Appendix 1

Calculations I: Elementary theory

A1.1 Yarn and strand numbering systems

A1.1.1 The basic philosophies

Textiles are often sold on a weight basis and consequently it is natural to express the fineness of a yarn in terms of mass (or weight). There are two basic ways in which this may be done. These are: (a) by specifying how much a given length of yarn weighs; or (b) by specifying what length of yarn there is in a given weight. These are known generally as the direct and indirect systems of yarn numbering.

$$\text{Direct number} = \text{mass/length} \qquad [\text{A1.1}]$$

$$\text{Indirect number} = \text{length/mass} \qquad [\text{A1.2}]$$

It will be noted that one is the inverse of the other. In the first case, the number gets larger as the yarn gets heavier, and in the second case it gets smaller. The term mass has been used because this is technically correct, even though the popular term is weight. Mass is the amount of material in an object and weight is the force that acts on it when it is accelerated. Since we all live in a gravitational acceleration of about 32 ft/sec^2, all objects are subject to a force acting towards the center of the earth; that force is what we call weight. The same mass on the moon would weigh a different amount.

Each system has its advantages and disadvantages; each has found areas in which it has endured and has become established by custom. It so happens that, because the lengths are so very long for any reasonable mass, the yarn numbers would get impossibly small or large unless special counting systems are used. (Within the normal range of linear densities, one pound of yarn laid in a line would extend many miles. The numbers are unwieldy.) The following paragraphs explain a selection of the most important counting systems.

A1.1.2 Direct systems

The technical name for fineness is *linear density*[1] and it is always expressed as

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[1] This should not be confused with the term *density* as used in physics.

mass/unit length. In commerce, the technical name is used less than in the fiber industry or scientific community, such units of measurement as *denier* or *tex* being often used instead. Sometimes the term *yarn number* (explained shortly) is used, but this can be ambiguous.

Two of the major subsections of the direct system will be cited. In one, the logically minded scientists have chosen the metric system and use g/km (the unit is called a *tex*). In the other, the technologists have chosen g/9 km (the unit is called a *denier*); this is based on an ancient measure of length but it still survives because it happens to be about the right size of unit to describe a typical fine fiber. The normal metric prefixes can be used in the tex system. For example, a decitex is one-tenth of a tex and a kilotex is 1000 times larger than a tex. One denier is equivalent to 1/9 tex or 10/9 decitex.

The denier is a popular unit in the fiber industry and many fibers of 1.5 denier are supplied to blend with cotton; in the tex system, the commercial equivalent is 1.5 decitex. (The 10% difference is normally ignored.) Microfibers fall into the range of 1 denier or less. A carpet fiber often runs at 15 denier. In passing, it should be noted that a 450 denier yarn made up of 1.5 denier filaments would contain 450/1.5 = 300 filaments in the cross-section.

There are also intermediate products, such as sliver, to which the direct system of measurements is applied. Sliver is a rope-like strand that is much heavier than yarn; a normal linear density is about 5 kilotex. In much of the industry, a system using grains and yards is used for sliver; typical values are in the range 30 to 100 grains/yd. There are 7000 grains per lb. In this book, the symbol n is used for measurements in the direct system of yarn numbering and the capital letter N is used for the indirect system. In all cases, the appropriate units of measurement should be placed after the quantity.

A1.1.3 Indirect systems

Indirect systems utilize terms of length per unit mass. There is a large variety of systems, which is a legacy of the ancient crafts. Generally all the systems in this category are called *yarn count* or *yarn number.* The term yarn count is preferred. It is normal to specify the yarn count in hanks/lb where a hank contains a specified length of yarn; unfortunately each of the systems specifies a different length. Therefore, it is helpful to always specify the sort of hank being used when quoting a yarn count. Some specified hank lengths are listed in Table A1.1 With the indirect system, the number gets larger as the yarn gets finer. In the English cotton system, a 4s yarn is very coarse whereas a 50s yarn is fine.

In cotton processing (and those technologies that have evolved from it), the units developed in England in the industrial revolution are still in use. A cotton hank is defined as 840 yd of yarn. (The number 840 is divisible by 1, 2, 3, 4, 5, 6, 7, and 8; one can imagine the value of that in early primitive societies.) Thus, if the count of a singles yarn is 20 cotton hanks/lb, there are 20 × 840 yd in a pound of yarn. It should be noted that the yarn count is usually written as 20s or 20/1. The symbol used in this book is N_e, where the subscript refers to 'English' and distinguishes it from N_m, which refers to the metric count (meters/gram). In the case of long-staple yarns, where the technology is derived from one of the processes for making yarn from wool, a worsted hank is defined as 560 yd of yarn. In this case the symbol N_w is used. Other systems of symbols are used by others. The American Society for Testing

Table A1.1 Strand numbering systems

	Direct		Indirect	
	Name	**Units**	**Name**	**Units**
Fiber				
Cotton	micronaire	Approx µg/inch[a]	–	–
Wool	fineness	mg/cm	–	–
Man-made	decitex	dg/km	–	–
Denier g/9 km	–	–		
Intermediate				
Card Fleece	lap weight	oz/yd	–	–
	sliver weight	grains/yd	–	–
Kilotex	g/m	–	–	
Roving (cotton)	tex	g/km	hank roving	ch/lb[b]
Roving (wool)	–	–	roving weight	wr/lb[c]
Roping	–	–	roping weight	wo/lb[d]
Yarns				
Man-made	denier	g/9 km	–	–
All yarns	tex	g/km	–	–
Cotton type	–	–	English cotton count	ch/lb[b]
Worsted count	–	–	Worsted count	wr/lb[c]
Woolen count	–	–	Woolen count	wo/lb[d]
All yarns (European)	Metric count	m/g	Metric count	m/g

Notes: (a) This is an arbitrary index of fineness, (b) ch = cotton hank (840 yd), (c) wr = worsted hank (560 yd), (d) wo = woolen hank (1600 yd).

Materials uses N_{ec} meaning English cotton count on some occasions, but ASTM Standard D2260 uses *cc* instead, and D1907 uses *N* (these are rarely used in mills throughout the world). The Textile Institute uses *T* for the direct system and *N* for the indirect system, and a variety of subscripts are used to distinguish between a number of subcategories.

A1.1.4 Conversion

In normal practice, it is unnecessary to go through a calculation each time a conversion is required; generally a conversion factor can be used (Table A1.2). In the case of converting from one direct system to another, one merely multiplies the known linear density by the conversion factor. A similar procedure is used when converting from one indirect system to another. When converting from indirect to direct, or vice versa, then the *factor* must be divided by the *known quantity.* Referring to the use of Table A1.2, an example is to convert from cotton count to tex. In this case, 590.5 must be divided by the cotton count. These are known as cross-conversions. Another example: to convert from cotton count to worsted count, multiply the given cotton count by 1.5.

A1.1.5 Plied yarns and examples of calculation

It is possible to make up a yarn by twisting together two or more finer yarns. The process is called plying and the yarns are called plied yarns. To show that a yarn is plied, it is normal to write both the yarn count and the number of plies separated by a slash. In some systems, the quoted yarn number is that of each component. A 100 den/3 yarn would mean that 3 plies of 100 denier yarns were twisted together to give

Table A1.2 Conversion factors

	Direct		Indirect			
To	**tex**	**denier**	**cotton count**	**worsted count**	**woolen count**	**metric count**
From						
tex	–	9	590.5	885.8	8.06	1000
denier	0.111	–	5315	7972	72.54	9000
cotton count	590.5	5315	–	1.5	0.525	1.693
worsted count	885.8	7972	0.667	–	0.350	1.129
woolen count	310.2	2791	1.905	2.857	–	3.224
metric count	1000	9000	0.591	0.886	0.31	–

a yarn whose equivalent linear density would be approximately 300 denier. The twisting causes a slight effect but this can be ignored for now. With a direct system, one adds together the individual linear densities to arrive at the total.

The problem is a little more complicated with an indirect system. Ignoring twist effects, imagine a number of cotton yarns lying side by side, each being of the same length L yards. If the masses of the strands are w', w'', w''' etc., then the total mass

$$M = w' + w'' + w''' + \text{etc.}$$

But $w' = w'' = w'''$, etc. $= L/840$

$$M = \frac{L}{840}\left\{\frac{l}{N'} + \frac{l}{N''} + \frac{l}{N'''} + \text{etc.}\right\} \qquad \text{[A1.3]}$$

where N', N'', N''', etc., are the counts of the individual component yarns. If the equivalent count of the ply is N_T, then:

$$N_T = \frac{L}{840\,M} \qquad \text{[A1.4]}$$

$$\frac{l}{N_T} = \frac{l}{N'} + \frac{l}{N''} + \frac{l}{N'''} + \text{etc.} \qquad \text{[A1.5]}$$

In words, the reciprocal of the count of the ply is the sum of the reciprocals of the component strands.

As noted in Chapter 3, the equivalent count is used by some in commerce, with no indication that the number quoted refers to the equivalent count. Thus, one finds yarn counts being written as, say, 10/2, meaning $10_{\text{equ}}/2$, whereas the practice elsewhere is to use the form discussed earlier (i.e. 20/2) for the same yarn.

Dealing with short-staple yarns, the practice is to quote the ply as, say, 20/2, whereas with long-staple yarns the numbers are reversed (i.e. 2/20).

A1.1.6 Simple draft calculations

The flow through a draft zone obeys the law of conservation of mass flow. In other words,

$$\text{Mass flow in} = \text{Mass flow out} + \text{losses of mass} \qquad \text{[A1.6]}$$

In mass flow, the element of time is introduced and velocity is substituted for length. Thus Equation [A1.6] may be re-quoted in the form:

$$V_i n_i = V_o n_o + \text{losses} \qquad \text{[A1.7]}$$

where V = velocity of the fibers and n = linear density.
Ignoring losses,

$$n_i/n_o \approx V_o/V_i \qquad \text{[A1.8]}$$

Often it is assumed that the speeds of the fibers and the rolls in contact with them are the same, but this is not always so, because of slippage. Also, it is sometimes assumed that the linear density of the final output product is the same as that of the material passing through the output rolls. This is not always true either, because there can be shrinkage immediately following the emergence of the strand from the front drafting elements. That is why the approximately equals sign appears in Equation [A1.8]. The ratio of linear densities of the output product and the input is called the *actual draft ratio* (often referred to as just *draft*). The ratio of the surface velocities of the media inducing flow (such as rollers) is known as the *mechanical draft ratio* or mechanical draft. When several stages of drafting are used, the overall draft across them is the algebraic product of the stage draft ratios. Taking two stages, designated by the subscripts 1 and 2, and realizing the output of stage 1 is the input of stage 2, then $n_{o1} \approx n_{i2}$ and $V_{o1} \approx V_{i2}$. Let $n \approx n_{o1}$ or n_{i2} and $V \approx V_{o1}$ or V_{i2}.
Thus, since:

$$n_{i1}/n \approx V_{o1}/V_{i1} \text{ and } n/n_{o2} \approx V_{o2}/V_{i2},$$

$$(n_{i1}/n) \times (n/n_{o2}) \approx n_{i1}/n_{o2} \approx \text{draft cross the two stages}$$

If n_{o1} and n_{i2} are used, the drafts would give a close approximation to the actual drafts. As mentioned, these are defined by the ratio of linear densities of the strand at the input and output of each stage. However, in practice, spot measurements of linear density of material moving through the system are rarely completely representative and accurate. For the purposes of simple mill floor calculation it is normal to ignore the losses, slippages and contractions, which are quite small. In such cases, normal equals signs may be used as in Equation [A1.9]. The drafts so calculated are mechanical draft ratios.

Thus, if $n_{i1}/n = \Delta_1$ = draft in stage 1, and $n/n_{o2} = \Delta_2$ = draft in stage 2

$$n_{i1}/n_{o2} = \text{total draft} = \Delta = \Delta_1 \times \Delta_2 \qquad \text{[A1.9]}$$

This can be extended to total draft = $\Delta_1 \times \Delta_2 \times \Delta_3 \times \Delta_4$ etc.

A1.2 Yarn diameter

A1.2.1 Diameter and cross-sectional shape of a yarn in service

It might be thought that the obvious way to describe a yarn would be by its diameter, but there are difficulties with this approach. A textile yarn, by its very nature, has to be soft and can squash; therefore, although it is approximately round in cross-section when it is in the free state, it rarely remains round in fabric form. Different fibers are used in all sorts of combinations and it is a complex matter to calculate fabric weights because of the physical differences in the fibers and fabric structures. Nevertheless, it is helpful at times to have an idea of yarn diameter. For example, the diameter helps determine how closely the yarns can be packed to make a fabric, or how well a given yarn will cover in a given fabric.

A1.2.2 Theoretical diameter of a yarn in the free state

Let the linear density of a yarn, n_y, be equal to the product of the number of fibers, m, and the average linear density of the fibers, n_f. Cover is the percentage area covered by one or more yarns as they lie in the fabric.

$$n_y = m \times n_f \qquad [A1.10]$$

Assume that the fibers are evenly spread throughout the cross-section at a rate of b fibers per square inch. A round yarn, of diameter d inches, has a cross-sectional area of A_y, but $A_y = \pi d^2/4$ sq inch, and the yarn contains $A_y b$ fibers.

From Equation [A1.10]

$$m = n_y/n_f, \text{ but also } m = A_y b$$

substituting for A_y,

$$m = \pi d^2 b/4$$

substituting for m,

$$n_y/n_f = \pi d^2 b/4$$

whence

$$d^2 = \frac{4n_y}{\pi b n_f} \quad \text{and} \quad d = \sqrt{\frac{4n_y}{\pi b n_f}} \qquad [A1.11]$$

In a normal yarn, n_f is relatively constant, but b is determined by the twist and structure of the yarn. With a given yarn with a fixed twist and structure, the only highly significant variable in the right-hand side of Equation [A1.11] is n_y. Consequently, we may write the value of the equivalent yarn:

$$d \approx K\sqrt{n} \qquad [A1.12]$$

The approximation sign is meant to take care of the uncertainties due to changes in yarn shape; K is often treated as a constant factor, but care has to be taken in exercising this option.

A1.3 Twist multiple calculations (staple spinning)

A1.3.1 Derivation of twist multiple as a function of yarn count

The *helix angle* at which the fibers lie is important in determining the properties of the yarn. Since there is a profusion of helix angles involved in a yarn structure, it is normal to define twist by the helix angle of the fibers in the outermost layer. This angle is very roughly 45° for a normal yarn.

A simple experiment will demonstrate the relationship between twist angle just discussed (i.e. helix angle) and diameter. Draw a line diagonally on a flexible transparent sheet and roll the sheet tightly. The line now appears as a helix consisting of numerous repeats along its length. Allow the roll to increase in diameter and it will be seen that the number of repeats decreases. Let the roll grow to such a diameter that there is only the single complete helix as shown in Fig. A1.1. If the diameter of the roll is now D, the length of a repeat (or wavelength) is λ, and the helix angle is β, then $\tan \beta = \pi D/\lambda$. But $\tan \beta$ is proportional to twist multiple.
Therefore

$$TM = K\pi D/\lambda \qquad [A1.13]$$

where K is a constant.

A twisting or spinning machine has to be set to give a certain number of turns per inch (say τ) but, if the yarn does not change in length, this is really the number of helical repeats in one inch of yarn. If λ is measured in inches, $1/\lambda = \tau$ (i.e. λ is the number of inches per turn). Yarn diameter is roughly proportional to the square root of the linear density (or to the inverse square root of the yarn count, according to the system used). Take an indirect system, where K_1 is a constant and N is the count, $D \approx K_1/\sqrt{N}$. Substituting in Equation [A1.13] and transposing:

Twist density = $TM\sqrt{N} \times$ constant, and the twist level is measured in turns/unit length.

The constant is normally taken as unity and the twist is given by:

$$\text{Twist density} = TM\sqrt{N}\ \text{tpi} \qquad [A1.14]$$

In this case, the twist is measured in turns per inch and this is usually contracted to

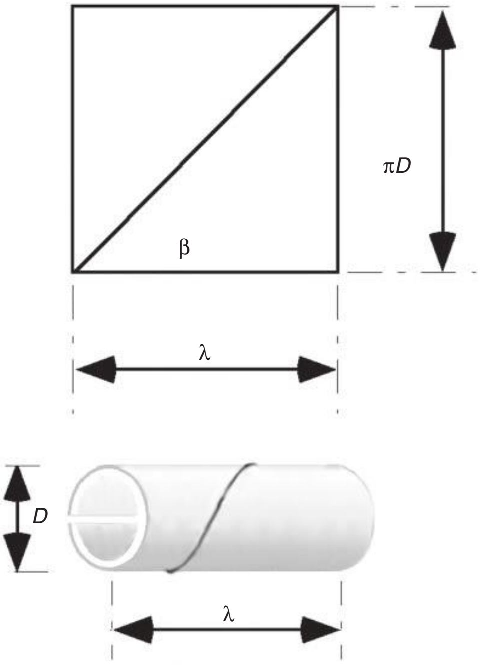

Fig. A1.l Geometric development of the strand surface tpi. However, it must be emphasized that ‘tpi’ is *not* the name of the variable but merely describes the units of measurement. The variable is called ‘twist density’ and we use the symbol τ to denote it. The result of applying the formula in this case yields an answer in turns/inch. A subscript is added to N in Equation [A1.14] according to whether the measurement system is English cotton count, worsted count, metric count, or another indirect system.

A1.3.2 Twist multiple as a function of linear density

In the direct count system, similar logic produces the relationship:

$$\tau = \text{constant} \times TM_{\text{direct}}/N \qquad \text{[A1.15]}$$

or

$$\text{twist density} = \alpha/n$$

The factor α is frequently used in Europe in place of TM.

An ASTM standard recommends using a twist density measured in turns/cm and assumes a constant of unity.

A1.4 Productivity of pre-spinning preparation machinery

A1.4.1 Opening line productivity

A normal opening line is capable of producing a fiber stream of the order of 1000 lb/hr and there are usually at least two opening lines in operation in a mill. Thus, the minimum fiber stream found is of the order of 1 ton/hr. Let the minimum opening line productivity be P_o. (It might be noted that 1 long ton (UK) = 2240 lb and this is approximately the same as 1000 kg (i.e. 2206 lb). The short ton (US) is 2000 lb.) The efficiency of the process, η, is sometimes measured per unit (pu) rather than as a percentage. Processing is carried out in a series of sequential stages. Machines following the opening line have much lower productivities and there have to be multiple parallel paths within a single stage of the later processes. The production should be approximately matched at all stages and it is necessary to calculate the number of each sort of machine required at each stage. The following calculations will be based on the assumption that all machines at a given stage have the same productivities and that the throughput is constant from stage to stage. This is not always true, but the calculation will lay out the basic rules. It is not a great step to modify the procedures to accommodate variations in the machinery mix.

A1.4.2 Sliver productivity

Cards, drawframes, combers, all produce a stream of non-twisted sliver and their production rate is the mathematical product of the linear density and the delivery speed. The productivity, P, is usually measured in lb/hr or kg/hr, the velocity, V, in yd/min, or m/min and the yarn count, n, in grains/yd or g/m; the constant K has to be adjusted accordingly and the efficiency, η, is expressed in per unit terms. Let the machine productivity be P.

$$P = KVn\eta \qquad \text{[A1.16]}$$

A1.4.3 Card productivity

The productivity of a card is usually measured by direct weighing and the result is expressed in lb/hr (or kg/hr). A typical figure, after losses, in the early 2000s may well be in excess of 300 lb/hr (say 150 kg/hr). Let this productivity be P_c is 100 lb/hr. If the cards run continually, there have to be at least P_o/P_c cards operating in parallel, to match the prescribed P_o output of the opening line. Prudence might suggest a spare to allow for maintenance but that would be expensive. Consequently for the figures suggested, we would require either $[1 + (P_o/P_c) = 1 + (2000/300)]$ or [2000/300] depending on the risk that could be tolerated. These results may be rounded up to 8 or 7 respectively (but we could just as well produce 2100 lb/hr with 7 or 6 cards) and speed up our opening line a bit. If production is stopped between can changes, efficiency drops and the number of cards required increases in inverse proportion to the per unit efficiency. If it is desired to reduce the throughput of the cards to improve on nep performance, or to prolong the time between maintenance stoppages, then a further increase in the number of cards is required.

A1.4.4 Drawframe productivity

Drawframes can deliver sliver at up to 1000 yd/min, even if normal production rates are somewhat lower. The linear density of the sliver usually varies between 60 and 100 grains/yd. To establish an order of magnitude of drawframe productivity, let us assume the sliver weight is 70 grains/yd (which is equivalent to 100 yd/lb), the delivery speed is 800 yd/min, and an automatic can changer is in use (which implies a per unit efficiency close to 1.0): also assume that the efficiency is 100%. Let the machine productivity be P.

$$\begin{aligned} P &= \frac{800\ \text{yd}}{\text{min}} \times \frac{70\ \text{grain}}{\text{yd}} \times \frac{\text{lb}}{7000\ \text{grain}} \times \frac{60\ \text{min}}{\text{hr}} \\ &= 480\ \text{lb/hr} \end{aligned} \qquad [A1.17]$$

Notice how the unit ‘yd’ cancels top and bottom, as do the units ‘grains’ and ‘minutes’, and we are left with lb/hr. The result shows that 4.17 breaker drawframes are needed to match the stated opening line output, and a similar number are required for subsequent stages of drawing. The resulting figures have to be rounded up; therefore the number needed would be at least 5 per passage. At least 10 drawframes would be required to match the throughput of the opening system if two passages of drawing were used.

A1.4.5 Roving productivity

With roving, the product is twisted and the production is limited by the twister speed. Flyer speeds can range up to 1000 r/min, and the twist levels are typically 0.9 tpi; hence the linear speed is 1000/0.9 inches/min. (The value 0.9 is used rather than a round number to facilitate tracking the calculation.) The linear density is often measured in hank roving, where 1 cotton hank contains 840 yd of roving. A 1.2 cotton hank roving contains 840 × 1.2 = 1008 yd/lb. The productivity equation[2] may be modified in form to give $P_r = K'V\eta/N_e$.

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[2] K' is a constant, N_e is the count, τ is the twist density, V is the linear velocity of the roving, and U is the rotational velocity of the flyer. Alternatively, Equation [A1.24] may be used by converting τ into TM.

Also, $V = U/\tau$ and substituting for V we get:

$$P_r = \frac{K'U\eta}{\tau N_e} \qquad [A1.18]$$

Thus, if $U = 1000$ r/min, $\tau = 0.9$ tpi and $N_e = 1.2$ cotton hanks/lb (these are common values for roving), a single spindle working without stop would produce:

$$P_r = \frac{1000}{\text{min}} \times \frac{\text{inches}}{0.9} \times \frac{\text{lb}}{1.2\text{ hank}} \times \frac{\text{hank}}{840\text{ yd}} \times \frac{\text{yd}}{36\text{ inches}}$$

$$\times \frac{60\text{ min}}{\text{hr}} = 1.837\,\frac{\text{lb}}{\text{hr}} \qquad [A1.19]$$

Again, the units cancel to leave the final units as lb/hr.

If the efficiency were 0.9, then the net production would be 1.653 lb/hr and 1210 roving spindles would be needed per opening system capacity of 2000 lb/hr. The result has, of course, to be rounded up to find the number of machines needed. Each machine has a number of spindles specified by the machinery maker.

A1.4.6 Roving wind-on speed

The winding-on speed is $U_w = \pm\,(U_f - U_b)$ r/min, according to whether the flyer or bobbin leads. Some designs have the bobbin rotating faster than the flyer, in which case $U_w = (U_b - U_f)$. The general case may use the absolute value, which takes no account of sign, and it is written as $|(U_f - U_b)|$ in the equation. When U is the speed in r/min and r is the radius of wind in inches (the subscripts refer to the flyer and bobbin), the linear velocity is:

$$V_w = 2\pi r|(U_f - U_b)| \text{ inch/min} \qquad [A1.20]$$

The roving supply velocity is V_s.

$$V_s = U_f/\tau \text{ inch/min} \qquad [A1.21]$$

but $V_s = V_w$, therefore

$$2\pi r|(U_f - U_b)| = U_f/\tau \qquad [A1.22]$$

But $2\pi r\tau$ is the number of turns of twist put in a single coil of roving of radius r; let this number of turns of twist be τ_c. Substituting τ_c in Equation [A1.22] and rearranging, the ratio between the bobbin and flyer speeds is:

$$\frac{U_b}{U_f} = 1 \pm \frac{1}{\tau_c} \qquad [A1.23]$$

where V_w = winding-on speed in inches/min
U_w = winding-on speed in r/min
U_f = flyer speed in r/min
U_b = bobbin speed in r/min
r = pitch radius of outer layer of roving in inches
τ = twist density in twist/inch
$|\;|$ = means that + or – sign of the resultant within the ‘bars’ should be ignored.

A1.5 Ring frame performance

A1.5.1 Ring frame productivity

The productivity equation for the production of a twisted strand shown in Equation [A1.18] can be modified further. In ring spinning, the twist multiple is the factor most likely to be kept fairly constant, irrespective of yarn count. If we insert the appropriate value of K' in Equation [A1.18] we get:

$$P = \frac{U\eta}{504\,TM\,[N_e]^{1.5}} \quad \text{or} \quad P = \frac{U\eta}{504\,TM\,N_e\sqrt{N_e}} \qquad [\text{A1.24}]$$

With a typical count of 24 N_e and a TM of 3.5 being spun on a spindle rotating at 15 000 r/min, with an efficiency of 0.97, we get a productivity of 0.0701 lb/hr. We would require at least 28 531 ring spindles to match our hypothetical 2000 lb/hr opening line. If a machine contained 800 spindles, then we would require at least 35.66 machines. Rounding this up, a practical number would be 40 machines. The requirement for spindles also changes if the average count of the mill changes. An operator running with a bare minimum number of spindles would encounter a shortage of spinning capacity when the average count goes finer. If the average count goes coarser, there will be some surplus spindles. In practice, the number of spindles cannot easily be changed and the speeds are manipulated to balance the system as far as possible. It should be mentioned that the average count and twist are usually determined by the marketplace and the spinner has limited choice in the matter.

A1.5.2 Elements of mill balance

The flow through the various production phases has to be balanced if the machines are to be fully utilized. The number of each sort of machine can be calculated from the quotient of total mass throughput divided by the productivity of the particular machine. Adjustments have to be made for fiber losses from each stage and the proportion of those losses recycled. An example of such a calculation is given in Q34 in Appendix 2. In addition, where dissimilar machines work in parallel, it is necessary to calculate the production of each of the parallel production streams and add the results to make a balance with the overall product flow.

A1.5.3 Bobbin flow

A spinning bobbin might only contain 0.1 or 0.2 lb of yarn; thus, a large number of bobbins has to be handled. In our hypothetical case, the mill operator would have to handle at least 10 000 bobbins per hour. This highlights why attention has been given to automating the transfer between the ring frame and the winder.

