + t_{22} V_1 \leq x < t_1 V_1 + t_2 V_1) \end{cases} \tag{8}$$

$$N_{tx}(x) = \begin{cases} A \int_x^{x+l} V_{21} dx = A V_{21} l & 0 \leq x < t_1 V_1 - l \\ A V_{21} l + \frac{1}{2} AB(x + l - t_1 V_1)^2 & t_1 V_1 - l \leq x < (t_1 + t_{21}) V_1 - l \\ A(V_{22} - V_{21})x + A V_{21}(t_1 V_1 + t_{21} V_1) + A V_{22}(l - t_1 V_1 - t_{21} V_1) + \frac{1}{2} AB(t_{21} V_1)^2 & \\ \qquad (t_1 + t_{21}) V_1 - l \leq x < t_1 V_1 & \\ A(V_{22} - V_{21})x - \frac{1}{2} AB(x - t_1 V_1)^2 + A V_{21}(t_1 V_1 + t_{21} V_1) & \\ \quad + A V_{22}(l - t_1 V_1 - t_{21} V_1) + \frac{1}{2} AB(t_{21} V_1)^2 & t_1 V_1 \leq x < (t_1 + t_{21}) V_1 - l \\ A V_{22} l & (t_1 + t_{21}) V_1 - l \leq x < (t_1 + t_{21} + t_{22}) V_1 - l \\ A(V_{21} - V_{22})x - \frac{1}{2} AC[(x + l - t_1 V_1 - t_2 V_1)^2 - (t_{23} V_1)^2] + A V_{22}(t_1 V_1 + t_{21} V_1 + t_{22} V_1) & \\ \quad + A V_{21}(l - t_1 V_1 - t_{21} V_1 - t_{22} V_1) & (t_1 + t_{21} + t_{22}) V_1 - l \leq x < (t_1 + t_2) V_1 - l \\ A(V_{21} - V_{22})x + \frac{1}{2} AC(t_{23} V_1)^2 + A V_{21}(l - t_1 V_1 - t_{21} V_1 - t_{22} V_1) + A V_{22}(t_1 V_1 + t_{21} V_1 + t_{22} V_1) & \\ \qquad (t_1 + t_2) V_1 - l \leq x < (t_1 + t_{21} + t_{22}) V_1 & \\ A V_{21} l + \frac{1}{2} AC(x - t_1 V_1 - t_2 V_1)^2 & (t_1 + t_{21} + t_{22}) V_1 \leq x < (t_1 + t_{21} + t_{22} + t_{23}) V_1 \end{cases} \tag{9}$$

Equations 8 and 9.

Thus the velocities of the back-mid rollers can be written as ***Equation 8***.

This function is a piecewise linear function with 4 pieces. In order to simply, we let

$$\frac{V_{22}-V_{21}}{t_{21}V_1} = B$$

$$\frac{V_{22}-V_{21}}{t_{23}V_1} = C$$

in the analysis below.

Theoretical prediction of the yarn number (linear density) and profile of ring-spun slub yarn

In the manufacturing process of slub yarn, the length ($t_{22}V_1$) of yarn delivered from the front roller during the time of t_{22} plays a key role in the yarn number (linear density) and profile of the slub yarn. Generally the yarn number and profile of slub yarn mainly depends upon the relationship between the above length and that of fibres. Hence the yarn number (linear density) and theoretical profiles of slub yarn are analysed and discussed under the following conditions.

Thickest yarn length of slub yarn greater than the fibre length, $t_{22}V_1 > l$

In this condition, the thickest yarn length ($t_{22}V_1$) of the yarn delivered from the front roller in the time of t_{22} is greater than the fibre length. The velocity of the back-mid rollers increases from the lowest speed V_{21} to the highest V_{22} during the time of t_{21}, then keeps the speed during the time of t_{22}, and finally decreases from V_{22} to V_{21}. The graph of function $V_2(x)$ can be drawn as the lower polyline in ***Figure 1.a*** according to ***Equation 8***.

Substituting ***Equation 8*** into ***Equation 6*** and integrating, function $N_{tx}(x)$ can be written as a piecewise continuous function with 8 pieces presented as ***Equation 9***.