A1.6 Winding performance

A1.6.1 An example of the reduction in winder productivity due to the need to splice

A winding machine might run up to 1000 yd/min and, if it were not for the interventions needed to perform its clearing function, the productivity when winding a 6s yarn could be in the order of 12 lb/hr (0.2 lb/min). If, for example, a 5 lb cheese of yarn has 30 splices in it, and each splice needs 10 seconds to locate the fault and perform the splice, then 5 minutes of winder time is spent on splicing during the build of the package. If it had not been for the splices, our hypothetical winder would have taken 25 minute to wind the yarn. For simplicity, assume that the time to doff the full packages and replace them by empty ones is negligible and assume there is no loss of fiber through the various processes. The total winder head time consumed would have been 30 minutes and the average speed would have fallen to 10 lb/hr.

A1.6.2 An example of the effect on winder productivity caused by poor yarn quality

If the yarn fault rate mentioned in Section A1.6.1 doubled and 10 minutes of winder time was on splicing, the average speed would drop to 5 lb/35 min = 0.143 lb/min, which is equivalent to 8.57 lb/hr. Thus, the number of winders required depends not only on the count of the yarn, but also on its quality. In the best of the two cases just discussed, we would have needed at least 14 winding spindles to deal with the production rates of our hypothetical mill. In the case of the higher fault rate, we would have needed at least 21 spindles.

A1.7 Rotor spinning machine performance

A1.7.1 General statement about productivity in rotor spinning

Rotor spinning needs no roving or winding facilities and the preparation of sliver is much the same as that already discussed. The biggest difference is in the speeds that can be attained. Rotor speeds of up to 130 000 r/min are possible, and preparation has to be good enough to prevent rotor fouling and provide reasonable long-term evenness. Equation [A1.24] applies.

A1.7.2 An example of rotor productivity

Appropriate data in this case might be: rotor speed = 100 000 r/min, spinning efficiency = 0.97, TM = 4.0, and yarn count = 24s. If we apply Equation [A1.24], the productivity is about 0.4 lb/hr and at least 5000 rotors would be needed for our hypothetical mill.

Appendix 2

Calculations II: Worked examples

A2.1 Yarn numbering

Q1. How many yards of yarn are there in 1 lb of 24s cotton yarn?
Ans. In 1 lb of cotton yarn there are 840 × 24 = 20 160 yd. In other words, there are 840 N_e yd/lb in the cotton system of units.

Q2. If there are 20 160 yd in 1 lb of yarn, what is the worsted count?

Ans. $L/W = 560 \times N_w$

where L = length in yd and W = weight in lb

$$N_w = L/(560\ W) = 20\,160/560$$
$$= 36 \text{ worsted hanks/lb or } N_w = 36\text{s}$$

From the foregoing, it will be realized that N_w is 50% larger than N_e for the same yarn.

Q3. If N_e = 24s, what is the linear density in g/m?
Ans. This is a conversion from an indirect system to a direct system; therefore, one is inversely proportional to the other. In other words $n' = \text{constant} \times (1/N_e)$, consequently N_e should appear on the bottom line of the equation.

There are 1.093 yards in 1 meter and 454 grams[1] in a pound.

A 24s yarn has a length of 24 × 840 yd/lb and, designating gram and meter by g and m, respectively:

$$n'' = \frac{1\,\text{lb}}{(24 \times 840)\ \text{yd}} \times \frac{454\,\text{g}}{\text{lb}} \times \frac{1.093\,\text{yd}}{\text{m}}$$

$$n'' = 0.0246\ \text{g/m}$$

Q4. What is the linear density of the yarn in Q3, expressed in tex?

---

[1] The French spelling, *gramme*, is often used, to avoid confusion with *grain,* especially when hand written.

Ans. The unit tex is the same as g/km.

$$n = \frac{1000\,\text{m}}{\text{km}} \times \frac{n''\,\text{g}}{\text{m}}$$

$$= 1000 \times 0.0246 \text{ g/km} = 24.6 \text{ tex}$$

Q5. If a 120 yd skein weighs 40 grains, what is the cotton count?
Ans. We have to change the units. Remembering that there are 7000 grains in 1 lb, and 840 yd in 1 cotton hank,

$$N_e = \frac{120 \text{ yd}}{40 \text{ grain}} \times \frac{7000 \text{ grain}}{\text{lb}} \times \frac{1 \text{ cotton hank}}{840 \text{ yd}}$$

Canceling out the units as well as the numbers, we get:

$$N_e = 25 \text{ cotton hanks/lb}$$

A2.2 Drafting

Q6. A roving of 1 hank roving ($N_e = 1$) is converted to a 24s yarn. If twist contraction is ignored, what is the actual draft ratio?
Ans. Actual draft ratio = (output value of N)/(input value of N) in compatible units.

N_{ei} = 1.0 cotton hanks/lb and
N_{eo} = 24 cotton hanks/lb
Actual draft ratio = 24.

Q7. The linear velocity of a yarn leaving a drafting system is 100 ft/min, and the entering material has a velocity of 2 ft/min. What is the mechanical draft?
Ans. Mechanical draft = V_o / V_i = 100/2 = 50.

Q8. A roller drafting system consists of two pairs of drafting rollers; the front rollers are 1 inch diameter and the back rolls are 1.25 inch diameter. The front rollers rotate at 90 r/min and the back rollers at 3 r/min. The system is fed with 2 hank roving (N_e = 2 cotton hanks/lb). What is the yarn count if twist contraction is ignored?

Ans. $V_o = \pi D_o U = 90\pi$ inches/min
$V_i = \pi D_i U = 3 \times 1.25\pi$ inches/min
Mechanical draft = $V_o V_i = 90\pi/3.75\pi = 24$
Output $N_{eo} = 2 \times 24 = 48$ cotton hank/lb.

Q9. If the yarn delivered in Q8 contracts by 3% before it is wound, what is the actual draft ratio?
Ans. Without shrinkage (output N_{eo}) = 48 × (input N_{ei}).
After shrinkage, the yarn is fatter and the output N_{eo} is less, thus the actual draft ratio = 48 × (1.00 – 0.03) = 46.56 cotton hanks/lb.

Q10. A sliver-to-yarn drafting system is fed with 50 grain/yd sliver and delivers a strand of N_e = 24 cotton hanks/lb. What is the actual draft?
Ans. The input is expressed in a direct system and the output in an indirect one. Thus, the first step is to convert one value into the units of the other, because compatible units must be used.

$$\text{Input } N_e = \frac{1\text{ yd}}{50\text{ grain}} \times \frac{7000\text{ grain}}{1\text{ lb}} \times \frac{1\text{ hank}}{840\text{ yd}} = 0.1666\text{ cotton hanks/ lb}$$

The second step is to state in the input and output counts.

Output N_{eo} = 24 cotton hanks/lb

The third step is to check the compatibility of the units and the fourth step is to calculate the ratio as follows:

Actual draft = 24/0.1666 = 144

Q11. A drawn filament bundle is made up of filaments of 1.5 denier (i.e. 1.5 dpf). The draw ratio used to orient the molecular structure was 5. What was the denier of the original 'spun' filaments before drawing?
Ans. Output linear density = n_o = 1.5 denier.
Input linear density = n_o × draw ratio = 1.5 × 5 = 7.5 denier.

Q12. A 150 denier yarn is made of 1.5 dpf fibers. How many fibers are there in the cross-section?

Ans. No of fibers in cross-section = $n_{\text{yarn}}/n_{\text{fil}}$
= 150 denier/ 1.5 denier
= 100 filaments/yarn.

Q13. A toothed drafting system takes in sliver at 53 grains/yd and converts it to a stream of fibers that average 5 fibers in the cross-section. The fibers have a linear density of 1.5 dtex. What is the draft ratio?
Ans. Linear density of input = n_i

$$n_i = \frac{53\text{ grain}}{\text{yd}} \times \frac{1\text{ lb}}{7000\text{ grain}} \times \frac{454\text{ g}}{\text{lb}} \times \frac{1.09\text{ yd}}{\text{m}} \times \frac{1000\text{ m}}{\text{km}}$$
$$= 3747\text{ g/km}$$

Since 1 tex = 1 g/1000m, linear density of input = 3747 tex, and of output = 5 × 1.5/10 = 0.75 tex. The units of input and output are compatible, hence

$$\text{Draft ratio} = \frac{3747\text{ tex}}{0.75\text{ tex}} = 4996$$

Q 14. The foregoing is a very high draft ratio, typical of these devices. What is the draft when the thin stream of fibers is condensed into a 30 tex yarn? What is the overall draft?
Ans. The new input linear density for the second stage is 0.75 tex and the output is 30 tex. Therefore the draft ratio is 0.75/30 = 1/40. In other words, the condensation stage gives a fractional draft. The overall draft is 3750 tex/30 tex = 125.

Q15. Four 40s yarns are plied. What is the equivalent count of the plied yarn if twist effects are ignored?
Ans.

$$\frac{1}{N_T} = \frac{1}{40} + \frac{1}{40} + \frac{1}{40} + \frac{1}{40} = \frac{4}{40}$$

from which it follows that N_T = 10 hanks/lb.

Q16. A 40s yarn is plied with a 20s and a 10s yarn to make a fancy yarn. What is the equivalent count, if twist effects are ignored?
Ans.

$$\frac{1}{N_T} = \frac{1}{40} + \frac{1}{20} + \frac{1}{10} = \frac{1}{40} + \frac{2}{40} + \frac{4}{40}$$

$$= 0.025 + 0.05 + 0.10 = 0.175\ (\text{hank/lb})^{-1}$$

This is the reciprocal of N_T, hence

$$N_{\mathrm{T}} = 1/0.175 = 5.71 \text{ hanks/lb}$$

This calculation is typical of all indirect systems. To apply it to a particular one, make sure to quote what sort of hank is involved. For example, if this had been wholly in the cotton system, the answer would have been quoted as 5.71 cotton hanks/lb. However, if it had been in the worsted system, the answer would have been 5.71 worsted hanks/lb. If the counting systems had been mixed, the answer could have been expressed in one of the systems but the units used in the calculation would have had to be consistent with the answer. Notice how the equivalent yarn count is smaller than that of any of the component yarns.

A2.3 Belt transmission

Q 17. Consider a belt or yarn being driven in the direction shown in Fig. A2.1, by a pair of rolls, one of which is 1.3 inch radius and it rotates at 110 r/min. The linear velocity of the yarn, V, equals ωr. What is the velocity? (Hint: care has to be taken with the units. If V is to be in ft/sec, then the rotational speed, ω, must be expressed in radians/sec and r in feet.)

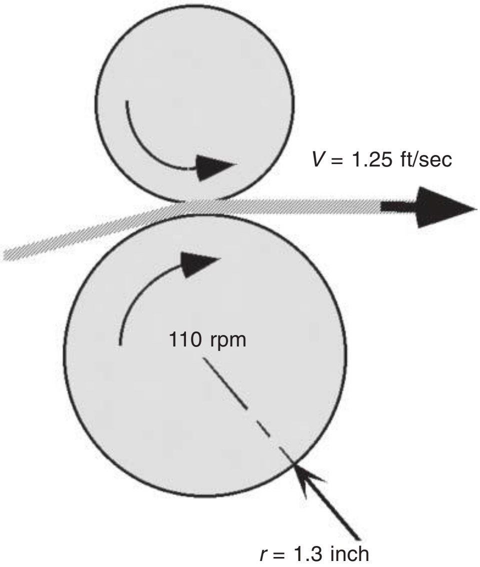


Fig. A2.1 Strand delivery

Ans.

$$V = \omega r$$

$$\omega = 2\,\pi \times \frac{110 \text{ rev}}{\text{min}} \times \frac{\text{min}}{60 \text{ sec}} \text{ rad/ sec}$$

$$r = 1.3 \text{ inch} \times \frac{\text{ft}}{12 \text{ inch}}$$

$$V = 2\,\pi \times \frac{110 \text{ rev}}{\text{min}} \times \frac{\text{min}}{60 \text{ sec}} \times \frac{\text{ft}}{12 \text{ inch}} \times 1.3 \text{ inch}$$
$$= 1.25 \text{ ft/sec}$$

Q18. Determine the speed ratio of the pulleys shown in Fig. A2.2(a). The large pulley has a radius of r_L inches the small pulley of r_s inches and they rotate at U_L and U_s r/min, respectively.

Ans. The belt speed can be determined by considering either the small pulley or the large one. The belt thus runs at:

$$V = KU_L r_L \text{ ft/sec, where } K = 2\pi/(60 \times 12)$$

The small pulley radius is r_s and it rotates at U_s r/min, which gives:

$$V = KU_s r_s \text{ ft/sec}$$

$$KU_L r_L = KU_s r_s$$

Thus

$$U_L r_L = U_s r_s$$

or $$U_L D_L = U_s\, D_s \qquad \text{[A2.1]}$$

where D = diameter and the subscripts have the same meaning as already explained. It will be noticed that the constants cancel because we are dealing with ratios.

Q19. An electric motor runs at 1800 r/min and drives a shaft by a pulley and belt

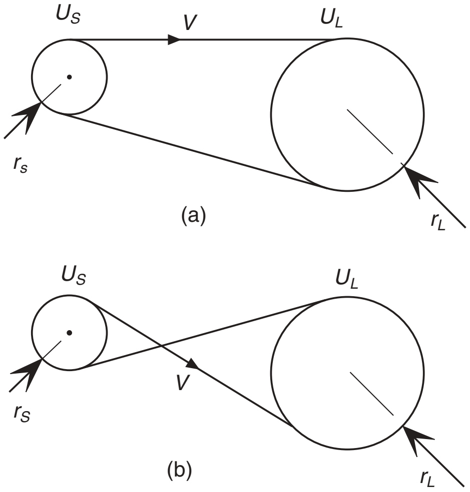


Fig. A2.2 Belts and pulleys

system. The pulley on the motor is 6 inches diameter and the pulley on the driven shaft is 18 inches diameter. What is the speed of the driven shaft?

Ans. $U_s = 1800$ r/min, $U_L = ?$ r/min
$D_s = 6$ inches, $D_L = 18$ inches

From Equation [A2.1], $U_L = U_s\, D_s/D_L$

$$= 1800 \times 6/18 = 600 \text{ r/min}$$

This answer is not completely accurate – see Q20 (b) and (c).

Q20. (a) What would be the effect if the belt of Q19 is crossed? (b) What effects would slippage have? (c) What effect does belt thickness have?
Ans. (a) If the belt were crossed as in Fig. A2.2(b), the direction of rotation of the driven member would be reversed and a minus sign can be introduced to take this into account. Thus the answer for the crossed belt case is minus 600 r/min.
Ans. (b) There is always a slight amount of belt slippage, which slightly reduces the speed of the driven member.
Ans. (c) The thickness of the belt cannot be ignored. It is usual to add one belt thickness to the actual pulley diameters in calculating the speeds. If a 1/8 inch thick belt were used in the foregoing example, and slip is ignored, the approximate speed would be:

$$\begin{aligned} U_1 &\approx 1800 \times (6.0 + 1/8)/(18 + 1/8) \\ &\approx 1800 \times 6.125/18.125 \\ &\approx 608 \text{ r/min} \end{aligned}$$

A2.4 Gearing

Q21. A motor runs at 720 r/min and drives a shaft by means of a sprocket and chain. The motor sprocket has 20 teeth and the driven sprocket has 80 teeth. What is the speed of the shaft?
Ans.

Let output speed = U_o

$$\text{Output speed} = \frac{720 \times 20}{80} = 180 \text{ rpm}$$

Q22. A compound gear system consists of a 20 tooth driver that meshes with an 80 tooth gear and the latter is locked concentrically with a 25 tooth gear that meshes with the output gear as shown in Fig. A2.3. The gear ratio is 16:1. How many teeth are there in the output gear?
Ans. Let the output gear have *m* teeth.

$$\text{Gearing ratio} = (-80/20) \times (-m/25) = 16$$
$$\text{whence } m = 16 \times 20 \times 25/80 = 100 \text{ teeth.}$$

A2.5 Machine speeds

Q23. To be able to get a reasonable output per card and yet only have a thin web of fibers on the main cylinder, it is necessary to have a high surface speed. Suppose

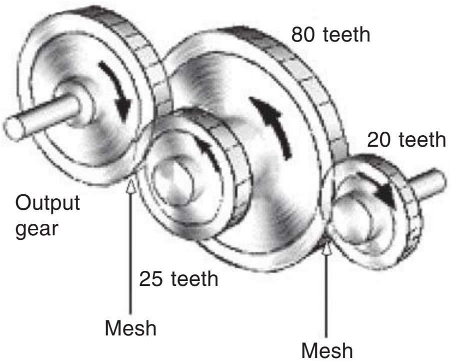


Fig. A2.3 Compound gears

there are 200 fibers/sq inch on the surface of a 40 inch wide card. There are 200 × 40 = 8000 fibers/inch of circumference on the card. If a single cotton fiber weighs 1.3×10^{-8} lb, there are roughly $8000 \times 1.3 \times 10^{-8} = 10.4 \times 10^{-5}$ lb/inch of circumference. Assuming an output of 100 lb/hr, what is the surface speed?

Ans.

$$v_o = \frac{100\text{ lb}}{\text{hr}} \times \frac{1\text{ inch}}{10.4 \times 10^{-5}\text{ lb}} \times \frac{1\text{ ft}}{12\text{ inch}} \times \frac{1\text{ hr}}{60\text{ min}}$$
$$= 1335\text{ ft/min}$$

Q24. What is the rotational speed of the cylinder in Q23 if the diameter is 40 inches?
Ans. $U = V/\pi D$ r/min.

The diameter concerned must be expressed in feet to be compatible with the velocity in ft/min. The diameter is 3.333 ft, $V = 1335$ ft/min, and $U = 127$ r/min.

Q25. If the output is to be 65 grains/yd sliver, what is the sliver delivery speed in Q23?

Ans.

$$V_d = \frac{100\text{ lb}}{\text{hr}} \times \frac{1\text{ yd}}{65\text{ grain}} \times \frac{7000\text{ grain}}{\text{lb}} \times \frac{3\text{ ft}}{\text{yd}} \times \frac{1\text{ hr}}{60\text{ min}}$$
$$= 538\text{ ft/min (or 179 yd/min)}$$

A2.6 Twist calculations

Q26. What is the twist density, in tpi, of a 4 *TM*, 25/1 cotton yarn?
Ans. From Equation [A1.14], twist density = $TM\sqrt{N_e} = 4\sqrt{25} = 20$ tpi.

Q27. A 20 tex yarn has a TM_{direct} of 36 ($\alpha = 36$); what is the twist level?
Ans. Twist level = $36/\sqrt{20} = 8.05$ turns/cm.

Q28. A yarn has 20 tpi and a count of 36s in the cotton system. What is the twist multiple?
Ans. Twist multiple = $TM = 20 / \sqrt{36} = 3.33$. No units need be quoted in this case.

Q29. Plot a graph of twist level versus count, for a *TM* of 3.0.
Ans. Set out a table of co-ordinates.

Table A2.l Co-ordinates of graph

N_e	4	9	16	25	36
N_e	2.0	3.0	4.0	5.0	6.0
τ tpi	6	9	12	15	18

The data are plotted in Fig. A2.4.

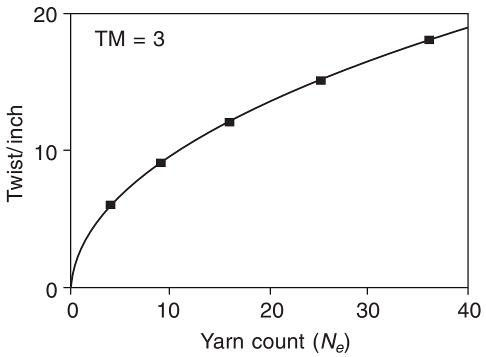


Fig. A2.4 Twist characteristics

A2.7 Production

Q30. The front roll of a drafting system advances a strand into a twister that rotates at 10 000 r/min. The roll diameter is 1.2 inch. Calculate the front roll speed when a yarn of $N_e = 25$ hanks/lb and TM = 3.5 is being made. What is the speed ratio between the spindle and the front roll?
Ans.

Twist density = τ

$$\tau = TM\sqrt{N_e}$$

$$= 3.5\sqrt{25} = 17.5 \text{ tpi}$$

U_t = twister speed in rev/min
V = linear speed of yarn in inches/min
$= U_t/\tau$

$$V = \frac{10\,000 \text{ rev}}{\text{min}} \times \frac{\text{inch}}{17.5 \text{ turn}}$$

$$= 571 \text{ inch/min}$$

But $V = U_{\text{fr}}\pi D$
where U_{fr} = rotational speed of front roller and D = diameter of front roller.
Substituting for V and D and rearranging:

$$U_{\text{fr}} = \frac{571\text{ inch}}{\text{min}} \times \frac{\text{rev}}{1.2\,\pi\text{ inch}} = 151\text{ rev/ min (i.e. r/ min)}$$

Velocity ratio = 10 000/151 = 66.

In other words, the spindle has to rotate 66 times as fast as the front roll of the drafting system.

Q31. A roving frame running at 1000 r/min and producing a 1.1 hank roving ($N_e = 1.1$) at 0.9 TM will produce P lb/spindle hour. What is the value of P?
Ans. Assuming the pu (per unit) efficiency is 1.0

$$P = \frac{U\eta}{504 \times 0.9 \times 1.1 \times \sqrt{1.1}}$$

$$P = \frac{1000}{504 \times 0.9 \times 1.1 \times \sqrt{1.1}}$$

$$= 1.91\text{ lb/spindle hr} \qquad [A2.2]$$

Q32. A traveler slides at 120 ft/sec on a 1.75 inch diameter ring. The twist density of the yarn being spun (τ) is 20 tpi and it is wound on to a 1.25 inch diameter bobbin. (Figure 7.3 shows a ring and traveler.) What is the percentage difference between the traveler and package speeds? What does this difference represent?
Ans.
Let ω_t = rotational speed of the traveler, and since $\omega_t = V/R$:

$$\omega_t = \frac{120\text{ ft}}{\text{sec}} \times \frac{2}{1.75\text{ inch}} \times \frac{12\text{ inch}}{\text{ft}} = 1645.7\text{ rad/ sec}$$

Let U_t = rotational speed of traveler in traditional units

$$U_t = \frac{1645.7\text{ rad}}{2\pi\text{ sec}} \times \frac{60\text{ sec}}{\text{min}} = 15\,718\text{ r/min (i.e. rev/min)}$$

V = the linear speed of the yarn = U/τ
Since $\tau = 20$ tpi, $V = 15\,718/20 = 785.9$ inches/min
d = 1.25 inches and the wind-on speed = $V/\pi d$

$$U_{\text{wind}} = 785.9/(1.25\pi) = 200\text{ r/min}$$

This is 1.27% of the traveler rotational speed.

$$\text{Ring spindle speed} = U_t + U_{\text{wind}} = 15\,718 + 200 = 15\,918\text{ r/min}$$

Note: As the bobbin diameter builds from (say) 1 inch to 1.6 inch, with a bobbin speed of 15 918 r/min, the wind-on speed varies from

$$785.9/\pi = 250\text{ r/min to } 785.9/(1.6\pi) = 156\text{ r/min}$$

and the traveler speed varies from

$$15\,918 - 250 = 15\,668\text{ r/min to } 15\,918 - 156 = 15\,762\text{ r/min,}$$

a difference of about 0.6%. As the bobbin diameter changes, a small variation in twist occurs but the effect of this is neglected.

Q33. A ring frame produces a yarn of average count of 25/1. The twist multiple is 3.5 and the spindle speed is 20 000 r/min with a spinning efficiency of 0.95. (a) What is the output for the given ring frame? (b) If the count were reduced to 36/1, what would be the output?

Ans. (a) Equation [A1.24] contains the group $N_e\sqrt{N_e}$ and it is easier to calculate this first.

$$N_e\sqrt{N_e} = 25 \times \sqrt{25} = 125$$

Substituting this in Equation [A1.24] we get:

$$P = \frac{20\,000}{504} \times \frac{0.95}{3.5} \times \frac{1}{125} = 0.0862 \text{ lb/ sp hr}$$

(b) Calculating $N_e\sqrt{N_e}$ as a preliminary step,

$N_e\sqrt{N_e} = 36 \times \sqrt{36} = 216$ and inserting this in Equation [A1.24] we get:

$$P = \frac{20\,000}{504} \times \frac{0.95}{3.5} \times \frac{1}{216} = 0.0499 \text{ lb/ sp hr}$$

At least 12 spindles are needed in one case, and 20 in the other, to produce 1 lb/hr.

Q34. A mill has an output of 2500 lb/hr of yarn of 16/1 (N_e) at 3.8 TM spun on ring frames running at 15 000 r/min at an efficiency of 0.92 and a waste level of 1.8%. The ring frames are supplied with 1.1 hank roving (N_e), made on roving frames running at 1200 r/min and with a TM of 0.996. The efficiency of the roving frames is 93% and the fiber loss is 0.2%. (a) How many ring frame spindles, and (b) how many roving spindles are required?

The mill has two passages of drawing and the drawframes run at 600 yd/min when producing 90 grain/yd sliver. (c) How many drawframe heads are needed if the operational efficiency is 95%, the sliver wastage is 1%, and each drawframe has two heads?

It is intended to install cards, each with a productivity of 100 lb/hr. The waste fiber from carding and opening is 2% and the operational efficiency is 96%. (d) How many cards would be needed, (e) what input fiber flow would be required, and (f) what flow of new fiber would be needed if 50% of the waste from spinning, roving, and drawing is recycled?

Ans. (a) Starting this question with the ring frames, the yarn flow required from them = 2500 lb/hr.

Calculating the value of $N_e\sqrt{N_e} = 16 \times \sqrt{16} = 64$, the productivity of one ring spindle

$$P_{\text{rf}} = \frac{15\,000 \times 0.92}{504 \times 3.8 \times 64} = 0.113 \text{ lb/ sp hr}$$

The number of ring spindles needed = 2500/0.113 = 22 124.

If there were 800 spindles per machine, 27.66 machines would be needed; rounding this up gives us 28 machines. (This number would have to be increased to allow for maintenance shutdowns and repairs.)

(b) Allowing for 0.008 pu fiber loss in spinning, the roving flow needed is:

$$2500 + (2500 \times 0.008) = 2500 \times 1.008 = 2540.16 \text{ lb/hr}$$

$TM_{\text{roving}} = 0.996$ and $N_e\,\sqrt{N_e} = 1.1 \times \sqrt{1.1} = 1.154$

$$P_{\text{roving}} = \frac{1200 \times 0.93}{504 \times 0.996 \times 1.154} = 1.927\,\text{lb/hr}$$

Number of roving spindles needed = 2540/1.927 = 1318, say 1400.
(c) Drawframe production/head for one passage, $P_{\text{df}} = V_{\text{sliver}} \times n_{\text{sliver}}$

$$P_{\text{df}} = \frac{600\text{ yd}}{\text{min}} \times \frac{90\text{ grain}}{\text{yd}} \times \frac{\text{lb}}{7000\text{ grain}} \times \frac{60\text{ min}}{\text{hr}} \times 0.95 \times 0.99$$

$$= 435.3\,\text{lb/hr}$$

Allowing for 0.002 pu (per unit) fiber losses in roving, the throughput is: (the value in Answer (b) × (1 + 0.002)) = 2540 × 1.002 = 2545 lb/hr.
Number of heads required = 2545/435.3 = 5.847 for one passage.
For two passages the number required = 5.847 × 2 = 11.69 and rounding up, this would be taken as 12.

With 2 heads/drawframe, 6 machines are required.
(d) Allowing for 0.01 pu fiber losses in drawing, the card output is:
(the value in Answer (c) × (1 + 0.01)) = 2545 × 1.01 = 2570 lb/hr.

Taking the efficiency into account, the production rate/card is 100 × 0.96 = 96 lb/hr. The theoretical number of cards required would be = 26.77. However, one cannot have a fraction of a card so the number required is rounded up to 27.
(e) After losing 2% of the fiber in carding and opening, the input rate is:

$$2570 \times 1.02 = 2621\text{ lb/hr}$$

(f) The specified wastes are:

$$\begin{array}{lll} \text{Spinning waste} & = 0.008 \times 2500 & = 20.00\text{ lb/hr} \\ \text{Roving waste} & = 0.002 \times 2540.16 & = 5.08\text{ lb/hr} \\ \text{Drawing waste} & = 0.01 \times 2570 & = 25.71\text{ lb/hr} \\ \hline \text{Total specified waste} & & = 50.79\text{ lb/hr} \end{array}$$

Recycled waste = 50.79/2 = 25.4 lb/hr, which offsets the losses and the total fiber requirement drops by this amount. Thus, the net input fiber required in this case is 2622 – 25.4 ≈ 2597 lb/hr.

A2.8 Texturing

Q35. A texturing machine has a six-disk stack. The coefficient of friction, μ, is 0.2, the run-on and run-off angles are both 30°, and the inclination on the periphery of the disk is 0°. Assume that all disks are working disks and that they give no aid in moving the yarn through the stack. Calculate the output tension and the torque produced by disks 1 and 6.

Ans. The angle of wrap for each disk = $(90 - \theta) \times 2 = 120°$ (equivalent to $2\pi/3$ radians). Let the input tension to disk 1 = T1 and, using Amonton's Law (i.e. $T_o = T_1\, e^{\mu\theta}$), output tension from disk 1 = $T_1\, e^{0.2\times 2\pi/3} = 1.52\, T_1$.

Since the passage past five disks accumulates an angle of wrap of five times that of the passage over a single one, and the angle appears as an exponent in the equation we may write:

Input tension to disk 6 = $1.52^5\ T_1 = 8.11T_1$
Output tension from disk 6 = $1.52^6\ T_1 = 12.3T_1$
The torque generated by a disk = $(T_1 + T_2)\ \mu \sqrt{n}\ K \cos\theta$

where n is the linear density of the yarn, μ is the coefficient of friction, and K is a factor.

Torque generated by disk 1 is $((1 + 1.52) \times 0.2 \times 0.866)\ KT_1 \sqrt{n}$

$= 0.436\ KT_1\sqrt{n}$
Torque generated by disk 6 is $((8.11 + 12.3) \times 0.2 \times 0.866)\ KT_1\sqrt{n}$

$= 3.54\ KT_1\sqrt{n}$

This torque for disk 6 is 8.1 times that generated by disk 1, but the maximum tension is $12.3T_1$; this is also 8.1 times the tension output of disk 1.

Appendix 3

Advanced topics I: Air conditioning and utilities

A3.1 Introduction

Water vapor is very important in yarn making in many ways. Frequently, steam is used as a heating medium. It is used because there is a unique relationship between pressures and temperatures of steam, which makes it relatively easy to control. There is often an advantage in applying moist heat to set polymers, especially when hydrogen bonding occurs within the polymer molecular structure. The air in which we live is really a mixture of air and steam. In a textile mill, where high humidities are needed, the proportion of steam is rather high and it is helpful to understand its characteristics.

A3.2 Units

Conventionally in the USA, units are expressed in pounds, feet, and seconds, whereas the SI system uses grams, meters, and seconds. The relationships between derived units may not be obvious and it may be of use to discuss them. In thermodynamics, the interest is in mass, temperature, and energy as well as some other parameters. *Temperature* is commonly measured on two scales (i.e. Fahrenheit and Celsius) with two important points being fixed by the freezing and boiling points of water under normal atmospheric pressure. On the Celsius scale, water freezes at 0°C and boils at 100°C. For many thermodynamics calculations it is necessary to work from absolute zero rather than from an arbitrary one fixed by the characteristics of a single substance. This absolute zero is –273°C on the Celsius scale, which is awkward; it is preferred to set absolute zero at the datum but use the same intervals as the Celsius scale. This is now called the Kelvin scale. Conversion is made by merely adding 273 degrees to the temperature in Celsius; the result is written as °K. The absolute zero measured in Fahrenheit is –460°F; when the intervals are the same as the Fahrenheit scale, the result is called the Rankine scale.

The *heat content* of a material is the product of mass × specific heat × temperature, where the heat content and temperature are reckoned from some arbitrary levels. This assumes that there has been no change in state, such as from solid to liquid or from liquid to gas. The *specific heat* is a property of the material; it is proportional to the amount of heat that has to flow to or from a unit mass of the material to change its temperature by 1 degree. In the conventional system, the specific heat of water is 1.0 and this is used as a reference for other materials. Temperature is a measure of thermal 'pressure'; heat will flow more rapidly through a material as the temperature increases. Care should be taken to discriminate between temperature and heat. A thermometer measures temperature but it is necessary to know the specific heat and mass of a substance before the quantity of heat can be determined. In the conventional US system, the unit of heat is the Btu and this is defined as that heat required to raise one pound of water through 1°F. Heat is a form of energy but there are other forms. For instance, *electrical energy* is measured in joules. *Mechanical energy* is measured in ft lb (that energy needed to raise 1 pound through 1 foot). These are mutually convertible; for example, 778 ft lb is equivalent to 1 joule. The Sl system expresses all forms of energy in joules. *Power* is the rate of using (or producing) energy. In engineering the common term is horsepower, which is defined as 550 ft lb/sec. In thermodynamics, the term is often expressed in Btu/hr, whereas in electrical engineering the unit is the watt. A watt can be variously defined as the energy flow in joules/sec or the product of voltage and amperage. One ampere is the flow of electrical charge in coulombs/sec; thus, since 1 coulomb may be defined as 1 ampere second, the two definitions come to the same thing. All forms of power are mutually convertible and the SI system uses the watt as the universal unit of power.

A3.3 Water vapor and steam

A3.3.1 Change of state

When a material changes from solid to liquid, liquid to gas, solid to gas, or any of the reverse processes, we refer to a *change of state.* A change of state is nearly always associated with a taking in or a giving out of heat. This is an important property of most materials; water and thermoplastic polymers are no exception. Many of the ideas discussed relate to water, but they have their counterparts with other materials. Naturally, the values of the data can be widely different.

A3.3.2 The properties of steam

Water absorbs energy as it is heated, with the result that the temperature rises until it reaches its boiling point. Beyond this boiling point, any further addition of energy causes water to be converted to steam but the temperature does not rise again until all the water has been boiled off. The boiling point rises with pressure. Table A3.1 shows how the *latent heat* changes. It can be seen that the temperature of wet steam can be controlled by the pressure in the steam vessel. With wet steam, some water remains in the steam and, as energy is added, the percentage of water drops. When all the water is converted, the steam is said to be 'dry'. In practice, it is much easier to control pressure than temperature, and, for this reason, the use of steam as a heating medium is quite popular. Within limits, there is automatic regulation of temperature all the time that the steam is wet and at constant pressure. If an autoclave (or steam kettle) is used to set or dye yarn or fabric, it is usually necessary to adjust the kettle to some pressure higher than atmospheric. For example, if a temperature of 150°C is required, the autoclave should be run at 70 psi or 482 kilopascals, as shown by Table A3.1. The term ‘steam’ describes water vapor without any other gas or vapor present. Steam that is just dry (i.e. the last drop of water has just been converted to steam) is called *saturated steam.* A dryness fraction, q, is used to define the actual specific volume of wet steam in respect to the specific volume of saturated steam at the same pressure and temperature. The term ‘specific’ means that the quantity relates to unit mass; specific volume is the volume taken by a unit mass of the substance. The specific enthalpy or energy content of wet steam, H, is given by the simple formula:

$$H = s + qL \qquad \text{[A3.1]}$$

where: s = specific enthalpy of water (i.e. sensible heat), L = specific enthalpy associated with a complete change of state from water to dry steam (i.e. latent heat), and q is the dryness fraction.

A3.3.3 The properties of air/steam mixtures

If two or more gases or vapors are mixed in a confined space and there is no chemical reaction, each component fills the whole volume and each exists at its own particular *partial pressure*. The sum of the partial pressures equals the total or applied pressure. This is known as Dalton’s law of partial pressures. With a perfect gas, the mathematical group *P Vol/T* remains constant for the particular gas and the constant is denoted by the symbol *G*, which relates to energy/unit mass, and stands for the universal gas constant. *P* is the pressure and *Vol* is the specific volume of the gas. The temperature must be expressed in absolute terms.

With an imperfect gas or vapor, such as steam, the characteristic equation mentioned is inaccurate and one must determine the specific volumes from tables such as Table A3.1. In the case of steam/air mixtures, the absolute volume and temperature are common to both the steam and the air. The mass of each component is the quotient (absolute volume/specific volume). The absolute volume is the whole volume occupied

Table A3.1 Properties of steam

Conventional units					**SI units**			
t °F	**P psi$_{abs}$**	**H Btu/lb**	**Vol cu ft/lb**	**L Btu/lb**	**t °C**	**P kP$_a$**	**H J/g**	**Vol m^3/kg**
32	0.0885	1076	3306	1076	0	0.61	2502	206.3
40	0.1217	1079	2444	1071	4.4	0.84	2491	152.5
50	0.1781	1084	1703	1066	10	1.23	2479	106.3
60	0.2563	1088	1207	1060	15.5	1.77	2465	75.3
70	0.3631	1092	868	1054	21.1	2.5	2451	54.2
80	0.5069	1097	633	1049	26.7	3.49	2440	39.5
90	0.6982	1101	468	1043	32.2	4.81	2426	29.2
100	0.9492	1105	350	1037	37.8	6.54	2412	21.8
150	3.718	1126	97.1	1008	65.6	25.6	2344	6.06
212	14.696	1150	26.8	970	100	101	2256	1.67
250	30	1164	13.8	945	121	207	2198	0.861
293	60	1178	7.17	915	145	413	2128	0.447
320	90	1185	4.9	895	160	620	2081	0.306
358	150	1194	3.02	864	181	1030	2010	0.188
417	300	1203	1.54	809	214	2070	1882	0.096

Notes: t = temperature, P = absolute pressure, H = total enthalpy of dry steam, Vol = specific volume, L = latent heat by the mixture. The specific volume of steam must be found from tables, whereas for air, the characteristic gas equation can be used, i.e.

$$P_a \, Vol = MG \qquad \text{[A3.2]}$$

where P_a is the partial pressure of the air, and *Vol* and *M* are the volume and mass of air involved respectively.

There are two cases in which steam/air mixtures assume importance. One relates to moist air, and the other to air leaks in autoclaves and boilers. In the second case, the effect of air leakage into a steam system is to reduce the partial pressure of the steam, which then causes a reduction in temperature. A normal gage can only measure the sum of all the partial pressures and it cannot detect the displacement effect of the intruding air. An inward air leak can cause a drop in temperature (which might be undetected), and this can cause difficulty in some dyeing and setting operations. The problem is compounded because water contains dissolved gases that are released on boiling; the released gases act in the same way as the air leak. Thus, boiler water should be de-aerated and steam traps should be used to permit removal of air and gas without loss of steam. The dissolved air can cause corrosion in boilers and equipment and it is prudent to remove it for this reason also. Air leaks are more likely where steam cools and the internal pressure drops below atmospheric.

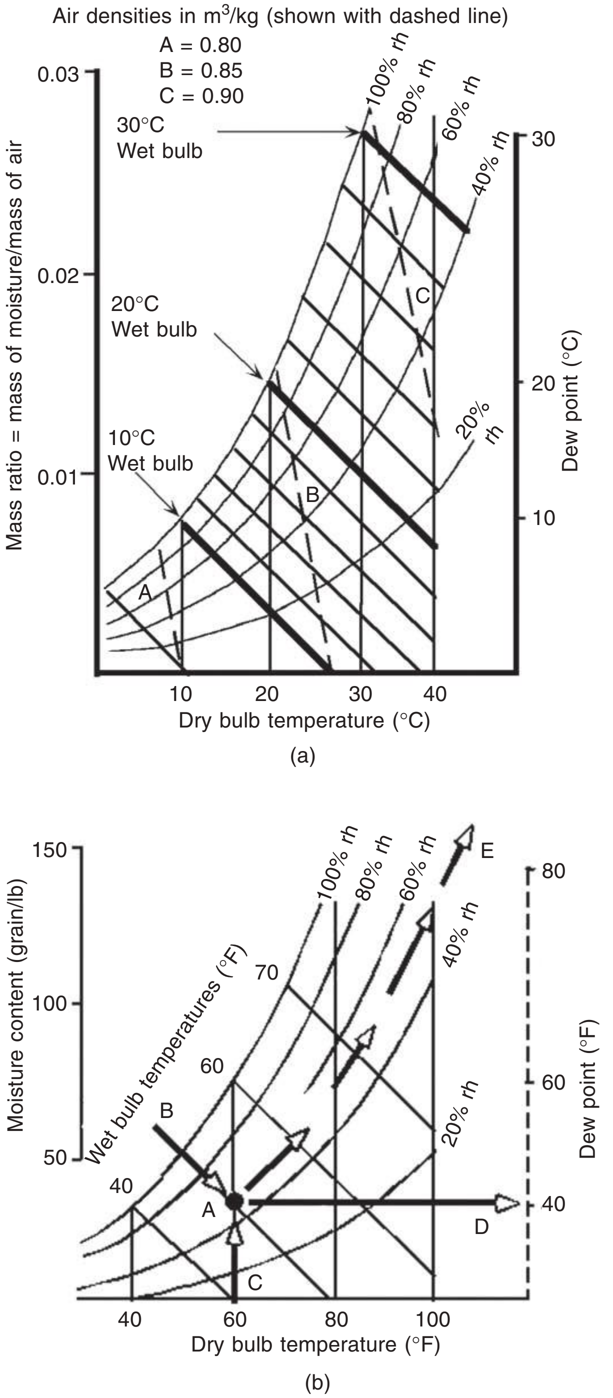
A3.4 Humidity

A3.4.1 Humidity in the workspace

Normal air is really a mixture of air and superheated steam. Superheated steam has been heated above its saturation temperature, but if the partial pressure is very low, the saturation temperature is also low. When the temperature of the humid air is reduced to its *dew point*, the steam starts to condense and droplets of water are precipitated to form a fog. In a workspace, water is deposited on cold surfaces and, since these are often of steel or iron, there can be a problem with rust. Thus, it is good practice to keep the temperature of the workspace above the dew point, always. As the temperature of the air is increased above the dew point, the specific volume of the air increases and the air is drier. The normal measure of wetness is *relative humidity* measured on a 0 to 100% scale. It is, in fact, the ratio of the amount of moisture that the air actually holds to the maximum that it could hold at the same temperature. It can also be defined in terms of the partial pressures. Steam tables such as Table A3.1 could be used to calculate such conditions, but it is more normal to use psychometric charts such as shown in Fig. A3.l. Two styles are given, one in SI (diagram (a)) and one in imperial units (diagram(b)). To use these charts, one needs to know the wet and dry bulb temperatures. These are measured by a pair of thermometers; one element is kept dry and the other is kept moist. The evaporating water from the wet bulb keeps the local temperature down to the dew point. It is possible to see how the moisture content increases as the air is heated at constant rh by tracking the line AE in diagram (b). It is also possible to see how the state point A is defined by (i) the wet and dry bulb temperatures or (ii) the dry bulb temperatures and rh.

A3.4.2 Air conditioning

A mill has to have a controlled climate if high quality yarns are to be made. In drafting, fibers can stick to the rolls and there are several possible causes for this



(a)

(b)

Fig. A3.1 Psychometric chart

problem. One is stickiness, caused by too damp an atmosphere. Another is electrical charging of the fibers, which causes them to be attracted to a surface. The charge becomes a problem when the atmosphere is too dry. The best rh of the air depends on the fibers and the roll coverings, but a typical value is 55% rh.

It is not a simple matter to get the rh to the correct value everywhere in the plant. For example, in a spinning room, it is not unusual to find zones that are too wet or too dry. Certainly, one must not rely on the wall-mounted hygrometers since they merely record at fixed locations. The use of a portable hygrometer will quickly reveal the bad zones. Hot areas, such as near a motor, give low values, and inappropriate values are often found near doors, especially when the outside conditions are far from ideal. To give an idea of the magnitude of the problem some mill experience will be quoted. In one mill where the ring frames were positioned very close to one another, the rh at the ring rail varied from 30% to 35%, even though the wall-mounted hygrometers read 55%. The mill performed badly. Another, with widely spaced ring frames and a well-adjusted air conditioning system only showed ±1% rh. Most mills fall between these extremes. The setting of the air diffusers and the pneumafil suctions can greatly affect the uniformity of the rh throughout the room. A hint of poor distribution is sometimes given by accumulations of fibers on the ceiling and light fixtures. Old buildings with exposed beams and glassed areas are particularly difficult because of the heat transfer through the roof and the large volumes of air trapped there. Careful attention to air conditioning and distribution can save many later operational difficulties. The ducting in the air distribution system must be designed to give uniform distribution throughout the room. Also, the flows from the supply have to be balanced with the main return air systems, as well as with the suction systems removing waste fiber.

A3.5 Mill environment

A3.5.1 Energy balance in an enclosed workspace

Considerable amounts of energy from electric motors and other devices are dissipated in the workspaces. Not only is there heat dissipated from the motors, but also from the machines themselves. The machines take mechanical energy from the motors and do work in overcoming the resistance to movement of the machine parts and this translates the energy into the heat form. Thus the machine parts get warm. For example, bearings and belts get hot. The movement of the parts disturbs the air and dissipates further energy; for example, the air leaving the rotors in OE spinning gets very hot. The temperature difference between the machine parts and the air also causes heat transfers to occur. Thus the original input electrical energy is translated into heat energy at every stage in the process. In cool winter climates, heat escapes from the entrances and exits as well as by conduction and radiation through the shell of the building. Balance is normally obtained by applying a heating system. In hot summer climates, the heat flows are reversed and air conditioning has to be applied to keep the temperature down.

Consider the energy balance in an enclosed space:

If E_{elec} = electrical energy input to the space,
E_{comb} = energy input derived from combustion of fuels
E_{therm} = thermal energy passed through the shell of the space due to a difference in temperature between inside and outside.
$E_{\text{therm}} = \text{Total mass of enclosure} \times (T_{\text{outside}} - T_{\text{inside}})$
T_{inside} = is normally controlled to be constant and E_{therm} may have a positive or negative value.
E_{ac} = thermal energy pumped out of or into the space by the air conditioning

plant. E_{ac} is negative in summer when energy is being pumped out by the refrigeration plant and positive in winter.

E_{mat} = is the sum of the differences between input and output in mechanical strain, thermal and other energies resident in the textile material, which differences are normally insignificant.

Since there is usually no chemical or nuclear reaction involved, the energies described must be conserved and if similar units are used for all forms of energy:

$$E_{elec} + E_{therm} + E_{comb} + E_{ac} \approx 0 \qquad [A3.3]$$

Availability of thermal energy is determined by the temperature at which it exists. Every transfer degrades its availability. Eventually, it is all dissipated as low grade heat that cannot be recovered economically. It is not just a question of balancing $E_{therm} + E_{comb}$ and E_{ac} but for every horsepower used within the space, there is a dissipation of 746 watts from the machines themselves in addition to losses from the electrical system. The energy from the lighting system is also dissipated as heat.

A3.5.2 Energy removal from the workspace

With a fixed amount of moisture present in the atmosphere, temperature changes are accompanied by changes in rh. Consequently it is necessary to control both temperature and rh. The additional heat from all these sources has to be removed to maintain an even condition.

In the past, air conditioning often has been given little priority, with small regard for the heat loading from the equipment within the building. However, as the equipment installed consumes ever more power in the quest for higher productivity, the importance of the heat loading becomes more apparent. In tropical or semi-tropical countries, each kW of power used must be pumped out again while the refrigerating air conditioning system is in use. This becomes particularly apparent with high speed rotor spinning. Schemes where the motors and hot parts of a machine are cooled *separately* from the main workspace have appeared and these are to be encouraged. This source of heat might be useful in a cold climate but in a hot one it adds to the air conditioning costs. Eckert [1] pointed out that a deciding feature of the air conditioning system for rotor spinning is the increased *direct* exhaust air capacity of the machine itself. The high temperature difference between the exhaust air and the ambient makes it easier to pump out the heat. He quotes values of 27°C difference. Since that article, speeds have risen and, because the energy consumed rises approximately to the 3rd power of speed, the temperature difference he quotes must be low by modern standards. The attractiveness of direct exhaust system cooling rises accordingly. Eckert also points out that the distributions of supply, exhaust, and return air are of utmost importance (as they are for any spinning operation). If the heat from the motor, head-, and tailstocks is directly exhausted, it is then only necessary to remove from the spinning room little more than the heat loading from the lighting and transmissions. This means that the amount removed from the room at normal ambient temperatures is less than one-third of the total. The remainder is removed at temperatures up to 40°C higher. A refrigeration process is sensitive to temperature differences across its cooling coils and this means that it is easier and cheaper to remove the heat from the hotter air. Also, heat removal by water washing of hot air reduces the temperature more quickly than it does with air at atmospheric temperature. Combinations of air-wash and refrigeration can be designed for optimum efficiency and the proportions for hot and normal temperature returns may well differ.

Against the gains in operating cost have to be set the costs arising from the extra capital investment needed. Ducts to carry away the hot air (preferably underfloor) have to be installed. Separated air conditioning systems are also desirable to deal with the two classes of return air. Obviously it is an advantage to install such systems when the plant is first built.

A3.5.3 Filtration

Not only does the air in a mill have to be maintained at an rh best suited to the particular task, but it has to be clean. In many regions of the world, air quality in mills is quite stringently monitored. There are regulations in many countries mandating maximum levels of particulate matter in the air in the opening and carding areas. Such filtration is especially important in cotton spinning because of the incidence of byssinosis (an allergic lung disease) in some workers. Even if automation is used to minimize the amount of human exposure, the regulations still apply. In other forms of processing, noxious chemicals can be given off and the climate has to be controlled there too. A further important reason for attention to cleanliness is the fire risk. Some airborne fibers and dust are flammable; fire and explosion risks are severe. Enclosed, spark-free motors have to be used and a number of fire hazards are outlawed. Special fire-fighting arrangements must be provided and most local authorities have a Fire Code, which requires compliance.

Lint and harmful dust have to be removed from the return air. Where the concentrations of dust and fly are high, such as in the returns from the carding and opening areas, cyclone separators are used to extract the heavier fraction of waste. Most of the remaining dirt is removed by electrostatic precipitators, fabric filters or the like. The air is usually washed as well.

One important concern is the maintenance of the atmosphere within the comfort zone of the operatives (Fig. A3.2), especially if maximum performance is expected.

A3.5.4 Fly

Another concern arises about the level of fibers in the air (fly) because it can and does cause defects in the yarn produced. An accumulation of fly landing on the yarn being made in a ring frame obviously creates a blemish. Not so obvious is the result of fly on other products. For example, fly landing on roving during manufacture is

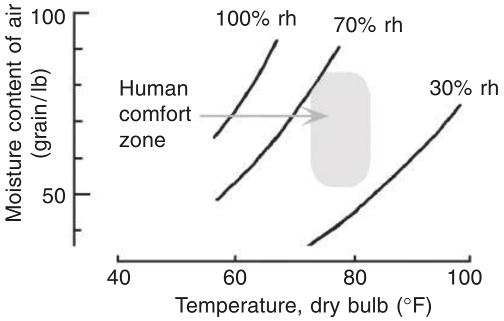


Fig. A3.2 Human comfort zone

often thrown off again during spinning, only to land on the yarn. A good spinner keeps an eye open for the sources of fly production and tries to eliminate them.

Fiber and dust can carry electrical charges, and so can the surfaces of machinery. Friction between moving surfaces, and separation of those surfaces, also produce electrical charges. Much of the dust and fiber is highly flammable and if the electrical charges build up sufficiently to cause a spark, then a dangerous conflagration can occur. The remedies are to keep rh at a proper level and to ground all machinery by connecting it to earth with a conductive cable. In that way, electrical charge build-up is minimized and any that does form is leaked to earth before it can cause damage [2].

There are also other reasons for controlling the electrical charge. If the rh is too low, electrified fibers coagulate and interfere with processing. The optimum level varies from fiber to fiber and from process to process. A common symptom of incorrect humidification in spinning is when roll laps occur.

A3.5.5 Lighting

Most workspaces in a modern mill are lighted exclusively with artificial lighting. The electrical load can be limited to about 16 watt/square meter and still provide the necessary 550 lux level of illumination. To achieve this economy, efficient light sources, good reflectors, and clean, well-maintained, light-colored ceilings must be used. Windows not only allow passage of light, but they form an easy path for noise and heat transmission. Thus, natural lighting is avoided because of the increase in load for the air conditioning plant and the increase in noise radiation to the outside. Maintenance costs of the windows are also avoided.

A3.5.6 Effects of chemical contamination

Fibers or subsequent products treated with noxious chemicals can form a hazard. Chemical emissions from any product or machine in the mill must be strictly controlled and the necessary venting must be supplied. Such emissions are usually subject to regulation by the local authorities. Where singeing is used, not only must the products of combustion be properly vented, but the work area must be sealed off from the main work areas to minimize the fire risks. The particulate level in the air should also be monitored because soot inevitably escapes into the atmosphere.

In filament texturing, where the filaments are raised to high temperatures, lighter fractions of fiber finish may boil off. It is important that the gases emitted are not toxic, harmful to the product, or harmful to the machine. Again, proper ventilation is required.

Man-made fibers have fiber finish which sometimes becomes removed from the fibers and accumulates on certain important surfaces on various machines. Also some fibers can produce oligomers which deposit on the working surfaces. In places, the deposit forms a so-called ‘snow’ that is a sure sign of this sort of trouble. Cleanliness in this respect is a necessary condition for the production of high quality products.

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Appendix 4

Advanced topics II: Testing of textile materials

A4.1 Divisions in testing

A4.1.1 Introduction

There is a gray area concerning quality control and testing. In one sense it is very clear that the technicians who carry out the testing should have some say in the sampling and interpretation of results. However, it is not always clear where the measurements and techniques stop, and where the use of the results as a control medium starts. The reason for testing is to acquire the data on which sound decisions can be made; the reasons for quality control are to ensure adequate quality of product and minimum trouble in processing. In a mill, testing is not an end in itself.

Testing falls into two categories: laboratory (or offline) testing and online monitoring.