In the first piece, when $0 \le x < t_1V_1 - l$, we get $N_{tx}(x)$ - $AV_{21}l$. It is a linear function and the graph of the function is a straight line. In the second piece, it is a quadratic function and its shape is a parabola that opens up between the two ends,

$$(t_1V_1\text{-}l,\ AV_{21}l) \text{ and}$$

$$((t_1 + t_{21})V_1 - l,\ AV_{21}l + AB(t_{21}V_1)^2/2).$$

The third piece is also a linear function, the range of which is

$$[AV_{21}l + AB(t_{21}V_1)^2/2,\ AV_{22}l - AB(t_{21}V_1)^2/2].$$

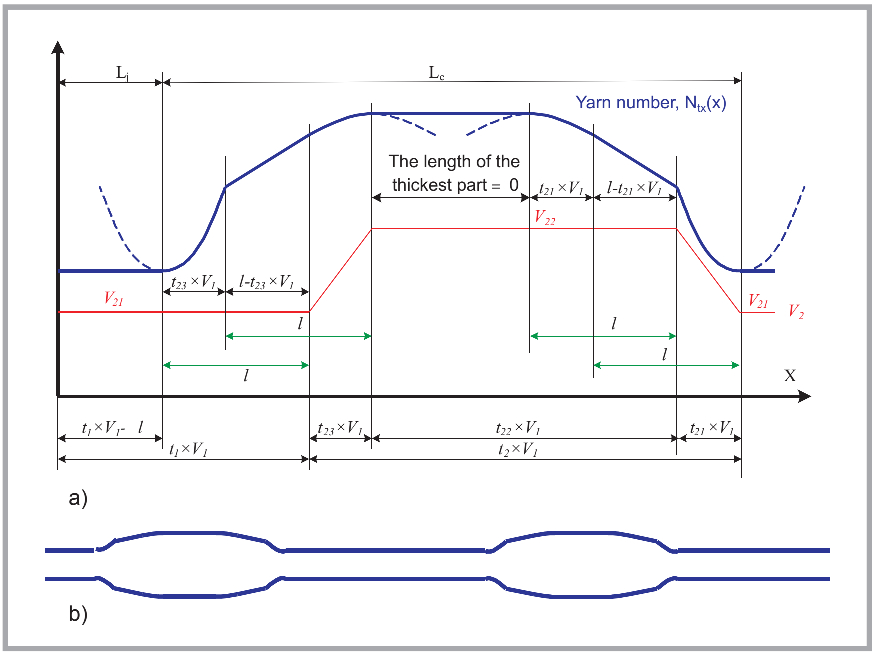

Figure 1. *a) Graphs of functions $N_{tx}(x)$ & $V_2(x)$ and b) theoretical profile of slub yarn under condition of $t_{22}V_1 > l$.*

The fourth piece is also a quadratic function and its shape is a parabola that open down. In the fifth piece, when

$$(t_1 - t_{21})V_1 - l \le x < (t_1 + t_{21} + t_{22})V_1 - l,$$

we obtain $N_{tx}(x)$ - $AV_{22}l$.

It is also a linear function, the graph of which being a straight line. The graphs of other pieces are similar and symmetrical to those of the first three pieces. According to the x value (domain) and graph of each piece, the piecewise graphs of all eight functions are drawn by taking each 'piece' and treating it as a separate function, as shown in ***Figure 1.a***.

The yarn number (linear density), $N_{tx}(x)$, indicates the yarn diameter or fineness to which that particular yarn has been spun. Hence the profile of slub yarn is similar to that of the function graph, as shown in ***Figure 1.b***.

Additionally the three important parameters: the length of basic yarn (L_b), the slub length (L_s) and the length of the thickest yarn (L_M) can be obtained from ***Equation 9*** and ***Figure 1***.

$$L_b = t_1V_1 - l \qquad (10)$$

$$L_s = t_2V_1 + l \qquad (11)$$

$$L_M = [(t_1 + t_{21} + t_{22})V_1 - l] + - [(t_1 + t_{21})V_1] = t_{22}V_1 - l \qquad (12)$$

From the above equations and discussion, we can draw the following conclusions:

1. Although the velocity of the back-mid rollers (V_2) can be increased or decreased linearly, the linear density of slub yarn, $N_{tx}(x)$, can not be increased or decreased linearly.
2. Although the velocity of the back-mid rollers (V_2) has reached its maximum, the thickest part of slub yarn will not occur until after the yarn has run over the distance of the fibre length, or over a time of l/V_1.
3. In this condition, the actual length of the slub is $t_2V_1 + l$, *i.e.*, the slub length is a fibre length longer than the slub length designed. And the actual length of basic yarn is less than that of the basic yarn designed, *i.e.*, $t_1V_1 - l$.