In the first mode, shown in Fig. A4.1(a), samples of the product are taken to the laboratory for testing. Various sorts of test apparatus are used. The test laboratory must be air conditioned because the moisture content of textile fibers varies with ambient conditions and many tests are strongly influenced by moisture content. Normally, a laboratory is maintained at 70 ± 2°F (21 ± 1°C) and 65 ± 2% rh for 24 hours/day over the whole year. Samples brought into the laboratory have to be conditioned for sufficient time before testing to allow the moisture content of the textile material to reach equilibrium with the laboratory environment. Whilst it might only take a few minutes for a single fiber to reach equilibrium, a can full of sliver might take several days. As a guide, a tightly wound yarn package should be conditioned for 48 hours.

In the second mode, shown in Fig. A4.1(b), sensors are fitted into the machine, which generate signals that describe some function of the material or machine performance; these signals are processed by a computer. The sensors should be insensitive to changes in the environment or should have corrections applied to neutralize any changes in anything other than the parameter being measured. The computer may be local or it may be a central unit. The output of the computer can be used either for control or for information or for both.

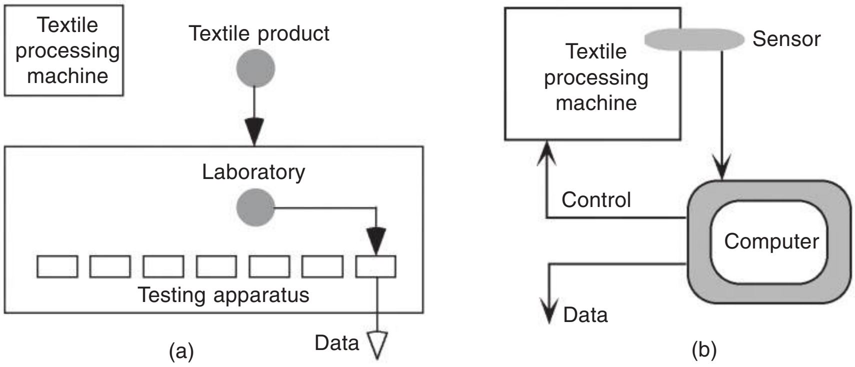

Fig. A4.1 Testing modes

A4.1.2 Laboratory testing

The priorities for testing filament yarns differ from those for staple yarns. In staple spinning, the most common measurements relate to variations in linear density, fault levels, fiber properties, yarn twist, and strength. Increasingly, laboratories are using high volume instruments (HVI) to measure many fiber properties in a semi-automatic measurement line. Other testing equipment is also becoming automated. Since the number and type of the individual measurements are likely to vary, no description of HVI lines will be described per se, but individual component tests will be described under the appropriate headings. In filament testing of yarn being used for household, apparel or industrial applications, bulk, fiber strength, elongation, and dyeability are among the most common tests made. For household applications, cover is a very important factor and consequently yarn bulk tops the list of priorities in these cases. In both staples and filaments, consistency of fabric appearance is important; consequently yarn defects, dye affinity, and variations in linear density, etc., are becoming of increasing importance. For many industrial uses, strength is the most important factor.

A4.1.3 Online monitoring of production

Many yarn and fiber attributes cannot be measured online because of the technical difficulties and costs involved. However, it is now established practice for the count of yarn, or any intermediate product, to be measured online. Also, yarn hairiness and defect levels are commonly monitored continuously. Sensors might be connected to devices that sound an alarm when the monitored attribute moves outside the control limits. Any of the signals generated by the sensors involved in monitoring might be used for control purposes, but in practice it is likely to be used only as a proxy for mass/unit length.

A4.2 Measurements on staple fibers

A4.2.1 Fiber length

Drafting waves in roller drafting are caused when there is a significant difference between the ratch and effective fiber lengths. The ratch settings are set to standard values but variations in fiber length occur within any given sample, as well as from sample to sample. Thus, there are always problems with drafting waves and some control of effective fiber length is desirable. It will be recalled that 'effective fiber length' refers to the *in situ* behavior of the fiber; the effects of hooks, lack of fiber straightness, and fiber ends are all taken into account. Thus, it is necessary to consider not only the fiber length distribution but also how processing affects the geometry of the fibers.

The traditional method of displaying the fiber length distribution is to progressively comb out fibers of descending length from a prepared sample. Fibers are then placed on a velvet board in the form of an array, as illustrated in Fig. A4.2(a) (the array shown is for American cotton). The actual procedure needs skill and is time-consuming. An alternative is to use a machine to create a fibrogram. The samples have to be prepared before being measured to ensure that the fibers are parallel and that unclamped short fibers are removed from the fringes to give a length-biased sample. This is done by using a comber roll. A fiber fringe is produced in which one end of the beard is clamped and the free ends extend away, with the fibers parallel to one another. A schematic sketch of such a fringe is given in Fig. A4.2(b). Fibers are viewed in a narrow aperture in an optical or capacitive system. The aperture is called a window in the diagram. The signal derived from the sensor elements provides an estimate of the number of fibers in the window. If the clamp is moved to change the dimension *X*, the number of fibers viewed in the window also changes. A plot of the number of fibers against *X* gives a fibrogram from which the distribution of fibers can be deduced. The fiber array is often typified by two span length readings. The span

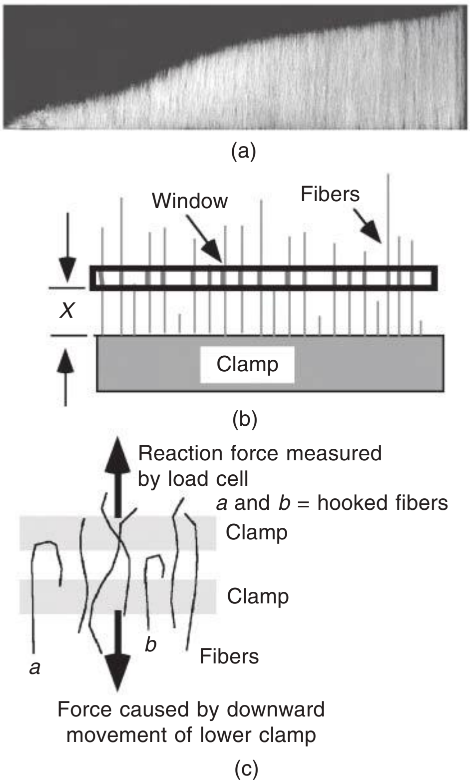

Fig. A4.2 Fiber measurement

length is the average length of those fibers that fall in the longest *y*% of the fiber population. Values of *y* commonly used are 2.5% and 50%, the long fibers being typified by the 2.5% span length and the short ones by the 50% span length. The span length changes and the hooks are pulled out as the material passes through the various draft zones. The added variance in drafting is greater for the 50% span length fibers than the 2.5% ones.

It is normal to report the upper half mean length, uniformity index, and the short-fiber content. Uniformity index is defined as the ratio between the 2.5% and the 50% span lengths; it is often quoted as a percentage. The short-fiber content is taken as the percentage of fibers less than 0.5 inches. Care should be taken in comparing results from the various sorts of length sampling; different machines may produce results that are not truly compatible because of differing sampling procedures. Some testing equipment is able to report using differing sampling schemes, which is of considerable value if test results are to be compared in different departments or different mills.

The clamping of hooked fibers can give ambiguous results. If hooked fibers are clamped at the base of the 'U' of the hook, then the fiber length, as seen by the testing machine, is shorter than the real length. If the fiber is clamped at the extremity of the longest leg, the measured length will be close to the real length. There are intermediate conditions, which give a variety of errors. This is despite the combing operation, which is part of the preparation procedure. It follows that, where there is a predominance of leading or trailing hooks, such as with sliver, the direction in which the material is mounted in the clamps becomes important. If there is doubt about the direction, the material should be tested in both and the higher of the two values should be used. Insufficient combing during fiber preparation produces error also. Some fiber breakage will occur during specimen preparation, but the error from this source will be small providing the fiber fringe is not too vigorously combed. A compromise between under- and over-combing has to be found for minimum error.

A4.2.2 Fiber strength

Fiber strength is measured on a beard of fibers clamped as indicated in Fig. A4.2(c). One clamp moves relative to the other to extend the fibers and a load cell attached to the fixed clamp measures the load on them. If the number of fibers in the cross-section is determined, the fiber breaking load can be determined. Further if the average fiber linear density is known, the fiber breaking stress may be calculated. On an HVI line these measurements are made on the same samples, which helps in the matter of accuracy of result. The system is similar in principle to that later described for yarn. Again, hooked fibers can reduce the indicated fiber stress with respect to the actual one; furthermore, insufficient combing will reduce the indicated stress because of the lack of fiber orientation in the direction of loading.

A4.2.3 Fiber fineness

Fiber fineness is measured by placing a given mass of fiber in a container of given volume and measuring the air permeability by passing air through the mass. Fiber fineness is related to this air permeability and the results are expressed as the *micronaire index*.

If a fiber is loosely packed into a standard tube and air at standard conditions of temperature and humidity is passed through the packed tube, a pressure drop will be found. This air pressure drop/unit flow volume is proportional to:

$$k\,(A_s)^2\rho M^2/\{(K\rho) - M\}^3 \qquad \text{[A4.1]}$$

where A_s is the surface area of the fiber sample, ρ is the packing density of the fiber, M is the mass; k and K are factors.

For a standard sample mass of a given fiber, the pressure drop is a measure of the surface area of the fiber, from which the fiber diameter or linear density can be estimated. The importance of maintaining standard conditions is evident from Equation [A4.1]; in particular, the denominator is sensitive to error. Accuracy in sample mass is very important. Uniformity of fiber packing in the test volume is also an important factor and any tendency for the fibers to occlude will produce an error. Despite the care needed to get reliable results, the test is simple and rapid and it is widely used in mills. The result is described by the term 'micronaire index' ('micronaire' for short). Cotton fibers from a given geographical zone often have factors k and K which vary but little, and the test is useful within such zones. For example, the 'micronaire' test is widely used within the USA because of its reliability under normal circumstances for US grown upland cotton or other varieties. However, if cottons from many geographical zones or varieties are mixed, there could be difficulties. Other more sophisticated instruments are available, as described in Section A4.2.4.

In the case of flax fibers, the fibers are gummed together at the beginning of the process and they have to be divided during processing. It is possible that some fibers are still gummed together at the end of the process and the variability in apparent fiber fineness might be more marked than desired. Also, since the product is a natural fiber, the fiber fineness is variable. Nevertheless, the fineness of the fiber is a parameter that should be controlled. The usual equipment for these measurements is a simple air permeability tester with a short test cylinder into which a U-shaped sample is inserted. Variations in the cross-sectional shape of the fibers affect the air permeability tests as just described. This is a disadvantage as far as measuring fiber linear density (micronaire) is concerned, but it brings with it the advantage of ease of use.

A4.2.4 Cotton immaturity

Immature cotton has a different cross-section from mature cotton, and the permeability test helps identify this important parameter. Immature cotton fibers also have dyeing characteristics that differ from those of mature fibers. Thus it is often important to determine if the fiber being used is mature or not. The fiber fineness test described in Section A4.2.3 is incapable of discriminating between the effects of changes in fiber cross-sectional shape and fiber 'diameter' (i.e. fiber fineness). In trying to measure two parameters with one measurement, there is always an ambiguity. Sometimes, with a restricted source of supply, the immaturity and micronaire correlate but outside that sphere it is necessary to conduct a second test. One way is to carry out second permeability tests on fibers swollen by treatment with caustic soda and make comparisons with the first test on unswollen fibers. Alternatively, double compression tests can be used. A constant airflow device is used to measure the pressure drop of a standard sample at two different fiber-packing densities. A second alternative is to use image analyzers, but the expense of the equipment limits this option. Projection and other microscopes can be used to look at single fibers or small groups of them, but the labor and equipment involved again makes this a fairly expensive alternative.

A4.2.5 Optical character

Color and reflectance are measured by an optical system; yellowness (+b) and reflectance (Rd) are reported. Trash content is also measured by an optical system that relies on the fact that trash is darker than cotton. The percentage of the viewing area of the specimen that is dark is taken as a measure of trash content. The measurements of fiber length, strength, fineness, color, and trash content can all be made on a single, automated machine known as a high volume instrument (HVI). The use of such machines has virtually replaced manual cotton classing in the USA and they are widely used elsewhere.

A4.2.6 HVI calibration

A problem that exists with the HVI relates to consistent calibration of the machines over time and between various laboratories. Since their use is mainly with cotton, emphasis is placed on the use of calibration cottons as a standard. The difficulty is that even the calibration cottons are variable; consequently, statistical control techniques have to be used to keep the machines within acceptable limits of calibration.

A4.3 Measurement of linear density of staple yarns

A4.3.1 Determination by weighing

A commonly used manner of testing for yarn count is to weigh skeins and derive an average value. (A skein usually contains 120 yards of yarn.) However, the variations in count from skein to skein must be closely watched in order to prevent barré in fabrics. Commonly, this form of measurement is used both in the production facility and the laboratory.

In a long specimen such as a skein, short wavelength errors escape detection; there can be no information gleaned about the inch-to-inch variation in linear density.

Sliver is usually measured by a yard board (Fig. A4.3) which is simply a template

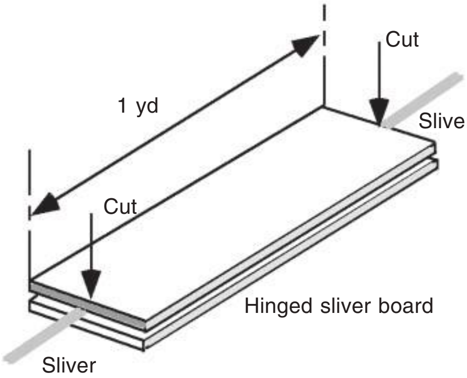

Fig. A4.3 Yard board

for cutting a set length of sliver. Other lengths can be measured using the same technique. It is a manual method often used in the mill, which is simple to use; it is a test that is reasonably accurate and the procedure is fast. Again, it is necessary to test a sufficiency of samples.

A4.3.2 Continuous measurement

The discussion in the previous section centered on the mid and upper limits of length. now consider the lower limits. In continuous measurement, sensors are used to measure some set of attributes that reflect the parameter to be monitored. For example, linear density might be measured by using a pair of electrodes to measure the capacity of the electrode gap with the staple yarn, roving or sliver passing through that gap (Fig. A4.4). An example of this type is the Uster evenness tester [1]. A small, varying electrical voltage across the plate enables differences in the electrical capacity of the electrode system to be detected. As the mass of yarn in between the electrode changes, so does the capacity. The length of the electrode, *L*, is only a few millimeters and so the data stream reflects very short wavelength changes. Thus, the equipment is able to monitor continuously the changing linear density of a running yarn and the resulting electrical signals are converted to coefficients of variation, spectrograms, and strip charts.

There is a relationship between the capacitance and the linear density under controlled conditions, which makes it possible to treat the output from the monitor as a measure of linear density [1]. As a second example, a beam of light can be used to project a shadow or image of the passing material and to translate that image into an electrical signal. In a properly designed system, the signal has a reasonably stable relationship with linear density and is often regarded as a measure of it. In these and other devices, the active sensor element is usually of the order of 1 mm, as measured along the length of the material being measured. Consequently there is no problem in resolving the data containing the complex spectrum. More detailed discussion of electrode width is given by Furter [3].

Some electrical circuitry in the system as sketched in Fig. A4.4(a) has been omitted for simplicity. Also, as a precaution against the effect of stray electrical fields, it is normal to surround the active electrodes with guard elements. These guard elements are set into the same plane as the active ones and are earthed, or held at a controlled voltage. If we take each of these in turn: capacitance is controlled by length, *L*, the dimensions of the gap, the cross-sectional shape of the strand, the position of the strand within the gap, and the dielectric constant of the material in the gap. Within limits, *L* can be adjusted electronically. It is important to use the correct set of electrodes with the proper gap size for a given material. Several gap sizes (or slot numbers) are available on the commercial testing machines. Air has only a negligible effect, but moisture in the fibers has a powerful effect. Thus, it is important to control the moisture content of the fibers if an accurate result is required. The effective electrode length can be changed by integrating the results over time. Such integrated values are used for inert tests in which the higher frequency variations are damped out and the signal is smoothed to give a moving-average value.

One form of record (Fig. A4.4(b)) relates the deviation of linear density to time elapsed. Since both the textile material and the chart travel at known speeds, it is a simple matter to translate time into length of material. These charts are known colloquially as strip charts and technically they are expressed in the time domain.

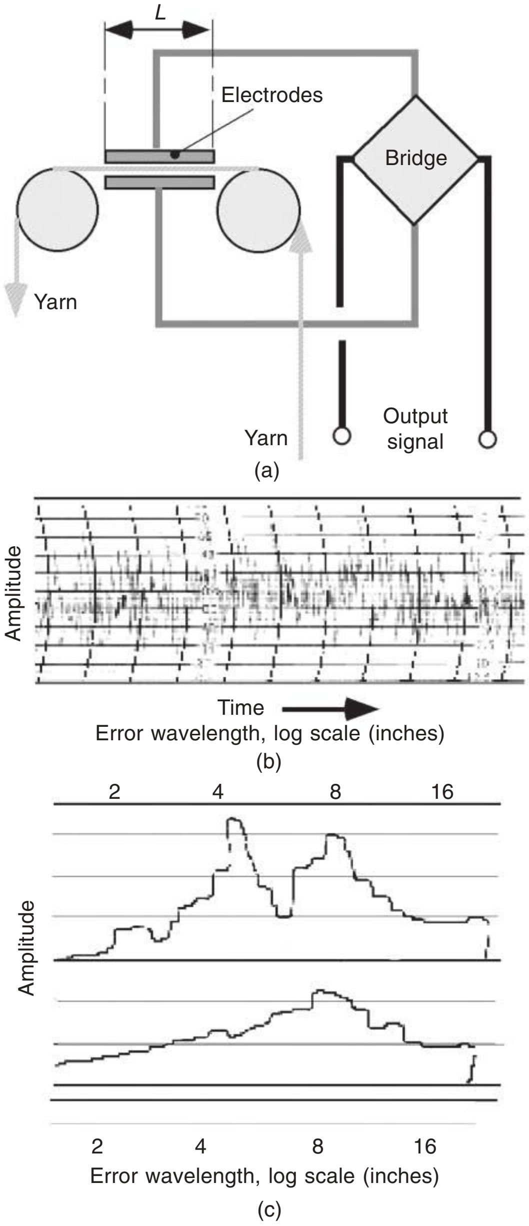

Fig. A4.4 Capacitive transducer system

Strip charts have their main value in making long-term variations visible. In this regard, long term relates to the length of textile material tested. Extra long-term trends cannot be seen. The charts are also valuable for detecting irregular yarn faults and disturbances that, because of their non-repetitive nature, do not show up on a spectrogram.

A second form of diagram is the spectrogram, which is a chart expressed in the frequency domain where repeating patterns of deviations are resolved by frequency or wavelength rather than time (Fig. A4.4(c)). For example, a simple sine wave can be expressed as a single line at the appropriate frequency or wavelength in the frequency domain. A complex wave made up of sine waves gives a spectrum of lines, but the rendering of the data is more economical and understandable in the frequency domain.

To be effective, a sufficient length of textile material has to be tested and a large amount of raw data is generated. As implied in the previous paragraph, a way of compressing data is to convert what, in essence, is a long time series into the frequency domain. To further compress the error wavelength scale, it is usual to use a logarithmic basis. In the terminology of textile processing, the chart expressing evenness data in the frequency domain is known as a spectrogram although, technically, it is a periodogram. The spectrograms in Fig. A4.4(c) show reasonably good and bad examples of roving evenness. The first is an example of a spectrogram of a very bad yarn, which shows two humps (probably caused by the interaction of a bad front roll on a roving frame, combined with improper roll settings). The second shows a spectrogram that would often be regarded as satisfactory. In the spectrograms, the ordinate is often merely referred to as amplitude, but this needs a little more discussion. The purpose of such equipment is to record mass variations or so-called 'evenness', 'regularity', or the negatives of these. Based on the work of Furter [4] and others, one may define the parameter in two ways. The first is:

$$\text{Mean deviation or } U\% = [100/(x_m T)] \int_0^T |x_i - x_m| \, dt \qquad [A4.2]$$

where x_i is the instantaneous value of linear density, x_m is the mean value, $|x_i - x_m|$ is the deviation of the instantaneous value from the mean, T is the evaluation time, and t is time in compatible units.

If s is the standard deviation, $s^2 = \sum (x_i - x_m)^2/(n_s - 1)$, and $CV = s/x_m$, the second definition is:

$$CV\% = [100/x_m] \sqrt{\left[(1/T) \int_0^T (x_i - x_m)^2 \, \mathrm{dt} \right]} \qquad [A4.3]$$

Subject to the data being Gaussian or normally distributed, the relationship between $U\%$ and $CV\%$ is stated to be $CV = 1.25 \times U\%$. Furter discusses in detail the meanings of various strip charts and spectrograms, as well as the measurement and importance of yarn faults.

Turning to online monitoring, suppose a device is measuring, online, the linear density of sliver emerging from a draw frame at 600 m/min, and that the output signals relate to successive 1 mm lengths. Each measurement requires a calculation and there would have to be 1000 × 600/60 = 10 000 calculations/sec. A central processing unit in a computer adequate for this traffic thus becomes essential. In a 24 hr day, there would be 864 million calculations for each measurement position. There has to be some means of filtering the output, otherwise the analyst would be overwhelmed. One way of filtering is to use periodic measurement, but if the measurements are spaced too far apart there might be difficulties with under-sampling. Another way consists of the equivalent of a control chart and provides a warning only when the parameter concerned moves outside the control limits.

An example of a control chart is given in Fig. A4.5, in which three values with round shaded plot symbols represent out-of-control points or outliers. Only these three points would be reported and the rest would be ignored except, perhaps, for a

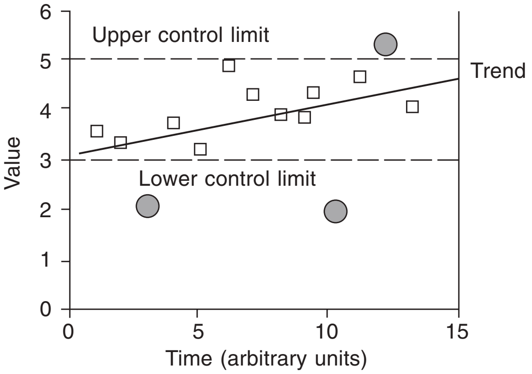

Fig. A4.5 Control chart

trend analysis that, in this case, shows the variables going steadily towards the upper control limit. As an aside, it should be noted that a record may be kept in the computer memory only for a limited period. When the data generated from the transducer is used in a control system, there are a number of ways to conserve computing power and keep the system under stable control. A transducer is a device that converts the variable to a usable signal. The digital data stream can be compressed to facilitate the transmission of signals to the controllers. Signals can be restricted to outliers, trend analysis can be used to modify the control, and other schemes can be applied to keep the volume of transmitted data within bounds.

A4.4 Measurement of twist

A4.4.1 Untwisting to zero twist method

With ring and twisted filament yarns it is possible to untwist yarns until the fibers are approximately parallel, and this condition can be determined with a fair degree of accuracy.

With filament yarns, the condition of zero twist can be determined by placing a thin blade between the filaments and then sliding the blade along the length of the yarn within the gage length [2]. When the blade can be moved without resistance from one end to the other, the yarn is at the zero twist condition. However, the use of such techniques becomes difficult with staple yarns. Ring yarns pass through what is essentially zero strength as they are untwisted, to zero twist. However, this is not true for rotor yarns. Zero twist staple yarns have little or no strength unless a bonding agent is present (which is highly unusual at this stage of processing). Consequently, the gage length is normally set below the staple length so that a sufficiency of fibers is gripped at both ends. It is desirable to test yarns under some tension to prevent the yarn from snarling when twisted. The tension applied when the yarn is at or near zero twist should not be so great as to cause the weakened yarn to break. The apparatus for such a test consists of two clamps attached to the yarn and some means of creating a sufficient controlled tension in the yarn between the clamps. One of the clamps rotates and untwists the yarn and the other is fixed.

The test is fairly labor intensive and is usually carried out in the laboratory.

A4.4.2 Twist contraction in staple yarns

Twist is measured in turns per unit length and, as the twist is changed, the yarn changes length. The change in length from the untwisted to twisted condition is known as *twist contraction* and it can be used to help measure twist. This should not be confused with the contractions that take place when filament yarns are textured.

A4.4.3 Reversed twist method used in staple yarn testing

A second technique requires one to carry on with what was the untwisting into the zone where the yarn becomes reverse-twisted [5]. Reverse-twisting continues until the gage length regains its original value, it being assumed that the twist contraction in the reverse direction is the same as the original direction. The reversed twist method is often known as the twist/untwist method (even though it would be more accurate to say ‘untwist/twist’ method). As shown in Fig. A4.6, a counterweight controls the yarn tension and the twist counter reads the change in the number of turns from the beginning to the end of the test. The twist indicated is assumed to be twice the twist in the yarn; consequently the twist density is half the indicated twist change/gage length. The initial tension in the twisted yarn should be maintained at 0.25 + 0.05 g/tex (or 2.45 + 0.49 mN/tex). The tension at the end of the reverse-twisting should be the same as the initial value.

A4.4.4 Twist testing rotor spun yarns

Rotor spun yarn never achieves a state during untwisting where all the fibers are approximately parallel. Thus, although the reversed twist method just described is normally used, there is an error due to the structure of the yarn. The measured values differ from those calculated from the machine parameters, as shown in Fig. A4.7 (for a polyester/cotton blend in this case). In this diagram, there should have been no change as the percentage polyester was altered. In the case of the so-called machine value calculated from the known rotational speeds of the machine components, this was true. The machine value was then used to normalize the other results. With the reversed twist method, changes in blend did affect the measured twist and this implies differences in yarn structure. This error is normally ignored because a standard of

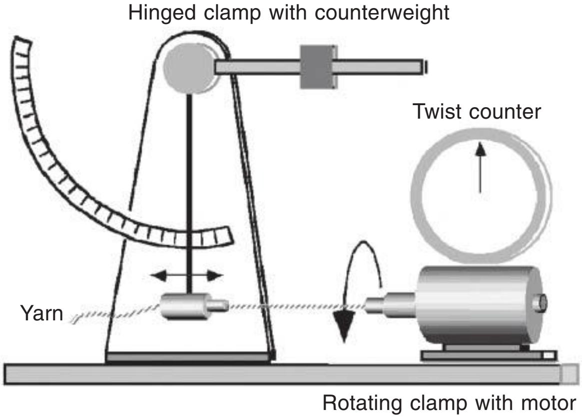

Fig. A4.6 Twist tester

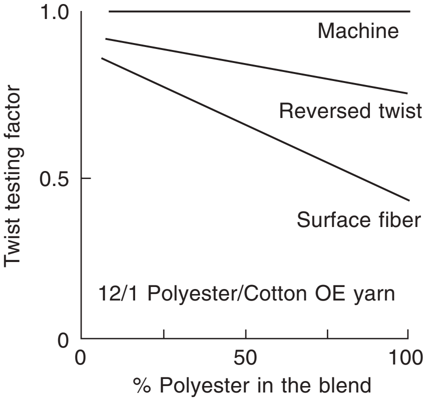

Fig. A4.7 Various methods of twist measurements for rotor yarns

judgment different from that used with ring yarns is applied. The effect varies with the fiber being used. If one judges the twist by the fibers on the surface of the yarn, there is even more error, and so this method is little used. The population of bridging fibers in rotor spun yarn usually varies from 10 to 25% and most of these produce the wrapper fibers on the yarn surface.

The fibers behave as if they are shorter than they really are and, as mentioned in Section 7.2.12, a higher TM is required than would be used in ring spinning.

A4.5 Visual examination of yarns

A4.5.1 Yarn board

One factor in assessing staple yarns is that of yarn grade. Fairly long samples of the subject yarn (which are normally white) are wrapped on a black yarn board (Fig. A4.8) or sleeves are knitted from it. These techniques are used to telescope the errors and make them more visible; they are useful for determining fault rates, short and mid-term errors of both staple and filament yarns. However, it cannot show errors longer than a fraction of the sample length, which is about 100 yards or so. A yarn blackboard is either a rectangular or trapezoidal board onto which yarn is wound, closely spaced to simulate fabric. Periodic errors produce patterning to appear on the yarn blackboard, which indicates a mechanical error. Slubbiness indicates drafting or drawing defects, and reflective differences indicate changes in yarn luster, or yarn

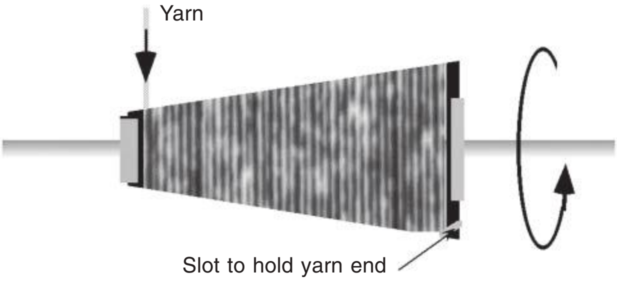

Fig. A4.8 Yarn board

hairiness, or both. For dyed filament yarns, differences in color, luster, and bulk can be assessed. The eye quickly becomes skilled in assessing the error characteristics and in judging the quality of the yarn. A yarn board is a very successful and simple device. However, it cannot show errors longer than about 100 yards or so because sample length is insufficient. The example of use in checking for variation in luster and/or bulk in a textured yarn has already been mentioned. Textured yarn has to be wound at constant tension because the structure of the yarn is such that the bulk changes with tension; thus surface reflectivity and yarn diameter also change. A knitted sleeve can be used to achieve a similar objective. In this case, the knitted material is robust enough to be dyed and, as explained in earlier discussions, this dyeing may well reveal faults created in previous processes. Faults caused by different temperatures or mechanical stresses would otherwise not be visible until it is too late unless differences in dye affinity can be harnessed in the test procedure. This is why the dyed knitted sleeve is valuable.

A4.5.2 Electronic yarn boards

Electronic equivalents to the yarn board have been developed (e.g. Cyros^{TM}) in which evenness data are used to produce a raster.[1] The brightness or thickness of the line being painted on the computer screen or paper is proportional to the diameter of the element of yarn being portrayed. The data can be acquired at the yarn testing stage or by online sampling using capacitive or optical sensors. In the latter case, no yarn would be consumed for testing. Each long series of data is divided into sub-series by deliberate choice and the selected series are plotted in the x and y directions on a monitor or print-out, to simulate a woven fabric. Such equipment is beginning to be used for fabric simulation and quality control in yarn manufacture. To be able to project what a given yarn will be like in fabric form is a useful addition to the means available to be able to control quality and assist sales. Furthermore, it can be done without the expense of actually making the fabric. It is likely that such an arrangement will permit recognition of very long-wavelength faults that are often missed with the present technology.

A4.6 Yarn hairiness in staple yarns

For the purpose of discussion, a fiber projecting from the surface of a staple yarn will be called a hair. It is, of course, sometimes difficult to define the surface of the yarn and the definition of hair is not very precise either. Error in measurement is thus inherent in some methods but such errors are better than no measurement or control. There are a large number of techniques [6] for measuring hairiness which range from microscopy to online measurement of projected optical or electronic images. Error in measurement is inherent in some methods but such errors are better than no measurement or control. For example, referring to hair A in the plan view of Fig. A4.9, the projecting hair length, when viewed in elevation, is foreshortened as shown. In addition, part of the hair length may be obscured by the body of the yarn, as also is shown. To increase

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[1] A common example of a raster is a television set where a light beam is made to oscillate across a screen in a two-dimensional pattern and the brightness is modulated to produce a picture.

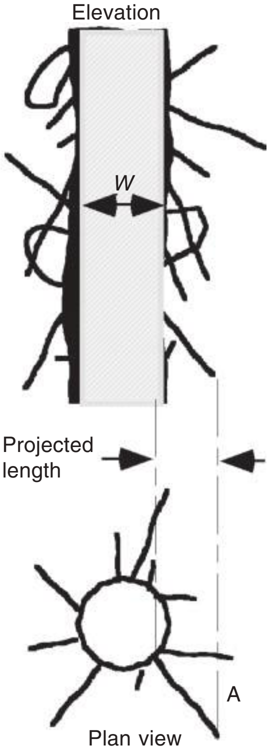

Fig. A4.9 Yarn hairiness

sensitivity of measurement, a mask of width *W* is often added; only the variations outside the shaded area are measured. If the width is smaller than the yarn diameter, signals from the body of the yarn are added to the signal as shown by the black areas bounding the shaded rectangle. This too produces an error. If *W* is too large, another error is introduced. Since yarn diameter is variable, some error is inevitable if such masks are used, but the increase in sensitivity reduces other errors in measurement and the net result is that it is worth using them. Often the information required relates to the outer surface of hairs, and the masking width is then increased to eliminate the portions of hair close to the yarn body. In these cases, the mask width, *W*, is a multiple of the yarn core diameter. Hairiness is variously described by the number of hairs/unit length at a given radius, or by the length of the hairs. The hairiness is dependent on the yarn diameter and has a roughly linear relationship with fiber length and twist over a reasonable interval.

Many different types of hairiness measuring equipment are used in laboratories and online means of testing are available. Outputs give hairiness data in both the time and frequency (wavelength) domains. Spectrograms of hairiness are becoming as common as spectrograms of linear density. Much of the comment made earlier about variability of linear density also applies to variability in yarn hairiness.

A4.7 Tensile testing of strands

A4.7.1 Testing single strands

A tensile testing machine consists of two yarn clamps that grip the yarn specimen and move apart to induce load in the specimen. Usually one clamp is held stationary and the other moves. The stationary one usually holds the transducer or load cell, which measures the load applied, and the movement of the other clamp reacts with a sensor to give the elongation of the specimen. Electrical or other circuits control the elongation of the specimen by changing the movement of the moveable clamp. The design of the load cell is an important part of the specification of the machine. Most load cells require a finite elongation in the direction of load to produce a signal. It is highly desirable that the system should be stiff so that the deflection of the machine is very small in comparison with the strain in the specimen. A discussion of the design of transducer is given by Furter [7].

Care has to be taken in interpreting the results because of the length factor. A long specimen has a low strength because of the number of weak spots in its length, whereas a short sample has more variable results. The short-term coefficient of variation of tenacity is of considerable importance in determining the efficiency of the ring spinning and subsequent operations. Despite the arguments for using single-end yarn testing, it is more expensive than skein testing and involves high skill by the technician. For these reasons, one finds mostly skein testing in the mills and single-end testing in research laboratories. Also, the materials are visco-elastic, which means that the results are dependent on the rate of loading of the material. This becomes an important matter when results from different test facilities have to be compared.

A sample should be tested in a representative fashion. One implication of this is that the correct length of specimen should be tested. The tests often yield the breaking strength and the elongation at break. Because most textile fibers and yarns are visco-elastic, the stress–strain curve is not linear. Consequently, if one wishes to characterize the behavior in normal use, where the loading is not high, attention has to be paid to the slope of the stress–strain curve near zero load. Examination of elongation at break gives data that helps one assess the visco-elastic nature of the yarn or fiber. For complete information about the visco-elastic behavior, it is necessary to cycle the load to determine the hysteresis, but such testing rarely enters into commercial mill practice.

Tensile test machines fall within one of three categories [8], namely:

1. Constant rate of extension (CRE);
2. Constant rate of traverse (CRT); or
3. Constant rate of load (CRL).

The test category should be cited with the test results because the type of test affects the numerical results. Selection of the category depends on the end use of the product being tested. It follows that inter-laboratory comparisons must be for like categories.

In strength testing, the values are nearly always measured offline because the test is destructive. The shortest effective sample in measuring strength is where the yarn clamps touch one another at the clamping points and the gage length is zero (Fig. A4.10(a).

Two problems arise. The first is that the yarn clamps induce a stress in the yarn around the clamping zones. This influences the characteristics of the yarn actually tested, and usually yields a lower breaking force than should have been obtained. The

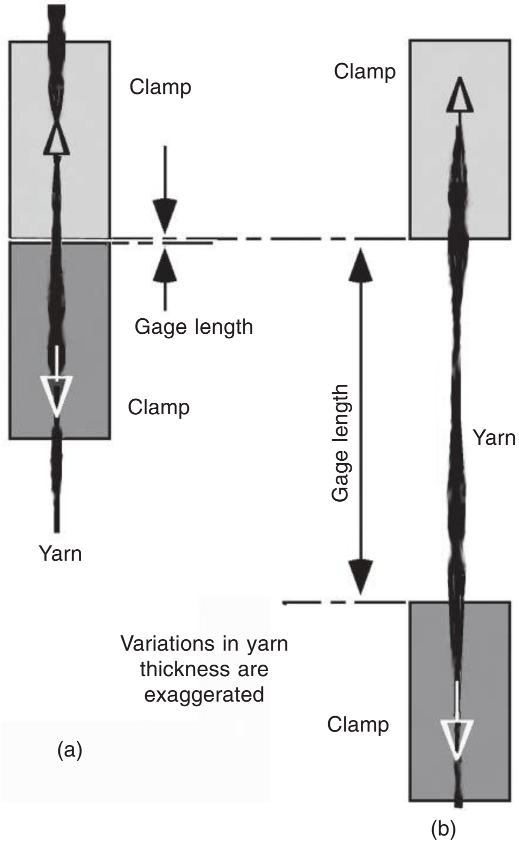

Fig. A4.10 Tensile testing of yarn

second problem is related to weak link theory and yarn variance. A chain always breaks at its weakest link and a yarn sample can be regarded as a chain of infinitesimally short links. A zero gage length test produces a variance amongst the results similar to that existing in the length of yarn from which the test specimens were taken. A long gage length contains a distribution of link strengths (Fig. A4.10(b)) and the weakest one fails; an erroneous conclusion would be that the single result is typical of the whole length tested. With insufficient testing to establish the variance, the single result would be no more than an approximation without any knowledge of the probable range of error. Clearly a long gage length has a greater probability of including a weak link and producing a low result than does a short gage length for that single test. Often a long sample is wrongly preferred because it is thought that the results are less variable and, therefore, the results are more reliable.

There is a wide range of stress–strain characteristics of fibers and yarns. Space precludes more than a sample, but Fig. A4.11 shows a wide range, especially between untextured filament and staple yarns. It will be noted that there are also wide differences in the shapes of the curves that reflect their visco-elastic character. It must be emphasized that the curves shown are single-end tests and that there are considerable variations within any one series of tests with a given yarn.

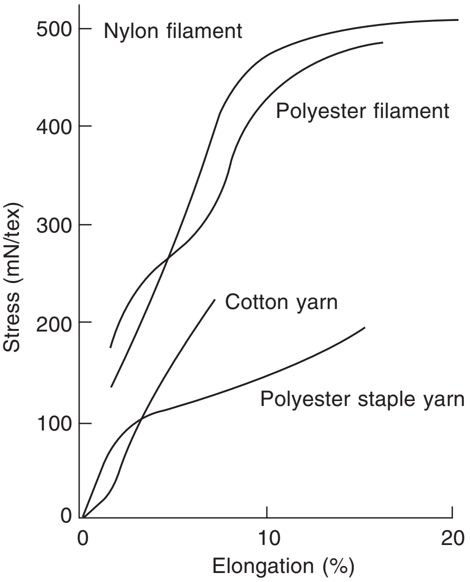

Fig. A4.11 Stress–strain curves

A4.7.2 Testing skeins

With the testing of single yarns as sketched in Fig. A4.11, the results should be averaged after sufficient tests have been made. An alternative method to obtain a value for yarn strength is skein testing [9]. However, if a skein is tested, many parallel portions of yarn are loaded simultaneously. Since all fibers gripped by both clamps experience the same extension, the load suffered by each gripped fiber depends on its longitudinal stiffness. A stiff fiber may take more load than less stiff parallel portions, with a result that certain fibers will fail before others have reached their breaking stress. Thus, the skein may appear weaker than might be expected. On the other hand there is an averaging effect between the parallel portions which reduces the effects of weak spots in the yarn. Long specimens of yarn in the form of skeins give strength values that are some sort of average; because of that, they are frequently used. Skeins of 120 yd are commonly used.

The strengths of both single yarns and skeins are often expressed in terms of tenacity. For a single yarn, the tenacity (T) often employs the units mN/tex. For a skein, the mathematical product of cotton count and breaking load in lbf (CSP – count-strength product) is customarily used.

ASTM D1578 suggests that:

$$\text{CSP} = KT$$

However, varying characteristics of yarns and skeins cause the factor K to alter from case to case. ASTM quotes $K = 21.23$ for cotton.

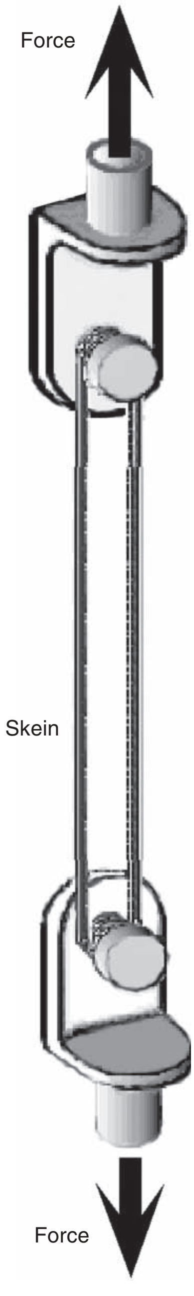

Fig. A4.12 Skein test

Variation from skein to skein gives no information about short-term errors because these have been averaged out, but does give information about the earlier processing stages. Practice varies somewhat but an example typical in the USA is that 20, 40, or 80 turns of yarn are wrapped on a reel of 1.5 yd circumference to form the skein. The skein is usually elongated on a tensile testing machine at 12 inches/min.

A sketch of a skein mounting portion of a testing apparatus is given as Fig. A4.12.

The result is quoted as the lea strength or CSP. The skein test is considered unsuitable for yarns that stretch more than 5% during the test. Some low cost testing machines have a pendulum arm fitted with a ratchet. When the moveable crosshead drops, the load on the pendulum lever causes it to rise along a quadrant on to which the ratchet mechanism is fixed. The weight on the pendulum rises with load, but when the skein breaks it is unable to drop back and so it records the breaking load.

A4.7.3 Multi-function fiber measurement

Because of the number of tests needed to control the blending of natural fibers, attention has been turned to assembly line layouts reminiscent of the automotive industry. This is particularly so with cotton testing. The so-called high volume instruments (HVI) consist of several working stations situated along a console. At each working station, one or more fiber attributes are measured that differ from the attributes measured elsewhere in the HVI. Data from every transducer is stored and processed in a computer. Thus, the testing of a sample is carried out at virtually the same time, under the same atmospheric conditions, with the sub-samples needed to make fiber beards taken from zones in close proximity. This arrangement expedites the flow of work and reduces the probability of error. Current HVI machines measure trash content, short fiber concentration, fiber fineness (micronaire), upper half mean length, strength, elongation, color, and reflectance. The acronyms used are trash, SFC, MIC, UHL, STR, ELO, +b and Rd. An earlier discussion (Section 11.2.1) deals with the definitions and importance from a quality control standpoint, whereas some other attributes will be measured in the future, and there certainly will be developments in the techniques of measurement.

The Advanced Fiber Information System (AFIS) device measures fiber properties while the fibers are being carried by an airstream. A scanning laser illuminates the moving fibers and transducers pick up the reflections. The fiber fineness, length, and color attributes can be assessed in this manner. The device is not in such wide use as the HVI and it does not measure fiber strength and elongation.

A4.8 Filament yarns

A4.8.1 Linear density of filament yarns

Normal untextured filament yarn has a linear density, which is virtually invariable along its length. Consequently, it is sufficient to reel off a certain length, and weigh it under standard conditions of temperature and relative humidity of the workspace. However, when the yarn is textured, the mass may no longer be evenly distributed along the length. Also, the modulus of elasticity of the yarn is low due to the texturing (i.e. it is ‘stretchy’). Thus, textured yarns have to be tested under constant tension conditions. Because of the variability, methods similar to those explained for staple yarns may be employed.

A4.8.2 Strength of filament yarns

For industrial uses, filament yarns are usually tested for strength. This is a straightforward tensile test; providing there has been proper sampling, it is a simple exercise in quality control. For apparel yarns, tensile tests are also used on occasion. The purpose in this case is usually to check for degradation of the filaments by overheating in texturing, or by some other cause. The tenacity loss can be up to 10% with polyester and nylon. Proxies for poor quality can be found by observing the manufacturing equipment. Excessive 'snow' (powdered oligomer and finish) around a texturing unit and excessive production of fumes from a heater are two such examples. Also, tests of evenness can be used to show errors. The problem is sometimes in the quenching after extrusion. Typically, a false twist textured nylon or polyester has a tenacity of 350 to 500 mN/tex (4 to 6 gf/den) and an elongation at break of between 25% and 35%.

A4.8.3 Definitions relating to the bulk of textured yarns

There are a number of terms concerning normal usage of textured thermoplastic filaments that need to be mentioned. *Bulk* is generated when filaments are caused to coil, to take up a zigzag shape, or to be deformed in any micro-convolution. Some early forms of texturing involved a zigzag texture, and bulk was then described in terms of *crimp*. This terminology has been extended by use to cover other sorts of texture. Thus, the ability for a yarn to contract under tension is called *crimp contraction* and the ability to recover is called *crimp recovery*. *Bulk shrinkage* is a term relating to the potential stretch and 'power' of stretch yarns, or a measure of bulk in textured yarns [10]. (The term 'power' is used to convey the recovery properties of so-called elastic yarns and fabrics; the term 'elastic' means the ability of the material to withstand large deformations, and does not relate to the engineer's definition as the relationship between stress and strain.) The term 'crimp' is used as a proxy for bulk, which is hard to define. A rough equivalent to bulk is yarn diameter, but the diameter is transient in the sense that it changes under load; also, when assembled into fabric, the cross-sectional shape changes according to the loads applied by the intersecting yarns.

ASTM standard D4031 [10] defines crimp contraction, in this context, as 'an indicator of crimp capacity or a characterization of a yarn's ability to contract under tension'. Crimp recovery is defined as 'a measure of the ability of a yarn to return to its original crimped state after being subjected to tension'.

When a textured yarn develops bulk, it shrinks, even under load. Some yarns have a structure that favors ease of elongation (so-called 'stretch yarns') and others favor yarn bulk. The elongational behavior and the hysteresis loss (ability to recover from deformation) can be measured on tensile testing machines, as described earlier.

A4.8.4 Measurement of bulk and crimp in textured yarns

Fabrics made from bulked yarns are intended to provide cover and insulation. The bulking processes are varied in nature and produce a wide range of yarn structures. Also the polymers available cover a wide range. Because the range of performance varies widely, there are several tests and sets of conditions available. ASTM suggests several loading options, which may be summarized as (a) 0.04 to 0.98 mN/tex, and (b) 8.8 mN/tex, the first being sufficient to extend the yarn without removing crimp and the second to remove crimp without significantly elongating the filaments. The recommended protocol prescribes that the low loading should be kept in place during the test, and that an extra load be added and removed when necessary to adjust the load between the two levels. Also, bearing in mind that the materials are visco-elastic, times of heating and loadings are strictly detailed as are other aspects of this series of tests. Information is kept up to date by ASTM, to whom the reader is referred for more information. During tensioning of the yarn under test, it can be immersed in water (Fig. A4.13), subjected to dry oven heat, or steamed. It is recommended that textured polyester yarns be tested first at the low load condition and then at the higher level of load. With textured nylon or polyester yarns, the water bath method can be used. For polyester yarns the bath should be at 97°C and a low stress level used, whereas for nylon a temperature of 82°C and a stress level of 0.13 mN/tex is recommended. The skein size is usually determined from the reel diameter (usually 1m) and the linear density of the yarn. ASTM standard D4031 quotes the numbers of turns on the reel varying between 25 and 63, according to the linear density of the yarn.

Crimp contraction is quoted as the percentage change in length between the high and low load conditions. Similar measurements are made before and after heating to develop crimp. Let the length of the skein at low load be X and at high load be Y. Also, let the condition before heating be designated subscript 1, and after heating by subscript 2. Thus, the length before heating at low load would be written X_1, etc. After heating, (a) the skein length at low load is measured, (b) the extra loading is applied to bring

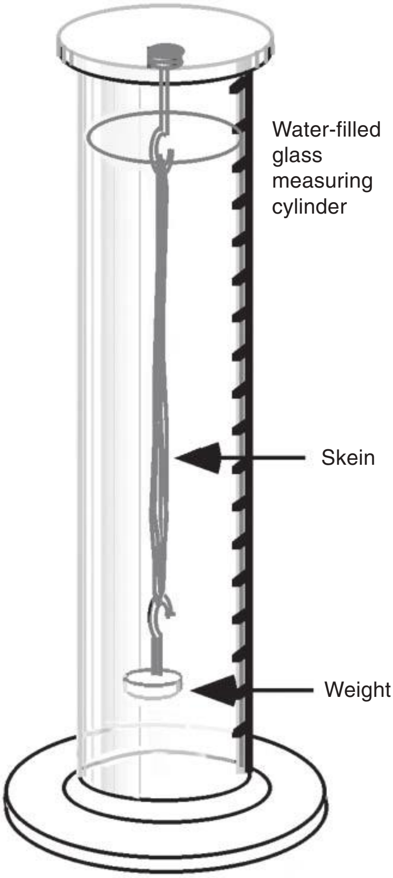

Fig. A4.13 Yarn bulk

up the load to the high level, (c) the skein length is measured again, (d) the extra loading is removed, and (e) the skein length is measured for the last time. Let X_3 be the length after heating and removal of the heavy load in the stage (d) just mentioned.

1 Skein shrinkage before heating $= 100\ (Y_1 - X_1)/Y_1$
2 Skein shrinkage after heating $= 100\ (Y_2 - X_2)/Y_2$
3 Skein shrinkage $= 100\ (Y_1 - Y_2)/Y_1$
4 Bulk shrinkage $= 100\ (X_1 - X_2)/X_1$
5 Crimp recovery $= 100\ (Y_2 - X_3)/(Y_2 - X_2)$

Items (1) and (2) give indications of how much mechanical and molecular forces play in the total relaxation and this information is useful for diagnostic purposes. Items (3) and (4) give the total shrinkage at high and low loads respectively. The crimp recovery, item (5), is the difference in length of the skein after heating caused by the final removal of the heavy load, which characterizes the hysteresis in the system.

A standard test for bulk is to use a modified skein shrinkage test (Fig. A4.13). The main difference between (a) the shrinkage test as a measure of potential stretch, and (b) the test as a measure of bulk, lies in the applied load. Care has to be taken when measuring bulk to ensure that all samples are tested with the same degree of 'lag'. A freshly textured yarn behaves differently from a yarn that has stood for an hour or so; this is because of stress decay in the thermoplastic material. Fresh yarns generally have higher skein shrinkage and lower strength than aged ones. The properties of the textured yarns can continue to change even over a period of 100 hours, but the change rate diminishes with time and eventually stabilizes. The highest change rate is in the first hour. In fabric form, finishing and other processing can cause further bulk to be generated and this is usually associated with perceptible shrinkage.

An alternative method of measuring bulk is to measure the volume taken up by a piece of fabric of a known mass, M grams. If the thickness is t mm and the area is A m^2, then the bulk, $1/\rho$, can be quoted in m^3/g, and:

$$1/\rho = tA/1000M \qquad [A4.4]$$

The structure of the fabric affects the cover factor and 'basis weight' (mass/unit area of fabric); for comparative purposes, the test is quite useful. The thickness is measured by a standard fabric thickness tester, which compresses the fabric slightly during the measurement (therefore there is some error).

A4.8.5 Stretch yarns

Stretch yarns fulfill a function different from that of bulked yarns. The objective of using a bulked yarn is to cover and insulate. A stretch yarn is designed to permit extraordinary extensions in fabrics made therefrom, thus the high load described in the previous section may not fully extend the yarn, and different levels may be necessary for testing some yarns. However, the procedures are similar to those described.

For stretch yarns, some use a standard weight of 20 grams acting on a skein of 12 500 denier, to give a specific stress of 0.141 mN/tex, whereas with a bulked yarn, a weight of 2 grams is used to give a specific stress of 10% of that just quoted. These figures are quoted merely to emphasize the difference between stretch and bulked yarns.

A4.9 Visual tests of fabrics

The simplest form of dye test is to knit a sleeve, dye it, and then make a visual assessment. There are standard procedures for the dyeing of the samples. The most sophisticated form of this sort of test is to dye a long knitted sleeve and subject it to automatic color testing. In this, the color is analyzed for its tri-stimulus components. The data can be recorded by a computer and related to fixed standards. Analysis of the averages and variances permits diagnostic work to be performed, and this, in turn, permits good control of quality. The test fabrics are usually inspected visually for filamentation, tight spots, etc., at the time the color tests are performed.

Continuous fabric inspection systems are useful for error diagnosis. Equipment using two scanning lasers may be used; a computer is programmed to recognize various types of faults and the data can be used to improve the quality of the yarn. Of course, it is far too late to wait until the fabric has been made to measure yarn faults. Nevertheless, there is hope that the techniques can be exploited to examine the yarn directly at an earlier stage.

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Appendix 5

Advanced topics III: Staple yarn structures

A5.1 Theoretical yarn structures

DeWitt Smith [1] stated that the basic geometrical features of a yarn determine the resolution of fiber tensions into components parallel and normal to the yarn axis. The summation of the components parallel to the axis provides the yarn strength and the normal components produce compressive forces that provide frictional cohesion. If a bundle is made up of parallel fibers and then twisted, it produces a helical structure somewhat similar to that shown in Fig. A5.1(a). The fibers are under tensions T_L and T_R, which vary according to the load applied. Interfiber friction can cause dissimilarity between T_L and T_R. The component tensions acting on the fiber at the various positions along it produce resultants directed towards the center because the fiber is wrapped around the core of the yarn. The radial compression arising from reactions of the many fibers, like the one shown in Fig. A5.1(b), causes each layer to compact the layers underneath. This increases the frictional restraints acting on the fibers in the core. Staple fibers could not survive in such a structure because the surface would abrade leaving the next layer vulnerable. This, in turn, would abrade and the whole structure would fail in short order. In fact, the staple fibers migrate radially during processing so that a single fiber occupies many different radial positions along its length. This phenomenon is known as *(lateral) fiber migration*; it causes the structure to interlock so that it retains its integrity over a surprisingly wide range of conditions.