Thickest yarn length of slub yarn less than the fibre length, $t_{22}V_1 < l$

In this condition, the thickest yarn length ($t_{22}V_1$) of the yarn delivered from the front roller during the time of t_{22} is less than the length of fibres. Generally the acceleration time (t_{21}) and deceleration time (t_{23}) of the back-mid roller are equal in order to produce high-quality slub yarn, *i.e.*, $t_{21} = t_{23}$. Thus we get $B = C$. A graph of the function $V_2(x)$ can be drawn as the lower polyline in ***Figure 2.a*** (see page 32) according to ***Equation 8***.

Based on the function $V_2(x)$, function $N_{tx(x)}$ can be integrated as ***Equation 13*** where $N_{tx(x)}$ is a piecewise continuous function with 6 pieces. In this function, the first three pieces and sixth piece are the same as the first and eighth piece in

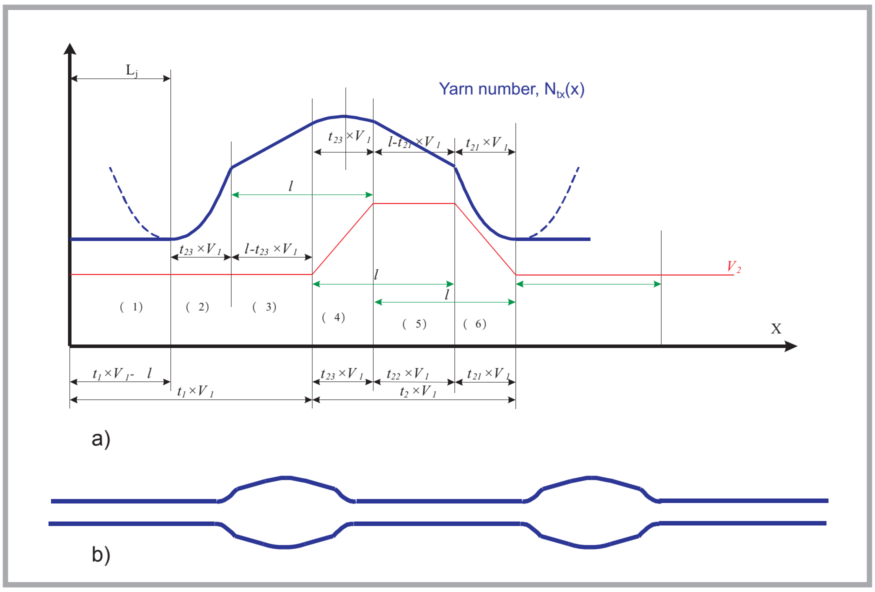

***Figure 2.** a) Graphs of functions $N_{tx}(x)$ & $V_2(x)$ and b) theoretical profile of slub yarn under condition of $t_{22}V_1 < l$.*