A simple experiment can be made with a piece of string. Helically wrap the string round a person's bare arm, and apply moderate tension. The subject will feel the inward pressure referred to and the string will be seen to bite into the flesh. In Fig. A5.1(c), the same situation is depicted with a fiber. If the yarn is sliced along the plane XX, the view normal to that plane in direction Z is as shown in Fig. A5.1(d). For a small angle of wrap, the fiber may be considered to lie in the plane of the cut. Thus we consider the tensions T_1 and T_2 rather than T_3 and T_4. A section of the core, in the plane XX, is elliptical as shown. Portion AB of the yarn projects as A′B′ in the lower part of the diagram; this is the small arc of contact between the fiber and yarn considered here. The length AB measured along the yarn is δL. The fiber lies at a

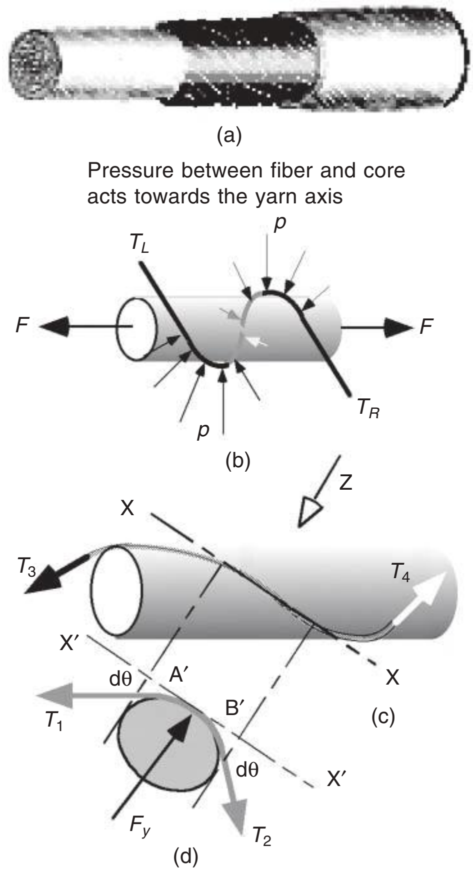


Fig. A5.1 Fibers in yarn

radius r with respect to the center line of the core. The twist is τ tpi and the force/unit length is:

$$F_R/\delta L \approx K(T_1 + T_2)/R \qquad \text{[A5.1]}$$

where R is the radius of curvature of an ellipse which is a function of (r, τ); K is a factor; and $\delta L \approx 2R\ \delta\theta$.[1]

Equation (A5.1) shows that the compressive force is a function of fiber tension, yarn diameter (or count), and twist level. The greater the twist, the smaller is the radius of curvature of the yarn surface, and the larger is the compressive force. Thus, the higher the twist, the tighter (or leaner) is the yarn.

---

[1] Radius of curvature = $[\mathrm{d}^2y/\mathrm{d}x^2]/\zeta$ where $\zeta = \{1 + (\mathrm{d}y/\mathrm{d}x^2\}^{3/2}$. The equation of an ellipse is $p^2 = ax^2 + by^2$, differentiating w.r.t x, $0 = 2ax + 2by\ (\mathrm{d}y/\mathrm{d}x)$ and differentiating again $0 = 2a + 2b[y(\mathrm{d}^2y/\mathrm{d}x^2) + (\mathrm{d}y/\mathrm{d}x)^2]$. When $\mathrm{d}y/\mathrm{d}x = 0$, $\mathrm{d}^2y/\mathrm{d}x^2 = -a/by$ and $R = -by/a$. The ratio of the major and minor axes is b/a and $b/a = 1/\sin\alpha$, $y = r$, $|R| = \mathrm{r}/\sin\alpha$ and the helix angle α is controlled by the twist.

A5.2 Actual yarn structures

A5.2.1 Fiber migration in ring spinning

Consider fibers traveling in the direction shown within the zone afdeh in Fig. A5.2(a). Fibers similar to the one marked abcd are typical of migrated fibers inherited from the roving, which pass into the twist triangle, def. Other fibers have lesser amplitudes of lateral displacement such as the fiber marked jg. Fibers along the nip line are squashed by the front drafting rolls such that it is very difficult for the fibers to slip with respect to the rolls. The strand is then translated into a roughly circular cross-section from the point d downwards by the application of torque. Fibers in or near the selvages of the twist triangle, such as the one marked de and df, take up much of the load created by the departing yarn and become quite highly tensioned. Many of the central fibers, such as that marked dg, cannot be taken up as quickly as they are delivered; they bear little or no load, and they buckle. In buckling, they tend to move to the outside of the newly formed yarn. Fibers passing down near the selvage of the twist triangle have the highest tension and tend to migrate into the center of the forming yarn structure, to relieve some of the tension.

Twisted roving is usually used and the roving twist provides a supply of fibers that periodically change their lateral positions across the ribbon of fibers approaching the triangle in a roughly sinusoidal manner. The portion abc of the yarn represents part of one of the fiber sinusoids. Also we consider fiber abc because it is one with a maximum lateral displacement amplitude and will, therefore, show the periodic effect most clearly. The parts are marked *a′*, *b′*, and c′ in Fig. A5.2(b) at a later time. (Meanwhile the portion in the vicinity of c that was highly tensioned now passes into the center of the yarn near d.) When the portion b′ of the same fiber eventually passes into the yarn, it is likely to be slack and to migrate to the outside of the newly made yarn. Comparing Figures A5.2(a) and (b), it will be realized that a single sinusoidal fiber moves across the nip line as it flows towards d. Even if the lateral displacement is not sinusoidal, lateral movement will still occur and produce a similar effect. Thus, some parts of a fiber are taut as they pass through the twist triangle and some parts are slack. Consequently, the fiber migration is periodic. Changing the roving twist can alter the characteristics of the yarn. The result of this is that the structure interlocks into a stable structure. The phenomenon is known as (lateral) fiber migration. A typical result is shown for a single fiber in Fig. A5.2(c). Imagine many of such fibers in a yarn. It becomes clear that the structure loses some of its order and that fibers pass from layer to layer, causing the structure to interlock as just mentioned. The loss of order results in more volume being required to accommodate the fibers; in other words, the yarn becomes more bulky. The enhanced insulation properties given by the extra airspaces in the yarn give fabrics made from the yarn a warmer, softer feel. Also, the fibers have room to deflect more easily, which improves the hand.

A5.2.2 Yarn hairiness in ring yarn

A good reference in the matter of yarn hairiness is given by Barella [2]. The geometry of the twist triangle not only controls fiber migration but also helps determine hairiness. Some of the buckled fibers extend from the surface of the yarn as hairs and loops. Air currents in the exit nip of the rolls also affect the process of creating hairiness, although this is more important in high speed spinning systems like air-jet spinning. Further hairiness is created in ring spinning as the yarn passes through the traveler,

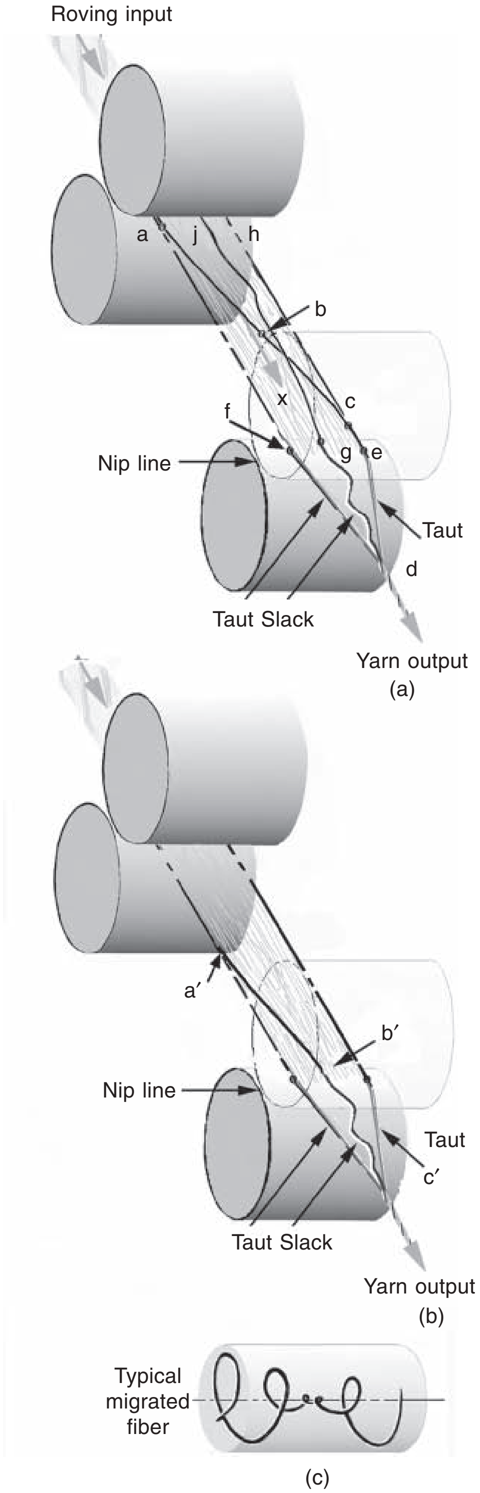


Fig. A5.2 Fiber migration at the twist triangle and again when the yarn is rewound onto cones or cheeses. A photomicrograph of portions of ring yarn showing the structure and hairiness is given in Fig. A5.3. There are single hairs and loops standing out from the surface. (It might be noted that the lighting of the yarns shown was adjusted to show each fiber structure most clearly, and, in consequence, the backgrounds vary.)

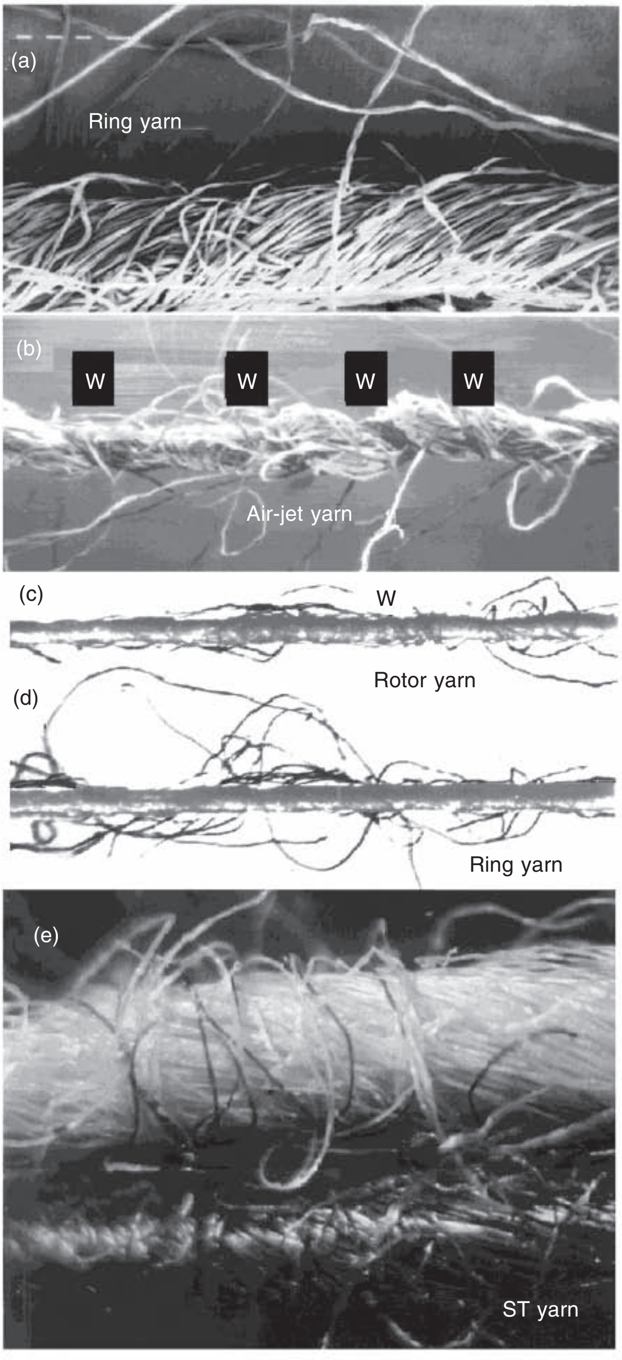


Fig. A5.3 Yarn micrographs

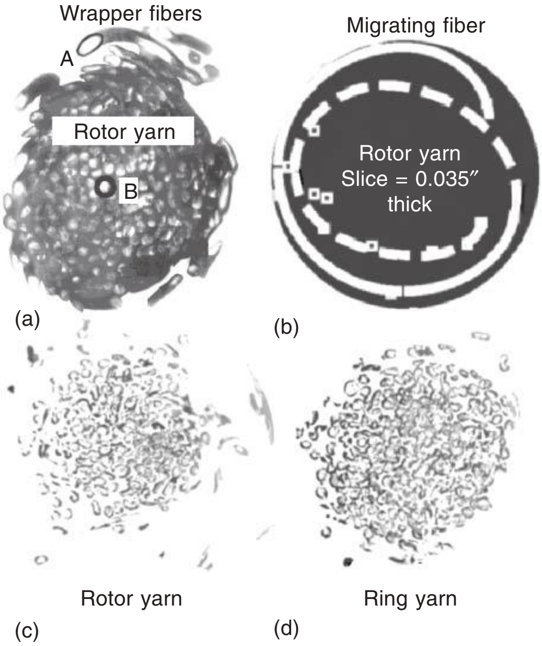
A5.2.3 Air-jet yarn

The twist triangle in air-jet spinning is short, the tape of entering fibers is wide, and the emerging yarn is temporarily very hairy. These hairs are then rearranged and embedded by a second twister to give the structure peculiar to air-jet yarns. The hairs are wrapped around the core and provide the forces that give the yarn cohesion. Hairs have to be long enough to give a reasonable probability of the outermost ends becoming anchored in the structure during the second twisting process so that they act as binders. With 1.5 inch 1.5 denier (or finer) man-made fibers there is little difficulty in this respect, but there are problems with short cottons. Longer cottons can be used, and a photomicrograph is shown in Fig. A5.3(b). The yarn was made from 1.125 inch of Californian cotton; the wraps can be seen clearly where marked W.

A5.2.4 Rotor yarn

The structure of rotor yarn is controlled mainly by the lying of fibers on a core that has both real and false twists. Thus, the structure contains a twisted core but the twist level varies from core center to the outside sheath. The difference in helix angle can be seen by the shape of fiber cross-sections such as the one shown in Fig. A5.4(a). In this case, fibers in the central area (circled at B) were almost round, which indicates that they were almost parallel to the yarn axis. Those on the outside were decidedly elliptical (indicated at A) because the fibers were cut at an angle. Wrapper fibers are produced when the yarn intersects the ingoing fiber stream and an example of the effect can be seen in Fig. A5.4(a). In general, cross-sections vary according to spinning conditions and the yarn being spun.

The structure needs higher twist levels than those used for comparable ring yarns. This reduces productivity and makes the yarn harsher. The percentage difference



Rotor yarn

Ring yarn

Fig. A5.4 Cross-sections of various yarns between the twist in the core and that of the sheath is a measure of the change in structure. According to Deussen [3], the difference in twist for cotton yarns ranges between 0 and 20%, whereas for polyester yarns it ranges between 10% and 45%.

Fibers migrate in rotor yarn, but not so strongly as with ring yarn because of the lack of a well-defined twist triangle. Figure A5.4(b) shows a sample view along a piece of rotor yarn in which sections [4] were made at 30 micrometers apart. To make presentation easier, readings have been plotted as a polar graph and only a portion of the total is shown. The thickness of the slice of yarn shown was 0.035 inches. The total fiber traced a spiral path, had seven coils, and migrated between 1.00 and 0.26 of the yarn radius. Its end was hooked. Of course, this is only one fiber among millions, but it is hoped that it helps to convey the idea of a typical shape. Figures A5.4(c) and (d) show a comparison of the cross-sections of rotor and ring yarns made from the same batch of fiber and spun to the same count. The rotor yarn section shows peripheral fibers at a relatively large diameter but these are part of a loose wrapper fiber system rather than hairs. Close examination of the packing density of the fibers shows that the center of the rotor yarn is more tightly packed than the outside, whereas the ring yarn is relatively uniform in this respect.

Wrappers are created when fibers entering the rotor are laid on the false twisted yarn at the take-off point near the rotor groove. The yarn passes in the region of the fiber entry stream once per revolution of the yarn tail. Thus, there are periodic wrappers along the length of the yarn. Fibers are collected in a roughly triangular groove and the prism of fibers collected there is subjected to a high twist as it is removed from the collecting surface. There is a sort of three-dimensional twist triangle in which there is some fiber migration and a relative movement of the fibers, which modify the structure when the wrappers become overlaid on the surface [5]. This refers to the wrapper fibers mentioned earlier. The zone is diffused, it lies inside the rotor, and is difficult to recognize. Following that, the whole structure is untwisted as the false twist is removed. The result is a complex structure with a rather rough-feeling surface due to the wrappers. This affects the hairiness, as illustrated in Fig. A5.3(c). The picture also shows the wrapper fibers and it should be noted that, although in general, rotor yarn is more bulky than ring yarn, the hairiness is less.

The structure is readily seen by attempting to untwist some rotor yarn. It will be found that there is never a state when all fibers are parallel in the untwisted yarn, as will happen with ring yarns. Either the core of the rotor yarn has some twist when the outer layers are untwisted, or the outside has reversed twist when the core is untwisted. Furthermore, when one section is untwisted, the neighboring portion may not be, as shown in Fig. A5.5; the ends of the portion of yarn shown were restrained from untwisting by wrapper fibers, whilst those in the center of the picture were almost completely untwisted to form a ribbon. Differences in yarn structure such as these make measurement difficult; hence, it is usual to rely on the calculated machine twist. The reversed twist method (i.e. twist–untwist) is sometimes used and it is also possible to measure the angle of the surface fibers, although this is a tedious process. Additionally, elongational straining of the yarns produces changes in characteristics. Strained yarns perform badly in weaving.

A5.2.5 Self-twist (ST) yarn

Referring back to Fig. A5.3(e), two staple yarns which have been self-twisted are shown. One yarn was made from black fibers and the other from white ones. The

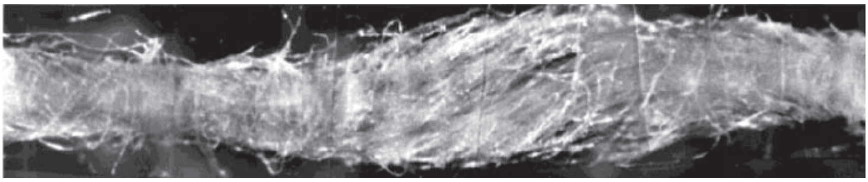


Fig. A5.5 Composite micrograph of untwisted rotor yarn

section shown is near a zone in the white yarn, which originally had zero twist, with S twist on one side and Z twist on the other. The yarn tries to relieve the torque by rotating and lessening the twist on either side. As it rotates about its axis, it is likely to ensnare fibers from the other yarn and wrap them about itself. Black fibers wrapped about the white yarn can be clearly seen. Also, white fibers were wrapped around the black yarn but these are difficult to see in the micrograph, it being remembered that the zero twist zones of the black and white yarns need not coincide.

A5.2.6 Comparing hairiness of various yarns

Many measurements have been made regarding yarn hairiness but the matter is complicated because any friction acting on the surface of a staple yarn raises hair from the surface. In ring spinning, the yarn is usually less hairy in the balloon than it is when it is laid on the surface of the bobbin. This is because the yarn is scraped over the traveler. Centrifugal force, arising from the rotation of the bobbin, causes fibers to stand out from the rotating surface. This creates a bed of outstanding hairs (rather like the surface of a pile carpet), onto which is wound the newly made yarn. The yarn twists as it is later removed in unwinding, and the surface is again modified. This is because some of the hairs become entangled with others from different coils of yarn on the same bobbin. Movement of the yarn over guides in the winder has a further effect. Thus, it is not surprising that the hairiness is sometimes quite variable and that research results vary. Some results from Salah [6] (Fig. A5.6), show that rotor yarns have a larger body than ring yarns. This supports the finding that the average packing density of rotor yarns is less than that of ring yarns.

With blend yarns the results became more scattered and this is possibly a reflection on the blending. Other studies have shown that the population of fibers at various

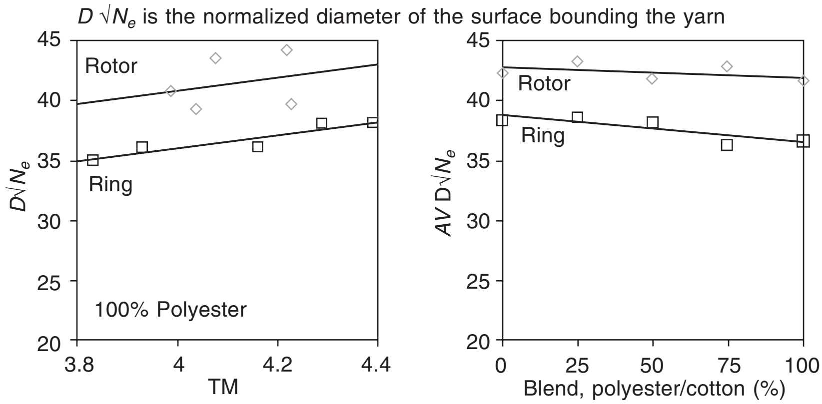


Fig. A5.6 Variations in normalized yarn ‘diameters’ stages of processing varies much more than many people expect. The percentage of polyester in a polyester/cotton blend had some effect but a trend line could only be established by taking averages over the range of twist multiple. However, it is quite clear that the fiber packing density, and therefore the hand and cover, vary substantially from yarn to yarn. Yarns from different machines of various designs differ, but the trends are similar. It might be noted that, in presenting results, a source of variance is normalized by multiplying the diameter of the theoretical cylinder by $\sqrt{N_e}$. There is still a weak dependence on count even after normalization. This implies that there is a small error in assuming that yarn diameter is inversely proportional to $\sqrt{N_e}$. Comparison of the cross-sections of ring and rotor yarns shows the ring yarn to be more densely packed. Despite this, the rotor yarn has a looser sheath structure, which is bound tightly in various places by fiber wrappers.

A5.3 Yarn behavior

A5.3.1 Frictional behavior

Structure affects the frictional behavior of a yarn. It is known that a hairy yarn has a different coefficient of friction from a less hairy one. Chattopadhyay and Banerjee [7] showed that a rotor yarn running over a ceramic guide had up to 20% lower coefficient of friction as compared to a ring yarn. Increased running speeds sometimes reduced the coefficient of friction. The particular polyester tested showed reductions in friction, whereas viscose rayon yarns showed an increase. For a given fiber, the frictional behavior is affected by the finish applied, or, in the case of cotton, the natural finishes removed. In the case of wool, natural finish is removed in scouring and the fibers are oiled; the quantity and lubricity of these oils affect the frictional behavior. Also, experience has indicated that winding and other processes affect the surface characteristics of the yarn. For these reasons, no more than an approximate guide can be given to the frictional characteristics of specific yarns.

A5.3.2 Shrinkage in yarns

Untextured filament yarns shrink very little unless the temperature is caused to rise above the glass transition point for the particular polymer. As discussed in Appendix A4.8, thermoplastic textured filament yarns can shrink, and the degree of shrinkage is determined by how well the yarns are relaxed. Shrinkage and yarn bulk are related, and this fact is evident in the fabrics made from the yarns.

All staple yarns suffer a small percentage twist contraction, and variations in fabric finishing and laundering can produce shrinkage. Cotton yarns can be treated chemically to reduce shrinkage of woven fabric in service, and woven fabrics made from popular polyester/cotton yarns are reasonably stable in this respect. However, in single-jersey knitted fabrics, the twist liveliness of a yarn affects the fabric structure significantly. Relaxing the yarn by steam or water treatments prior to knitting helps to control this problem.

Wool is a special case. It is a scaly, visco-elastic fiber that has many superior crease recovery properties but is vulnerable to post-spinning shrinkage. Shrinkage has been a problem for many years because of the ratcheting mechanism of the scaly surfaces of wool fibers. One method of reducing the shrinkage is to coat the fiber with a polymer to smooth over the scaly surface. Rosa *et al.* [8] showed a micrograph of a treated wool fiber that illustrates the character of a surface smoothed by a chemical additive. Of course, care has to be taken not to interfere with the other very desirable properties of wool. Henshaw [9] mentions several authors who have worked on the problem of shrinkage and he cites high drafting forces as being another cause. Fiber crimp tends to be most pronounced in the trailing ends of fibers. The contribution to bulk and hand varies according to the position of the fiber in the yarn. Fiber migration is extensive.

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Appendix 6

Advanced topics IV: Textured yarn structures

A6.1 Yarn hysteresis

A6.1.1 Internal friction in the yarn

The twisting of the filaments under heat can affect both the real and apparent frictional behaviors of the yarn. If the surface of the filaments is overheated, the fiber finish might deteriorate by oxidation or some other process and this can change the actual coefficient of friction between the filaments. Of course, the heating affects the morphology of the visco-elastic polymer and this affects both the elastic and the viscous forces acting within the material. External lateral forces acting on a softened polymer can cause flats to be formed on the filaments as shown in Fig. A6.1.

All the time that lateral forces persist, it is difficult for the individual fibers to rotate about their own axes. The filaments try to rotate about their own axes when twist is removed from (or added to) the yarn, but the flats cause an impediment to this untwisting (or twisting) process.

The next result of these factors is to cause the torque/twist[1] characteristic of the

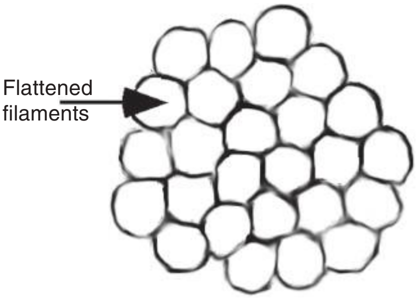

Fig. A6.1 Filament yarn cross-section

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[1] Torque may be regarded as the torsional analog of extension. Thus, a torque/twist curve has many similarities to a load/extension curve.

yarn to have a distinct hysteresis loop, as shown in Fig. A6.2. Some of the energy used in distorting the material in normal use is dissipated in overcoming friction and is not available to return the structure to its original shape; this makes the hand of the yarn feel crisper. Furthermore, it affects the development of bulk as is explained in the next sections. In addition, the flattening of the filaments changes the luster of the material and may produce a sparkle.

Overheating the fiber causes it to shrink and to change polymeric structure. The change alters dye affinity and is sometimes associated with polymer discoloration. Some fibers, such as acrylics, are prone to yellowing if overheated in an atmosphere containing oxygen. Deterioration in fiber finish is also expected, and there may be damage to the surface of the yarn. On the other hand, insufficient heating leads to improper heat setting and poor yarn performance. Thus, careful control of temperature, and sometimes atmosphere, is needed to ensure high quality and adequate performance of the yarn. A non-oxidizing gas, or steam, may be used to control the atmosphere.

Within the thermoplastic classification there are a number of yarn manufacturing methods available of which one is the false twist method. Also, there are a number of variations within the false twist category. Systems have undergone a great deal of development over the years.

A6.1.2 Visco-elastic effects in the yarn

Consider false twist yarn. Yarn becomes heat set when the twisted yarn is at a temperature above T_g. (The glass transition temperature is the temperature at which polymer softens.) As the yarn leaving the false twister is cooled and untwisted, the individual filaments become stressed. If the filaments are separated and then relaxed, they occupy a greater volume than formerly. They try to go individually into one of the minimum energy shapes (e.g. Figures A6.4(a) and (b)). However, they will not completely succeed in doing so because of interfiber friction and viscous effects within the polymer. The effects of fiber migration and interference between various helices and snarls tend to magnify the effects of friction. Frictional and viscous effects cause the torque/twist curve to take the form of a hysteresis loop. The coercive torques and residual twists vary throughout the process, as shown in Fig. A6.3. In stage (a) of the process, the filaments are taken from their original stress-free, straight

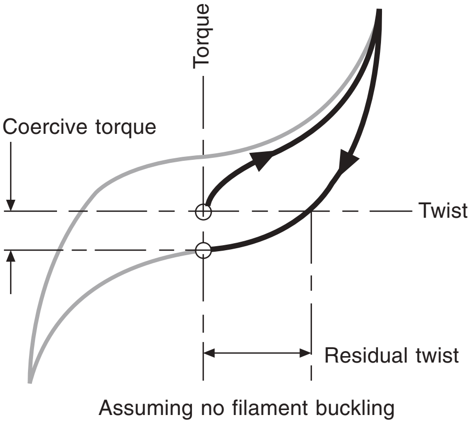

Fig. A6.2 Hysteresis in twisting yarns

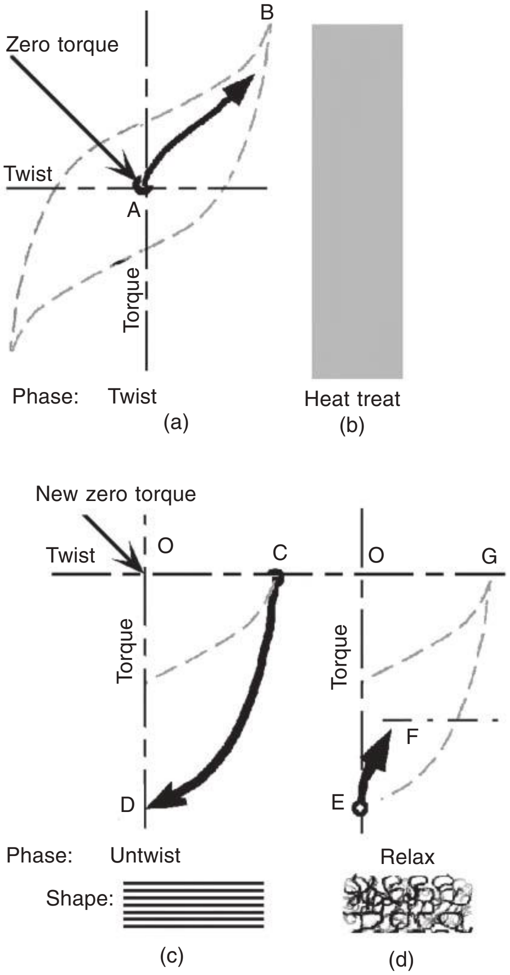

Fig. A6.3 Hysteresis in the false twist process

condition to a helical, stressed condition (curve AB on the hysteresis loop). The yarn is then heated above T_g and cooled again to remove the stress so that the filaments reach a stress-free, helical condition at stage (b). The yarn is next untwisted and the filaments go from the stress-free helical condition to a stressed but straight condition (curve CD on the hysteresis loop in stage (c)). In the last stage, the yarn is relaxed under conditions that allow filament separation and movement towards the new minimum energy condition (curve EF). The units for the abscissa become coils/inch (or coils/meter) instead of turns/inch (or turns/meter). Frictional and viscous forces determine how far up the curve is the final point. At point E, there is a large torque OE acting, and this tends to produce a snarl rather than a helix, if the yarn is completely relaxed (Fig. A6.4(b)). If, however, the yarn is heat treated under proper tension and the stress is removed at some point F, the tendency will be to produce a helical minimum energy shape rather than a set snarl (Fig. A6.4(a)). It follows that a second heat treatment under proper conditions in the zone EF produces a bulky yarn. Lack of such a second heat treatment tends to produce a stretch yarn.

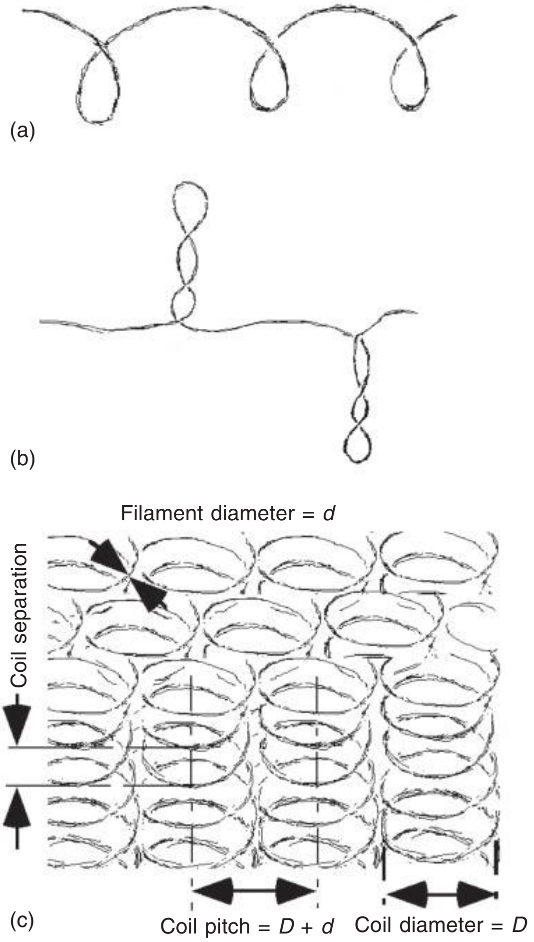

Fig. A6.4 Filament shapes

A6.2 Yarn bulk

Yarn bulk depends on the geometry of the helices and how closely the coils pack together. Consider the case of adjacent coils of similar diameter, packed as shown in Fig. A6.4(c). Assume that:

1 There are sufficient lateral forces to keep adjacent filaments in contact.
2 The fibers exist as coils.
3 All helices are closely packed.
4 Adjacent helices differ in geometry, with frequent helix reversal points (which makes it unlikely that one helix will intermesh with another).

At first assume that the enclosing box for a single helix is a unit of unshared volume and we will refer to this as a unit standard cell. The average height of the cell is designated as L (i.e. the coil separation) and the pitch is $(D + d)$. Hence the average standard unit cell volume is $(D + d)^2 L$. If, however, some coils do not touch within the cell, or they are intermeshed, a factor K may be introduced to take this into account.

Thus, the average volume of a practical unit cell is:

$$Vol_c = K(D + d)^2 L \qquad [A6.1]$$

One coil contains a filament of about πD units in length. If the coil height is h, the volume per coil is approximately $K(D + d)^2\, h$

$$\text{Volume/unit length of filament} \approx K(D + d)^2 h/\pi D$$
$$\approx Z'D(1 + d/D)^2 \qquad [A6.2]$$

but $(1 + d/D) \approx 1$ and volume/unit length of filament $\approx Z'D$.

Volume/unit length of filament is related to the specific volume (volume/unit mass). The factor Z' is intended to take into account the obliquity of the coil as well as the value of K. As an approximation:

$$\text{bulk} \propto (D \cos \theta) \qquad [A6.3]$$

This parameter can be related to the final state on the hysteresis loop (G in Fig. A6.3). The abscissa in Fig. A6.3 might be thought of in terms of $(\text{bulk})^{-1}$. The final position depends on the original torque, the tension and temperature during the second heating phase, and the characteristics of the filaments themselves. If the cells intermesh, $K < 1$ and the bulk might be affected drastically. There is not likely to be a great deal of similarity between adjacent helices and severe collapse is unlikely. The model is reasonably valid providing the coils do not flip into the snarled state.

A6.3 Fiber migration in textured yarns

A6.3.1 Filament migration

Filament yarns, when false twisted, theoretically have no net twist when they emerge from the process. However, it is quite possible for there to be alternating twist with zero mean. Most of the points along the yarn might have some twist in the filaments, S twist, or Z twist, or some combination thereof. A typical filament shape is shown Fig. A6.5, wherein the twist reversal points are indicated.

Fiber migration tends to prevent intermeshing of the coils and keep them separated. Consequently, the parallel coil structure is realistic. This is important because such a structure entraps large volumes of air, which greatly improves insulation and compressibility of the yarn. To reiterate, this gives improvements in hand that are perceived as the warm, soft feel. An interesting collection of micrographs of textured yarns is given by Lodge [1]; a variety of coiled, zigzag, and buckled filament shapes produced by the various texturing systems are shown.

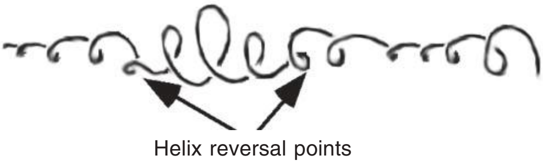

Fig. A6.5 Fiber migration in textured yarns

A6.3.2 Snagging and pilling

An undesirable facet of some of the yarn structures when assembled into fabric, is the tendency for them to snag and pill. A snag relates to yarn withdrawn from the surface of a fabric to make an unsightly fault in the material. Single-jersey knitted fabrics are particularly susceptible to this problem because yarn can be withdrawn from a course with relative ease. The very strength of the filaments ensures that, if a protruding end is caught on an external object, yarn is withdrawn from the fabric instead of breaking off at the surface. This might cause a collapse of several adjacent loops of yarn, and any such distortion spoils the surface of the fabric. One solution to this problem is to modify the structure of the knitted fabric; another is to degrade the strength of the filament.

Pilling is the formation of many tiny balls of fiber on the surface of the fabric. Abrasion of the surface tends to texture the protruding fiber ends or loops, causing them to form into tiny balls. This problem is common to both textured and staple yarns made from such man-made fibers. Again, an important factor is the strength of the fiber. If such pills form with a weaker fiber, they break off during laundering, or wear away, and the fault goes relatively unnoticed. For this reason, many man-made fibers and filaments used for apparel are deliberately de-rated in strength to combat the problem. For this sort of end use, the strength of the filaments is more than adequate.

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Appendix 7

Advanced topics V: Blending of staple fibers

A7.1 Introduction

A7.1.1 Introduction to blending

In the present context the errors are assumed to be random. Blending smoothes random errors but is not an acceptable solution to the problem of periodic errors. Most periodic errors are man-made and a reliable solution is to eliminate the cause of the error.

Consider first the everyday case of blending ingredients in a bowl. With sufficient mixing it is possible to create an almost perfect blend of the materials in the bowl. Consider next mixing a series of bowls from a continuous supply containing long-term variations in the proportions of the ingredients. Whilst each bowl might be perfectly mixed, the mix would vary from bowl to bowl. In a system in which the said ingredients flow through a single mixing chamber, the output would be smoothed to varying extents and the mass of ingredients in the mixing chamber would control the variance in blends from sample to sample. Small samples would be well mixed but large ones would not be. If the sample were smaller than the mass contained in the chamber, the variance within the sample would be very low but there would be a variance from sample to sample. If the sample mass were much larger than that of the mixing chamber, there would be appreciable variance within the sample. The irregularities in the blend would be smoothed only for a certain length along the stream of ingredients.

Forwarding this idea to the textile field, one could consider the supply from the bale storage, the mill itself acting as a mixer. If we make the impractical assumption that the mill is a perfect mixer and the very practical assumption that there are long-term errors in the supply, we could come to the conclusion that all the yarn produced during the consumption of a bale laydown would be acceptably smoothed over something of the order of a billion yards or meters of yarn. There would be some smoothing over this length, but it might not be acceptable. There certainly might be unacceptable laydown-to-laydown variation, which the mill would be unable to cure by any internal blending scheme. Next consider a drawframe, where the supply would be the cans of sliver in the creel. Assume the mass of fiber in the creel is, say, 1000 lb (≈ 454 kg), and the amount of yarn produced from that creeling to be of the order of a million yards (or meters). Then the mass constant would be related to the 1000 lb (≈ 200 kg) and the limiting long-term error that could be smoothed would be related to the million yards (or meters). In rotor spinning there is blending inside the rotor, the mass in that mixing chamber is of the order of, say, 5 mg. The associated mass constant is a tiny quantity and the limiting long-term error might be only, say, 6 inches (roughly 150 mm). In the vernacular of this chapter, *mass constant* is proportional to the mass contained in the mixing chamber under working conditions and the lengths quoted as proportional to the maximum *error wavelengths* that can be smoothed by that mixer.

A7.1.2 Problems in defining a blend

If, say, polyester and cotton are blended, it is easy to define the blend because a micrograph of a cross-section shows the two sorts of fiber as having distinctive shapes. If two fibers of the same type are blended, the question is no longer simple. For example, take the case of blending two cottons. Not only is it difficult to discriminate between the blend components in a micrograph, but often the input materials are variable.

In the early stages of production, fibers exist in clumps; the average value of any attribute varies from clump to clump and so does the variance within the clump. The material is not very homogenous and it is difficult to define. For a good estimate, it is necessary to measure enough samples to calculate the average and CV of each attribute. Processing reduces this sort of macroscopic variation by dividing the clumps into smaller portions and mixing them. However, processing produces its own variations and it becomes difficult to characterize a blend with absolute accuracy. The attributes of a fiber do not vary in synchronism and the CVs also vary in unexpected ways.

Some machines have the function of fractionating the fibers and removing some of the fractions. An obvious example of this is combing, where the fraction removed, called noil, has a high proportion of short fibers. This obviously changes the blend. For example, in cotton processing it is desirable to remove the short fibers, which have a great variability. In removing fibers in the fractionating process, the distributions of other attributes also change but not necessarily in synchronism. Thus, for example, changes in fiber fineness are not necessarily related to alterations in the percentage of short fibers.

A7.1.3 Definition of efficacy of blending

It is known that ‘blending’ can mean different things, according to which is the fiber property of interest. Each fiber attribute probably exists in a given zone in the fiber flow line at a percentage that differs from that of the other zones. Furthermore, the spectrum of percentages changes along the direction of flow. If sufficient samples are taken at various times from the flow line, the CV of those data provides a good estimate of the efficacy of the blending process. If the process is perfect, the CV would be zero, but if the clumps are incompletely separated or the process changes the order of certain blend components with respect to others, the CV changes. The CV of a particular blend attribute indicates how well the blending process has worked for that attribute.

A7.2 Bale management

A7.2.1 Warehouse management

Consider a case where a fiber is bought for a period and stored in a warehouse (which might be in a broker's facility or elsewhere). If bales were to be used to meet the production requirements without thought to the remaining stock of fiber, there is a strong possibility that the best fibers would be skimmed off first. The stock would then degenerate in quality as time continues. In the case of man-made fibers, the fiber makers often take care of the problem by making fibers in large 'merges'. The attributes of the fibers are made to change very slowly from merge to merge. With natural fibers the case is different. For one thing, the raw material is inherently variable within and between seasons. Any skimming could lead to an inadequate stock at some point through the year (especially if the fiber that is bought is, on average, only just good enough for the end use). Buying fiber of minimum quality in the name of an economical purchasing policy can sometimes be a false economy. From this, it is clear that the laydowns must be based on the technical figures of merit of the fibers left in the warehouse. Furthermore, the variance within the stock must be minimized always, otherwise there would be an impairment of ability to furnish bale laydowns with acceptably low variance at all times

Natural fibers, such as cotton, are seasonal and large quantities of the material have to be stored for periods in the order of a year. Thus, there are several factors concerning the blending of such fibers. Factor (a) is to manage the stocks of fiber in the warehouse so that those laydowns withdrawn on a daily basis are reasonably consistent. Lack of control in the warehouse leads to ultra long changes; this causes problems if the old and new fibers become mixed. The time frame of the drift in properties is measured in months. Factor (b) is the consistency of fiber quality within a bale. This is determined by gin practice for cotton, sorting practice for wool, and industrial practice for man-made staple fiber. The time frame is in days. Factor (c) is to minimize the CV of the various fiber parameters in a laydown so that periodic removal of fiber from the bales in turn does not produce error. The time frame here is in minutes. Even the shortest time mentioned covers a period during which, perhaps, 100 000 yd of yarn are produced – a time that would still fall in the category of long-term error as far as yarn is concerned.

It is common to divide the store of bales into attribute categories to make the management problem more tractable, because the range of values of the various fiber attributes is very large. Each bale is sampled, the samples are tested, and the bale is assigned to one of the attribute categories by using some formula that the mill operator thinks best serves his or her business. The number of categories depends on the complexity of the business. Bales of fiber do not have equal value, and storage of poor quality or high cost bales with little chance of their being used is a financial burden. It is desirable that the rate of movement of bales of each category be logged so that slow moving categories can be eliminated, unless there is special reason for having them. Management of the fiber warehouse requires a knowledge of the technical figures of merit and their mean values over long periods. It also requires the use of financial figures of merit that take into account the fiber and storage costs, as well as the value in yarn form.

Warehouse management becomes a problem of maintaining constant proportions of the fibers that fall in carefully defined categories. Typically, each category contains only fibers of a certain range in fiber fineness, length, and color attributes. Other fiber attributes may be added but the number of categories expands exponentially with the number of attributes controlled. A large number of categories make commercial application very difficult. Hence, the bales issued for a given laydown can only be defined within limits and there is bound to be some variation within bales drawn from a given category. Blend proportions can be defined for any single fiber characteristic, but they do not all behave in the same way. For example, if one is interested in fiber strength above all else, then the blend must be arranged to minimize CV of fiber strength. If, as is more likely, the need is to reduce barré, then the blend should concentrate on the reduction of the CV of factors that affect color. These factors include not only the normal color measurements such as yellowness (+b) and reflectance (Rd), but also factors that affect dye affinity such as micronaire. A further factor is the surface structure, which can affect the perception of color.

A7.2.2 Bale laydown

The quality of a blend is determined by (a) the fiber buying policy (cost and fiber quality), (b) the testing and application of the incoming raw material, and (c) the treatment of reworkable waste being returned from downstream processing. It should be pointed out that the affordable cost depends on what the end product will bear. The bales selected for the laydown should depend on the application. As mentioned, the pattern of laydown is important to get not only good performance of the mill but to maintain a consistent inventory of fiber in the warehouse. Apart from variations inherent in normal production, there are particular changes that have to be managed with care. The latter are referred to as *merge changes* and they occur at crop change time in natural fiber production. Merge changes from the production of fibers in a synthetic fiber maker's plant occur when significant alterations are made to the process or product. Every care has to be taken to minimize the possibility of a customer mixing lots of yarns containing dissimilar fibers. The result of uncontrolled fiber application and flow will be barré in the final fabric. This is especially true when significant step changes in important fiber properties are involved. Many complaints from customers relating to finished fabrics have their origins in yarn production. Settlement of claims often involves the yarn maker paying for fabric production and finishing of defective material if the yarn is faulty. An expensive error!

To help in reducing the variability of the blend components, it is now possible to use (HVI) and AFIS testing to measure fiber properties on a mass production basis. Discussions on AFIS and HVI are given in Section A4.7.3, and also further discussion on HVI appears in Section 11.2.1. Software programs to manage the laydowns appropriately can further augment results from such testing. A leading example of this is the EFS software produced by Cotton Incorporated. Table A7.1 gives examples that compare the values in bale material to those measured in sliver from the same laydown slice. The comparison shows that the CV, and therefore the blend evenness, was not always better after carding. In this particular case, sliver samples were taken at 10 yard intervals (equivalent to perhaps 1000 or 2000 yards of yarn) but these cannot be regarded as 'long term' relative to the bale samples. Consequently, the data should be interpreted to mean that the relatively short-term variation in many of the blend attributes, usually deteriorate~~s~~ in carding. The idea of a single 'blend efficiency' to describe performance is seen to be misleading because one must concentrate on the blending of components that matter for the given product. Also, the short- and

Table A7.1 Percentage coefficients of variation

	MIC	UHM	STR	ELO	Rd	+b	SFC%
Bale*	3.3	0.7	3.1	4.7	4.6	4.8	11.1
Sliver	2.4	1.5	4.3	5.4	8.0	6.7	17.3

Note: * = between bales. The acronyms are defined in Section 5.8.2.

long-term variations have to be balanced to give minimum trouble in year-long processing.

Of course, there is a wide range of variability in natural fibers according to the type of fiber, growing area, climate, and seasonal changes, and some bales are more variable than others. The best summary of the position is that variation within the bales is not negligible. Here, it is only possible to cite a given case and no representation is made that it is typical; the purpose is to demonstrate that the problem is significant. The case in point resulted from a study in which the bales were specially selected to give as low a CV in micronaire as possible. The choice was made using test results from many bale samples. Space precludes giving full details but suffice it to consider a sample of nine bales, as shown in Table A7.1. Variances were averaged for each horizontal slice of all the bales in the laydown (the reader is reminded that variance is proportional to the square of CV). The sliver figures are based on the average variances in samples of card sliver taken systematically over the period over which the bale slices were consumed. The sliver data include the variances between bales, within bales, and any effects caused by processing. Upper half mean length varied little in this case. However, short-fiber content was high and there was a substantial within-bale variance, or processing had produced an extra variation, or both apply. This is important because short fibers cause instabilities in roller drafting, which add to the CVs generated in later processes and thus degrade the final product. The CV of micronaire was variable despite attempts to control it by selecting bales on the basis of the cotton broker's data. Micronaire is important not only because of varying cross-sectional size, but because of varying wall thickness in immature fibers that sometimes occupy the low micronaire portion of the distribution. It is possible that carding exercised a fractionation function and removed some fibers of high or low micronaire values and thus reduced the CV in that attribute. High CV of micronaire has come to be recognized as one of the causes of barré. The substantial difference in the reflectance of the fibers (Rd) is difficult to explain by processing. Perhaps the values are linked to other attributes vulnerable to change by mechanical processing or perhaps some fiber crimp is removed and this affects the reflective capabilities of the fiber. Again, this is only anecdotal and the values quoted should not be taken as typical for all cases. The points are that the within-bale values are not negligible compared to the between-bale figures and processing can affect the results. On a number of occasions the author has observed variations of the different fiber within a bale that are of the same order of magnitude as those between the bales.

Another set of circumstances sometimes confronts a yarn supplier to the knitting industry. The product is often judged in the greige state and fiber color becomes important. In such cases, variability in the +b and Rd values assume greater importance. (Greige refers to fabrics in the state that they leave the loom or knitting machine [1], and by extension, it refers to the yarn used in making such fabrics.) In the case of acrylic yarns, yellowing of the fiber might be a factor.

Obviously, a prime requirement is to assemble a laydown with as little variance between bales as possible. Since the variability of one fiber attribute does not necessarily match that of the others, it is necessary to set up a priority system. Each fiber attribute is given weighting calculated on the end use of the yarn, so that there results a figure of merit customized for the particular product. To be workable, the figure of merit must have many combinations of fiber attributes that satisfy the requirements for a given end use.

A7.3 Mixing in the blow room

A7.3.1 Mixing the fibers flowing through the opening line

In a bale laydown, only the fibers from a limited number of contiguous bales can be mixed before the fibers pass to the cards. Assume that there is a moving zone that includes a portion of one or more rows containing ($m = m_1 + \ldots + m_2$) bales shown shaded in the simplified bale laydown in Fig. A7.1. Also, assume that only the fibers removed from the bales in this moving zone are intermixed. Bales from outside the zone are assumed not to participate in the mixing until the moving zone encompasses them. Participation stops when the moving zone passes by. The bale plucker moves slowly down the line of bales in the direction shown and the zone trails the cutting head. When the cutting head reaches bales 1/2 or Y/Z,[1] it reverses. It slowly reciprocates between bales until the demand temporarily ceases, or until the fiber flow system calls a halt, or until the laydown is consumed. The moving zone always consists of the horizontal slices taken from the last *m* bales passed by the bale plucker as it moves to and fro. Some systems take slices at an angle, but the idea expressed is still similar. The fiber passes into a series of mixing zones that consist of several elements. Each machine in the opening line causes a degree of mixing between adjacent volumes of moving fiber and even turbulence in the ductwork contributes to the process.

Where laydowns are formed with several bales set side by side to form a pattern *w* bales wide and *m* rows long, averages are taken for each row to yield *m* average rows. Fiber from these rows progresses through the system in line astern along the *m* direction. In theory, it is assumed that a step change exists in fiber characteristics as the cutter of the bale plucker leaves one row of bales and passes to the next. It is further assumed that the fibers from all the bales in a row are adequately mixed. The plucking head moves on a fairly regular, periodic basis, but there are occasional

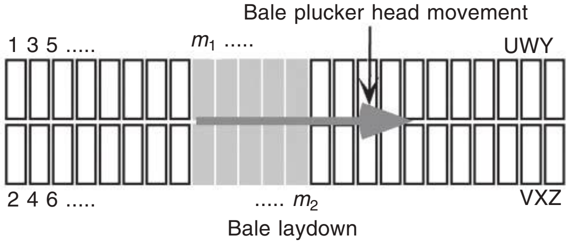

Fig. A7.1 Bale laydown

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[1] Z often is greater than 40, and the number tends to grow as the technology improves.

dwells to keep the fiber flow in synchronism with the demand by the cards. However, the flow may be considered to be more or less continuous and the characteristics of the fiber delivered can be considered to vary periodically.

A7.3.2 Errors due to fiber removal from the bales

The characteristics of the fibers can vary cyclically along the fiber flow path because of the reciprocation of a bale plucker over a bale laydown with varying bale to bale fiber characteristics. The effect is worsened by any inadequacy of a mixing machine(s) in the opening line. A peak in the spectrum occurs typically at an error wavelength related to one traverse of the bale plucker. It is useful to express this error in terms of a length of card sliver delivered from one of the cards connected to that opening line. Here, this length is defined as the amount delivered during the time it takes for the plucker to complete one cycle of its travel. This value is of the order of 1000 yards with current machinery. The result may be represented in the frequency domain in the manner of a spectrogram. Some examples of practical results are given later.

A further problem exists. Bales are not uniform throughout. The profile of fiber characteristics from one cut across the laydown is not the same as another taken at a different time. The profile varies continuously as the laydown is consumed. This means that there can be some extraordinarily long errors from the system. Even if the order of presentation to the spinning machine is scrambled, unlike yarns will be produced on adjacent spindles. This is a recipe for barré.