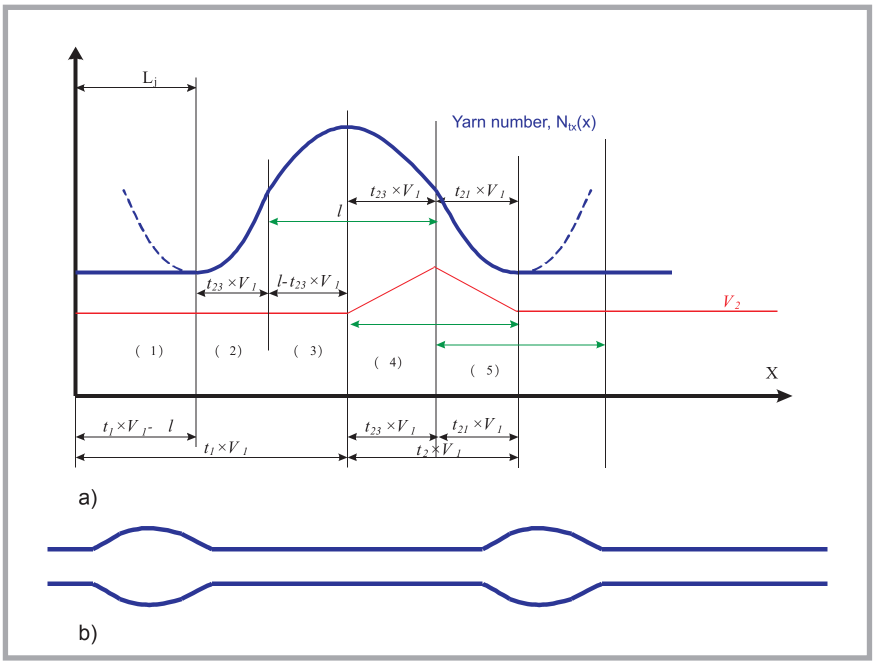

***Figure 3.** a) Graphs of functions $N_{tx}(x)$ & $V_2(x)$ and b) theoretical profile of slub yarn under condition of $t_{22}V_1 = 0$.*

$$N_{tx}(x)=\begin{cases} A\int_x^{x+l} V_{21}dx = AV_{21}l & 0 \le x < t_1V_1 - l \\ AV_{21}l + \frac{1}{2}AB(x+l-t_1V_1)^2 & t_1V_1 - l \le x < (t_1+t_{21})V_1 - l \\ A(V_{22}-V_{21})x + AV_{21}(t_1V_1+t_{21}V_1) + AV_{22}(l-t_1V_1-t_{21}V_1) + \frac{1}{2}AB(t_{21}V_1)^2 & (t_1+t_{21})V_1 - l \le x < t_1V_1 \\ AV_{22}l - AB[(x-t_1V_1)(x-t_1V_1-t_{21}V_1)] - \frac{1}{2}AB(t_{21}V_1)^2 & t_1V_1 \le x < (t_1+t_{21})V_1 \\ AV_{22}l - ABt_{21}V_1(x-t_1V_1) + \frac{1}{2}AB(t_{21}V_1)^2 & (t_1+t_{21})V_1 \le x < t_1V_1 + l \\ AV_{21}l + \frac{1}{2}AC(x-t_1V_1-t_2V_1)^2 & t_1V_1 + l \le x < (t_1+t_{21}+t_{22}+t_{23})V_1 \end{cases} \quad (13)$$

Equation 13.

Equation 9. The fourth piece is a parabola that open down with the range,

$$[AV_{22}l - AB(t_{21}V_1)^2/2, AV_{22}l].$$

The fifth piece is a linear function, the range of which is

$$[AV_{21}l + AB(t_{21}V_1)^2/2, AV_{22}l - AB(t_{21}V_1)^2/2].$$

The graphs of all six functions are drawn in ***Figure 2.a***. The profile of slub yarn is similar to that of the function graph, as shown in ***Figure 2.b***.

Additionally the three important parameters: the length of the thickest yarn (L_M), the slub length (L_s) and yarn number (linear density) of the thickest yarn (N_{tM}) can be obtained from ***Equation 13*** and ***Figure 2.a***.

$$L_M = 0 \quad (14)$$

$$L_s = 2\times l + t_{21}V_1 \quad (15)$$

$$N_{tM} = AV_{22}l. \quad (16)$$

Two extreme conditions

The first contition $t_{22}V_1 = 0$

In this condition, it is clear that $t_{22} = 0$. We can also get $t_{21} = t_{23}$ and $B = C$ in the same manner as in the previous cases. The graph of function $V_2(x)$ can be drawn as the lower polyline in ***Figure 5*** according to ***Equation 8***.

According to $V_2(x)$, there are 5 pieces in the piecewise function (17) of the yarn number (linear density) $N_{tx(x)}$.

In this function, the first two pieces and the fifth piece are the same as that in ***Equation 9***. The functions of the third and fourth pieces are the same, but the domain is different. The graphs of all five functions are drawn in ***Figure 3.a***. Hence the profile of slub yarn is similar to that of the function graph and can be drawn as in ***Figure 3.b***.

The three important parameters: the length of the thickest yarn (L_M), the slub length (L_s) and yarn number (linear density) of the thickest yarn (N_{tM}) can be obtained from ***Equation 17*** and ***Figure 3.a***.

$$L_M = 0 \quad (18)$$

$$L_s = 2l \quad (19)$$

$$N_{tM} = AV_{21}L + AB(t_{21}V_1)^2 \quad (20)$$

The second contition $t_{22}V_1 = l$

Like the above three conditions, the graphs of the two functions, $V_2(x)$ and

$N_{tx(x)}$, and the profile of slub yarn can be drawn as in ***Figures 4.a*** and ***4.b***, respectively.

The four important parameters: the length of the thickest yarn (L_M), the slub length (L_s), the yarn number (linear density) of the thickest yarn (N_{tM}) and length of the base yarn (L_j) can be obtained from ***Figure 4.a***.

$$L_M = 0 \quad (21)$$

$$L_s = 2l + (t_{21} + t_{23})\times V_1 \quad (22)$$

$$N_{tM} = AV_{22}l \quad (23)$$

$$L_j = 0 \quad (24)$$

Experimental validation

In order to verify the theoretical prediction, we carried out some experiments with the different conditions above. Generally the slub length of slub yarn made from the same raw materials cannot be obtained correctly by the direct observational method due to its unidentifiable boundary between the base yarn and slub. In order to avoid this problem, two strands of black polyester filament yarns (15.3 tex, Fangyuan chemical fibre Co. Ltd., Suzhou, China) were used as the base yarn, and (310 tex, fibre length = 29 mm) was fed into the drafting zone to produce the slub. A schematic diagram of the spinning process modified is shown in ***Figure 5***. A digital sample spinning machine (DSSP-01, Digitized Textile Technology Institute of Tianjin Polytechnic University, China) which can control every roller's speed by means of a computer was employed to produce slub yarns using intermittent acceleration of the back-mid rollers under different conditions in the experiments. The spinning parameters are listed in ***Table 1***. The four sets of parameters correspond to:

1# $t_{22}V_1>l$,
2# $t_{22}V_1=l$,
3# $t_{22}V_1<l$,
4# $t_{22}V_1=0$.

After spinning, the slub yarns produced were recorded by digital camera (Canon G10, Canon Co. Ltd., Japan), as shown in ***Figure 6*** (see page 34). In order to reduce the error, each slub yarn was measured at least 20 times at different positions under each condition and the mean value was calculated. The experimental results obtained from the different spinning conditions are listed in ***Table 2*** (see page 34). The experimental results showed that the

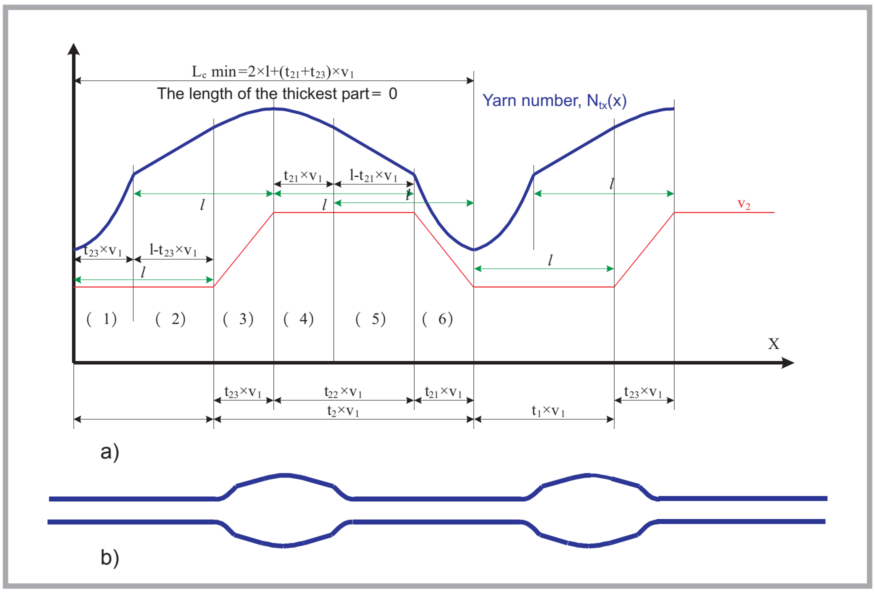

Figure 4. *a) Graphs of functions $N_{tx}(x)$ & $V_2(x)$ and b) theoretical profile of slub yarn under condition of $t_{22}V_1 = l$.*

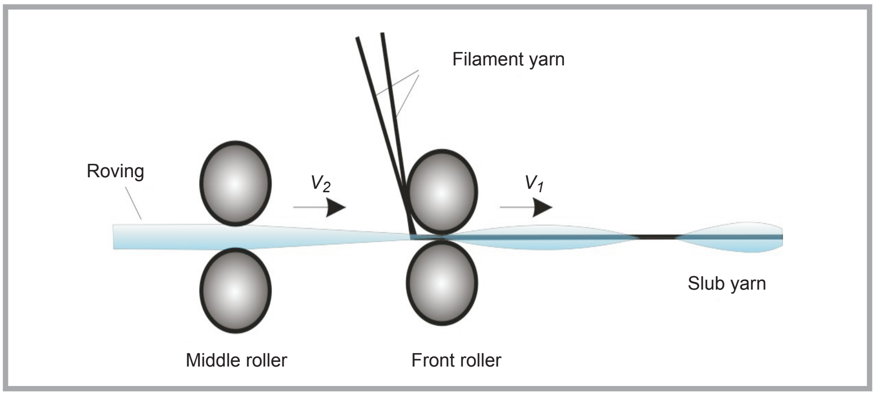

Figure 5. *Schematics of the ring-spun slub yarn spinning process.*

Table 1. *Spinning parameters in the experiments; V_{ss} - spindle speed, Mdr - mechanical draft ratio, Dt - designed twist.*

	$t_{22}V_1$, mm	$t_{21}V_1$, mm	$t_{23}V_1$, mm	t_1V_1, mm	V_{ss}, R/min	Mdr	Dt, turns/m
1#	40	14.5	14.5	29	4200	13	480
2#	29						
3#	15						
4#	0						

$$N_{tx}(x)=\begin{cases} A\int_x^{x+l} V_{21}dx = AV_{21}l & 0\le x < t_1V_1 - l \\ AV_{21}l + \frac{1}{2}AB(x+l-t_1V_1)^2 & t_1V_1 - l \le x < (t_1+t_{21})V_1 - l \\ AV_{21}l - \frac{AB}{2}(x-t_1V_1)^2 + AB(t_{21}V_1)^2 & (t_1+t_{21})V_1 - l \le x < t_1V_1 \\ AV_{21}l - \frac{AB}{2}(x-t_1V_1)^2 + AB(t_{21}V_1)^2 & t_1V_1 \le x < (t_1+t_{21})V_1 \\ AV_{22}l & (t_1+t_{21})V_1 \le x < (t_1+t_{21}+t_{23})V_1 \end{cases} \quad (17)$$

Equation 17.

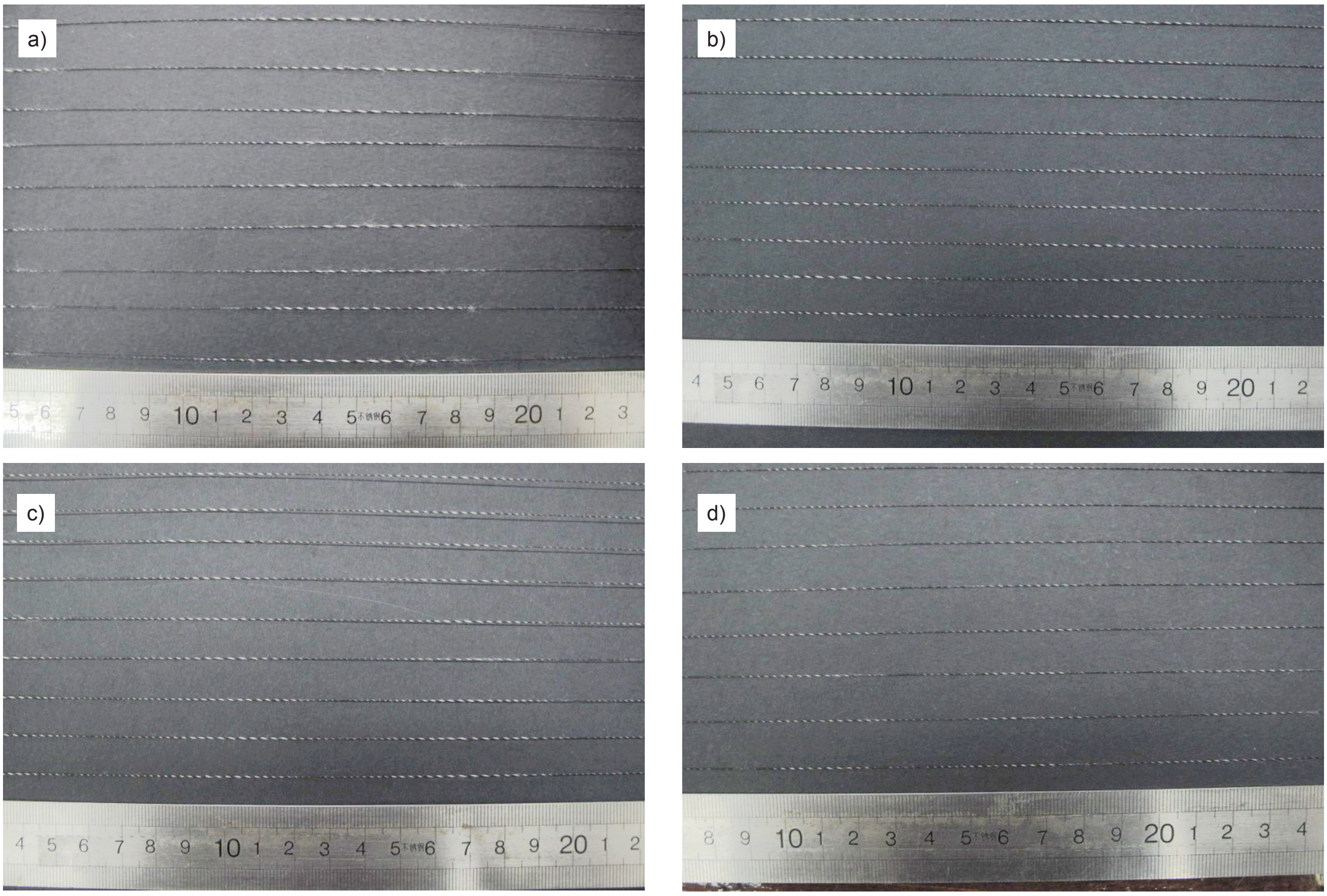

Figure 6. *Images of the slub yarns produced from the four experiments under different conditions, a) $t_{22}V_1 > l$, b) $t_{22}V_1 = l$, c) $t_{22}V_1 < l$, d) $t_{22}V_1 = 0$.*

slub length and that of basic yarn measured agreed well with the theoretical predictions and showed that the model has high prediction accuracy.

Conclusions

A theoretical model was proposed to deal with the yarn count and yarn profile of the ring-spun slub yarn spinning process according to the process parameters. Spinning experiments were carried out to validate the model. The experimental results show very good agreement with those obtained from the theoretical predictions. The conclusions presented provide a general way of understanding and producing slub yarn with the profile desired in the ring-spun slub yarn spinning process.

Acknowledgments

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Table 2. *Results obtained from the different spinning conditions; L_{db} - length of basic yarn designed, L_{dl} - length of slub designed, L_{tb} - theoretical length of basic yarn, L_{tl} - theoretical length of slub, L_{mb} - measured length of basic yarn, L_{ml} - measured length of slub. All parameters is in mm.*

	$t_{22}V_1$	L_{db}	L_{dl}	L_{tb}	L_{tl}	L_{mb}	L_{ml}
1#	40	29	69	0.15	98	1.5	95.3
2#	29		58	0.21	87	0.2	87.1
3#	15		44	0.18	73	0.2	72.0
4#	0		29	0.13	58	1.1	58.0

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