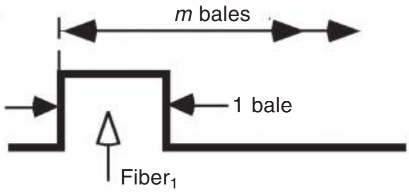
A7.4 Theory of blending capacity

A7.4.1 Dispersion in the flow through mixers

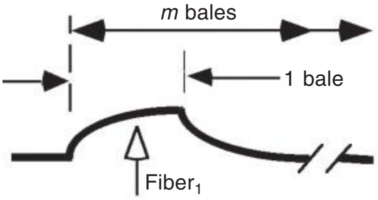
The foregoing discussion has indicated that variations can occur over a range of processing times varying from a few minutes to a year. The opening and blending line can only deal with changes that occur at less than a certain characteristic time peculiar to a given installation. As an analogy, consider water flowing down a river into a lake, which discharges into another river and out to sea. Under steady conditions, certain levels become established between the two rivers and the lake. If a sudden deluge causes a rise in the river entering the lake, the effect is not passed on in an unchanged way to the downstream (discharge) river. This is because the volume of the lake absorbs some of the sudden rise. The discharge river rises much more slowly. A similar situation occurs in the opening line; a sudden change in one of the fiber parameters in the bale laydown is not immediately passed on to the sliver emerging from the card. The intervening volume and the degree of variability in the fiber flow control the output.

Consider the flow of fiber passing into a reservoir, as shown in Fig. A7.2(c). Assume an incremental volume of new fibers (which we will call fiber$_1$) enters the mixing volume Q and is immediately mixed with all the other fibers (i.e. fiber$_2$) in that main volume. The excess is ejected and contains the same proportions of each fiber as exists in the fixed volume Q.

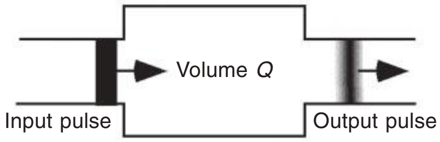
Let the total volume of fiber$_1$ derived from a single pass over one bale be Q_{in}; the rate of bale plucker movement be V bales/unit time, and the fixed volume be Q. When the bale plucker passes from one bale to the next, a front is created by the step change



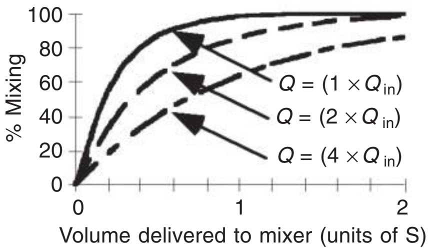
(a) Input



(b) Output



(c)



(d)

Fig. A7.2 Volume delivered to mixer in units of S (S = normalized fiber volume supplied to the mixer).

in fiber characteristics. The flow of fiber between successive fronts is called a fiber pulse. If the normalized flow of fiber is constant at *S*, then it can be shown that the volume of fiber$_1$ in the mixer increases exponentially as the new front passes through it. Normalized fiber flow = $S = V\,Q_{\mathrm{in}}/Q$. The percentage value can be expressed by the equation:

$$Q_{\mathrm{m}1} = Q(1 - e^{-S})100\% \qquad [A7.1]$$

where $Q_{\mathrm{m}1}$ is percentage of fiber$_1$ in the mixer.

The greater the volume *Q*, the smaller is *S*, the slower is the rise in percentage of fiber$_1$ in the output and the longer it takes to approach the limiting value of 100%. Thus, a sudden change of fiber, such as is met when the offtake from the bale laydown passes from one bale to the next, causes the mix to change. The output pulse leaving the mixing zone is modified by the mixing process and is diffused.

In one of the theoretical examples plotted in Fig. A7.2(d), the mixing volume is four times the proportion of the bale slice removed as the offtake mechanism passes over a single bale. It would barely reach 50% of fiber$_1$ before the offtake moved past the bale. Equation [A7.1] is applicable only while fiber$_1$ is being supplied. When the supply of $fiber_1$ is replaced by that from the next bale in the laydown, the percentage of the fiber that had originated from the bale just passed declines exponentially, and the contribution from the new bale begins to rise. Two diagrams illustrate the idea. Figure A7.2(a) shows a rectangular input pulse, which represents the bale slice being removed. Figure A7.2(b) represents the percentage of fiber from that slice appearing in the output. Mixing blurs the boundaries and elongates the volume that contains some component of $fiber_1$. The rate of change and the length over which the fiber is distributed depends on the size of the mixing volume and the efficiency of mixing. For our purposes, the larger the volume Q, the better, because it blurs the boundaries between consecutive zones in the flow line and thus improves the local blending. The length over which distribution occurs may be thought of as a sort of mass constant. In practice, all machines in the opening line contribute a mixing volume, each of which works similarly. Each machine contributes its quota to the mass constant of the whole line.

A practical opening line would have no difficulty in blending a single bale slice with its neighbors. The point of the exercise was to show how fibers from a subject bale are spread amongst its neighbors in a mixing operation. More to the point is *how far* fibers from a subject bale can be spread. A modern bale plucking machine travels over a laydown causing a cyclic removal of fiber. The corresponding period in the sliver is usually related to twice the number of bale rows in the laydown. To eliminate periodic variations in fiber attributes, it is necessary to mix the fiber from a bale being worked with all the others. This implies that the mass constant of the opening line should equal or exceed the amount of fiber removed in a single pass over the laydown. For example, if the mass constant of an opening line is 100 lb and the bale plucker removes 2 lb per bale slice, the size of the laydown should be no larger than 50 bales. Many operators try to achieve synchronism of making a new laydown correspond with the work shift schedule by increasing the number of bales in a laydown. The result of this might be the introduction of a periodic variation in fiber characteristics with a period equal to one round trip of the bale plucker. Also, if the bale slices are heavier, a similar situation will arise. Either circumstance is to be avoided if possible. It has to be recognized that there are limitations to the possible courses of action. For example, the mass of an average bale slice might be (say) 2.5 lb (assuming a throughput of 800 lb/hr and a maximum rate of bale plucker movement of over 320 bales/hr). Continuing the example, let there be 100 bales in the laydown. If we use the criteria just suggested, the mass constant (blending capacity) would have to be increased to 250 lb.

The discussions above have assumed a steady delivery from the bale pluckers. However, most bale pluckers stand idle at times, waiting for demand to catch up with output. Anything that can be done to keep the bale plucker in full use, or to decrease cutting depth, helps blending efficacy.

A7.4.2 Dispersion in drawing and combing

The fiber flow through the mill might be considered analogous to flow through a pipeline. The system starts with a reservoir containing, perhaps, 25 000 lb of fiber, and flows through an opening line at roughly 1000 lb/hr. This assumes that 50 bales were used in the laydown. The flow branches to supply the cards and each card works at roughly 100 lb/hr. The card sliver is gathered in cans and forms a secondary reservoir behind each drawframe. The secondary reservoirs might each contain up to

500 lb. Before combing, there is yet another reservoir, which we will call the tertiary reservoir, which contains, say, 1500 lb.

Ingoing material is doubled in drawing and lapping which reduces the variance. Consequently, according to some practitioners, there is a reduced need for good blending at the early stages. With all the doubling that occurs up to finished sliver, fewer than four or five bales/creel are involved. Whilst it is true that the doubling and mixing at these stages helps within that compass, it certainly cannot be completely effective, especially when viewed against the 25 000 lb or so in the bale laydown. The idea of mass constant may be applied similarly to that applied to the blowroom. Also, it should be noted that the ratio of creel mass in the drawframe to the laydown mass is only of the order of 5:100. Clearly the value is so low that the creeling can only have a very small impact on extra-long-term errors. Even with multiple-sliver processes, the effect of step changes in bale laydowns still cannot be offset and this explains why consistently good blending is needed in the early stages.

A7.4.3 Channeling

Under certain circumstances, differences in fiber supplied to one card compared to that supplied to another can cause barré problems, and so can differences in performance of one card compared to another. The problem arises when a drawframe and the following processes are fed exclusively from a dedicated set of cards. If the mean of the product from one set of cards differs from that of the others, the yarns differ, and when they are mixed in winding there can be undesirable step changes in yarn properties. This phenomenon is known as channeling. A solution is to cross-feed the drawframes and combers in a pattern likely to minimize the variations. Often color banding of the cans is used to determine their destination.

A7.4.4 Periodic variations

Assuming that relative short wavelengths of periodic error are controlled by good inspection and maintenance, there still remains the question of ultra long-term errors. Difference from top to bottom of a laydown and differences between laydowns produce a mixture of random and periodic errors. The doubling is effective in reducing the errors within the limits already described, but doubling is ineffective in cases where all cards within a set produce a periodic error of the same frequency. Ultra long-term errors arising from the bale laydown could affect all slivers produced by that opening line.

Doubling of periodic errors in the creels of subsequent machines produces a vector addition of errors of similar frequency and amplitude but of random phase. Phase is determined by the relative longitudinal positions at which the sliver ends are laid in the creel. Such additions of periodic errors can result in output error components varying from zero to m times the periodic error originally in the sliver, where m is the number of doublings. The problem is that these errors are so long that they are rarely detected. The probability of such an error at a significant level is of the order of one in several hundred creelings. This means the problem shows itself rarely, but when it does, the error can be significant for the duration of that one creeling.

When there are periodic variations of different frequencies in the slivers being creeled, the waveform of variation is complex. The various frequencies beat together and produce a difference frequency, which may be expressed as a very long wavelength.

Thus, there are infrequent periods when the vectors are aligned. At these times, the amplitudes of the component errors add together algebraically on a temporarily regular basis. Errors at these times are large and similar in amplitude to the case just mentioned. Doubling does not diminish periodic errors reliably; thus it is prudent to avoid this sort of error. Hence, sources of periodic error should be diagnosed and the fault eliminated as far as possible.

A7.5 Fiber migration and blending

A7.5.1 Longitudinal fiber migration

If the fiber flow consists of large fiber clumps, the blend will be uneven because of the variations between them. At the beginning of the process, there are large migrations and very considerable blend irregularities. Unevenness in mass distribution is created when the blend is uneven and there is fiber migration. The effects of this are offset by the doubling that occurs at each condensation stage. Consequently, quite large errors might be generated, even if they are later reduced by doubling. Doubling will not reverse the migrations and the composition of fibers flowing through the system will show effects of both types of process.

The equation of flow can be considered as a spectrum of sinusoidal variations. Let one of these sinusoids have a wavelength of λ, and let the fiber migration be m, where both variables are measured in consistent units of length. Figure A7.3 shows a simple

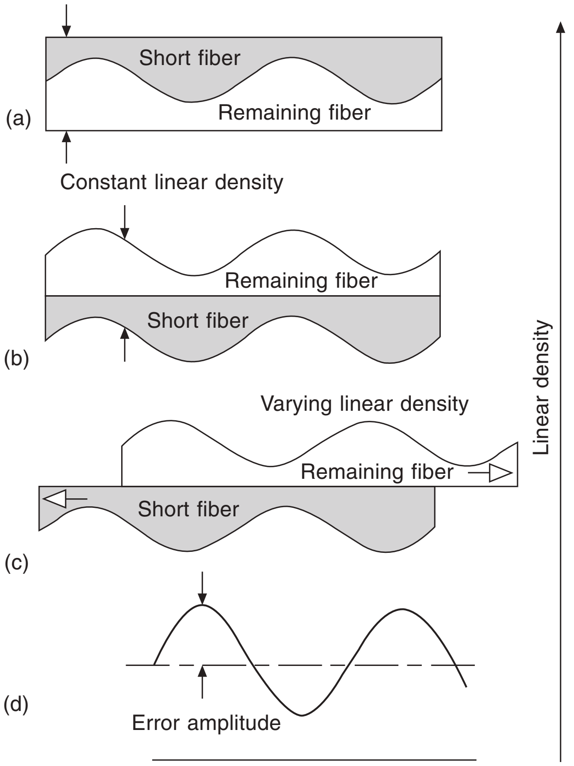


Fig. A7.3 Effect of longitudinal fiber migration sinusoidal blend error in a perfectly leveled strand. In Diagram (a), the leveled strand has a constant overall linear density, but the two fiber components vary sinusoidally in a complementary fashion. The two components are shown as short fibers and the remaining fibers respectively. The short fiber has a linear density of $n_1 + A \sin \alpha$, where A is the amplitude of variation in linear density of the component and α is the length along the flow line expressed as an angle. For explanation purposes, let the curves be transposed as in Fig. A7.3(b). To account for the longitudinal migration, the remaining fiber portion is moved horizontally to the right as in Fig. A7.3(c). Diagram (d) shows the addition of the ordinates for short and remaining fibers, and this represents the overall linear density after migration. Clearly migration has changed the overall linear density so that it is no longer level. The amount of error introduced by this mechanism depends on the changes in the blend ratio; if the blend had been perfectly even, no amount of migration would have produced an effect. In practice, there are many wavelengths of error and the amount of error produced varies; more complex analysis is required but the exercise has demonstrated how the interaction occurs.

Expressing the results mathematically, the phase change, ϕ, due to the migration is:

$$\phi = 2\pi\ (m/\lambda) \text{ radians} \qquad [A7.2]$$

The fiber moves $(\phi/2\pi)\lambda$ length units. The top curve in Fig. A7.3(c) is represented by:

$$n_1 = y_1 + A \sin \alpha \qquad [A7.3]$$

and the bottom one by:

$$n_2 = -y_2 + A \sin (\alpha + \phi) \qquad [A7.4]$$

The curve in Fig. A7.3(d) is the difference between Equations [A7.3] and [A7.4].

$$n_m = k + 2A(\cos(\alpha + \phi/2) \sin \phi/2) \qquad [A7.5]$$

where n_1 is the linear density of the top portion, n_2 is the linear density of the bottom portion, and n_m is the linear density of the strand after migration. The values y_1 and y_2 represent the mean values of a long length of the two portions and $k = n_2 - n_1$.

This means that the error introduced in linear density is a function of the error wavelength of the interface and the phase change referred to earlier. One of a number of critical phase changes is when the fiber migration equals half the error wavelength of the interface. The effect is worse when $\sin \phi/2 = 1.0$ (for example, when the phase change is 180°). However, there is no effect on linear density when the phase change is zero or any multiple of 2π radians (360°).

To repeat, the practical importance of this is that (a) there has to be significant fiber migration, and (b) there have to be differences in the blend proportions along the strand, before errors in linear density are caused by the phenomenon. Generally, the greater the gradient of the change in a blend component along the length of the strand, the greater is the change in linear density of the strand. Therefore, sudden changes in blend should not be allowed to happen; changes should occur very slowly if problems are to be avoided. As a practical matter, this means: (a) keeping the fiber clump sizes as small as possible at every stage, (b) arranging to avoid dissimilar bales being in proximity in the bale laydown, and (c) promoting as much mixing as possible in the largest mixing volumes possible. There is also a requirement that the average value of the moving zone shown in Fig. A7.1 should vary by a minimum amount and this requirement may conflict with others.

A7.5.2 Incremental effects of migration on staple fiber blends

For simplicity, consider a two-component system, shown in Fig. A7.4, in which Component B contains fibers that all have a common fiber attribute and Component A contains the rest of the fibers. However, let the proportions of the two components vary along the length. A migration of one component with respect to the other along the line of flow causes blend changes with respect to all fiber attributes. For instance, if fiber length is a major variable, then the fiber migration will change the distribution of fiber lengths along the strand.

In Fig. A7.4(a), the two components are labeled A and B. The masses of fiber at any position x from the zero point in the central zone are described by two equations. This zero point is shown by a black dot on the o–o line. The ordinate reference line is o–o and the total mass at position x is $(y + y_1)$. The local blend proportions are $b = y/(y + y_1)$ of Component B and $b_1 = y_1/(y + y_1)$ of Component A. In Fig. A7.4(b), Component B has migrated to the left by an amount ϕ and we shall consider only the zone Z. The equation for y_1 is unchanged but the shift of origin causes the other equation to become:

$$y = m(x + m\phi) + b$$

The blend proportion for component B after migration becomes:

$$b_m = (y + m\phi)/(y + y_1 + m\phi)$$

and when $m\phi$ is small with respect to $(y + y_1)$

$$b_m \approx b + m\phi/(y + y_1) \qquad \text{[A7.6]}^2$$

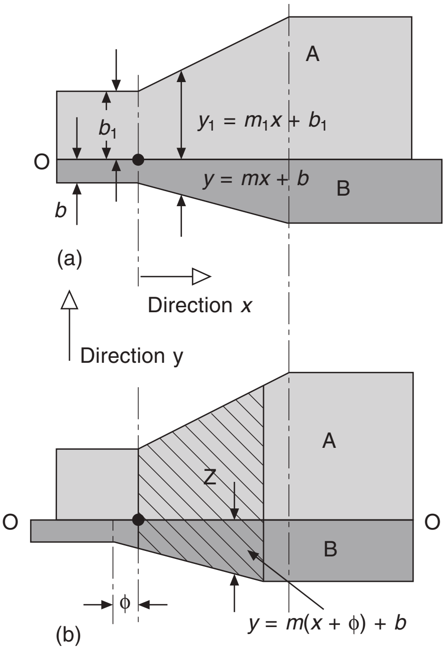


Fig. A7.4 Fiber migration gradient

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[2] Differentiating, $\mathrm{d}b/\mathrm{d}\phi \rightarrow m(y + y_1)$.

Equation [A7.6] may be interpreted as implying that the rate of change of the blend proportion due to migration depends on the gradient of the components.

In other words, if the entering blend component is of variable mass along its entering length, there will be changes in blend proportions in the output due to the migrations caused by drafting. This is distinct from the linear density of the total strand. As before, if the entering blend components are level, no amount of migration will cause a blend change.

A7.5.3 Blending by migration

If the blend proportions vary along the length of the strand, the migration causes changes. Thus, the drafting of an irregularly blended but perfectly even strand not only causes irregularity in output linear density but also causes changes in blend proportions. Fibers leaving a machine that drafts the fiber are in a different order from those arriving. Sequential cross-sections contain samplings along the flow path of the input and output material and the cross-sections vary in content from one to another. Calculating the linear densities of the two components from Equation [A7.3] and taking the ratio of the two components, gives us the blend proportions. The average original blend proportion is taken as 0.5 in this example and ϕ is the phase angle representing the longitudinal fiber migration. The effects are cyclic and at certain phase angles the variation in blend becomes a minimum, as shown in Fig. A7.5. An actual blend contains a spectrum of cyclic components and, for a given fiber migration, there is a spectrum of relative values of ϕ. The result of this is that some cyclic components are emphasized in comparison to others and there is a sort of resonance pattern. Thus, while the overall effects of migration tend to improve the blend, strong patterns of variability can arise which can have deleterious effects in the subsequent processes and products.

A7.6 Real blend variation

A7.6.1 Variations in mechanical attributes of fibers

An illustration of the levels of variability of mechanical attributes was given by a set of experiments carried out at Cotton Incorporated. About 7000 yards of sliver were measured at 10 yard intervals along that length for the various fiber parameters. For the examples quoted here, it was preferred to use periodograms (similar to spectrograms)

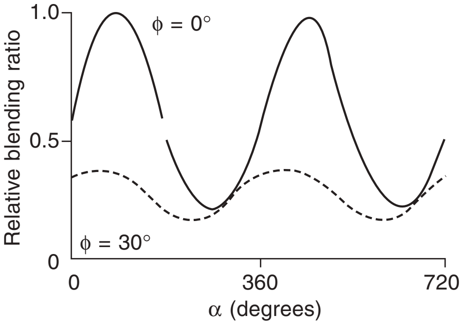
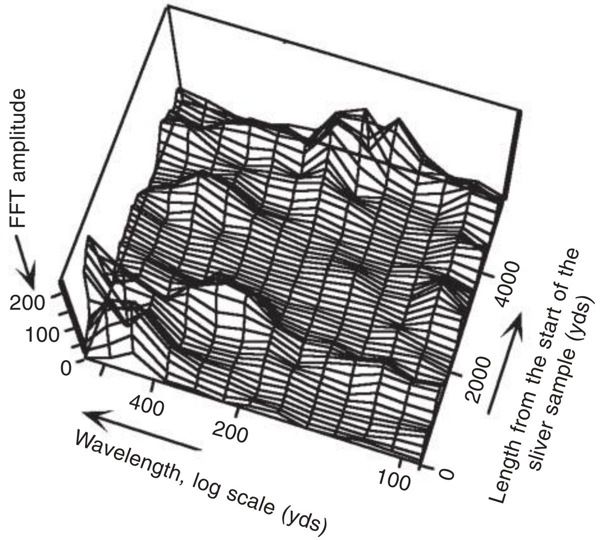
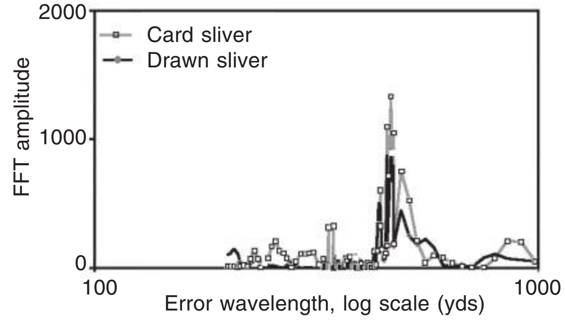


Fig. A7.5 Phasing of blend components rather than frequency based curves. Each parameter yielded a time series to which a fast Fourier transform (FFT) was applied to change it into the frequency domain (or wavelength domain). To get the range of wavelengths to describe the phenomena, it is necessary to use a log scale in a fashion similar to that used with spectrograms. To lessen the confusion from the multitude of results, only short-fiber content and micronaire are quoted here. Variations in the short-fiber content are shown in three dimensions in Fig. A7.6(a). The calculated value for error wavelength of the bale plucker cycle was about 700 yards; that compared well with one of the major peaks in the practical values. There were quasi-random variations denoted by the 'mountains' in the diagram. These illustrate the danger of applying an FFT to a limited time series; often-anomalous results can be obtained. However, there were also periods when a strong FFT component was noted at the wavelength corresponding to the bale plucker movement. The strength of these peaks varied along the length of the material and this, in part, might be due to the intermittent demand on the supply to the mixer.



(a) Short-fiber content



(b) Micronaire

Notes: Input micronaire is the average of the values from 8 creel slivers.
Error wavelength for drawn sliver expressed in terms of card sliver.

Fig. A7.6 (a) Three-dimensional view of short-fiber content; (b) Comparison of micronaire at the input and output of a drawframe

The length of sliver depicted took about an hour to produce, during which time about 5% of the bale laydown was consumed.

Micronaire values affect the dye performance of the yarn. A typical pattern measured with card sliver is given in Fig. A7.6(b). As expected, a distinct peak was present at the bale plucker cycle frequency. These variations showed as color barré in fabrics made from the yarn produced from the sliver mentioned. The barré had a periodicity, which related exactly to the cycle frequency just mentioned. The FFT analysis was meaningful and accurate in this case.

A blend can be judged in a number of ways. Consider the real case of the 100% cotton sliver shown in Table A7.2, which has been selected because it was a rare, almost worst case scenario. The scenario arose from a badly organized commercial bale laydown and it was compounded by the lack of a blending machine in the line within the particular industrial plant. Card sliver was sampled every 10 yards and the samples were tested for various fiber attributes.

The drawframe was creeled with 10 card slivers in the input and the draft ratio was 10. It may be recalled that, according to doubling theory, the ratio should have been $\sqrt{10}$ in favor of the output. As might be expected, the actual output sliver had considerably larger values of CV than the theoretical values (Table A7.2). The output did not vary in sympathy with the input, despite the synchronization of the testing. Similar experiences have been had in carding and opening. Correlation between input and output has been determined to be statistically insignificant. This is because of the differential longitudinal migration of fibers in the fiber stream within the process concerned.

A7.6.2 Coefficients of variation

It is possible to use coefficients of variation (CV) or variance in a specific fiber characteristic, for example, if one is trying to control fiber micronaire or short-fiber content (because of drafting problems). However, each of the spectra for different fiber attributes exhibits a different characteristic. Figure A7.6(b) compares some spectra before and after the first passage of drawing.

The draft in drawing was moderate, and the degree of fiber migration small. The resulting effects were also small and thus drawing was found to produce only a modest effect on wavelength distribution of each of the many fiber parameters actually tested. Opening and carding produced irregular peaks, which sometimes corresponded to the bale plucker movement.

A7.6.3 Color variations

Standard colorimetry can be used to measure color of loose fiber, sliver, roving, yarn, and fabric. In modern mill practice, fiber color is measured on HVI equipment and it is expressed as yellowness (+b) and reflectance (Rd). In staple yarn mills, it is rare

Table A7.2 Variations in sliver (%CV)

	MIC	UHM	UI	STR	ELO	SFC
Card sliver (drawframe input)	3.0	1.7	1.1	3.4	5.2	11.4
Theoretical output value	1.0	0.5	0.3	1.1	1.6	3.6
Drawn sliver (drawframe output)	3.1	1.8	1.1	3.6	4.2	11.9

Note: The acronyms are defined in Section 5.8.2.

to measure the color of yarn or the intermediates in this respect, although this might change because of the growing availability and use of optical measuring devices. In the following text, some preliminary data relating to measurements made on yarn and intermediate products is given in the hope of providing some guidance on the possibilities.

A7.6.4 Color measurements on greige fabric

Some knitted fabrics were made from the carded sliver referred to in Fig. A7.6(b). Sliver-to-yarn spinning was used to avoid any distortions from the processes of drawing and roving. Also, the samples of sliver actually knitted were contiguous to the samples used for HVI testing. A sample of the results at a color wavelength of 700 nm (i.e. red) is given in Fig. A7.7. Similar curves were produced for other color wavelengths. The error wavelength were determined by applying a Fast Fourier Transform (FFT) to the time series of measured results.

The similarity of the spectra implies that micronaire is related to the color response in fabric form. It is known that the dye uptake of cotton fibers is affected by the micronaire values and therefore it might be expected that the changes noted would show up even more clearly in dyed fabric.

The exaggerated data shown here imply that bale-to-bale variation of fibers in the bale laydown affected the color of the product cyclically and that blending in the blow room had been inadequate. This latter fact was true for the particular case but it must be emphasized that it was a departure from normal, modern practice.

A7.6.5 Color measurements on sliver

Further blending reduces variations in blends but complete homogenization is not possible. Thus, it should be expected that some variations occur in all the fiber attributes when measured in yarn or in any of the intermediate products. This observation

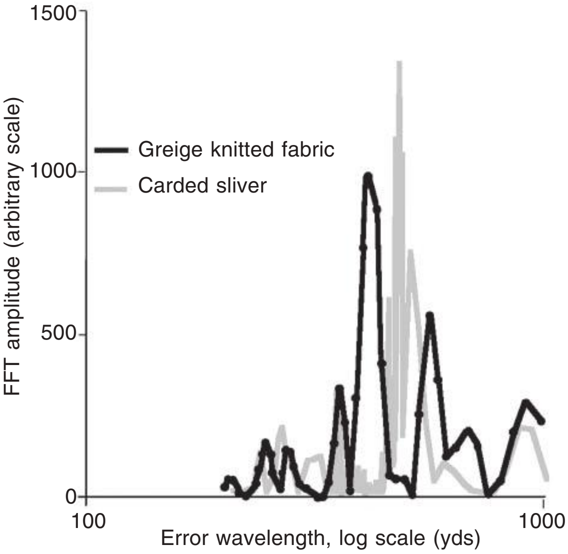


Fig. A7.7 Comparison of color is card sliver and fabric made therefrom

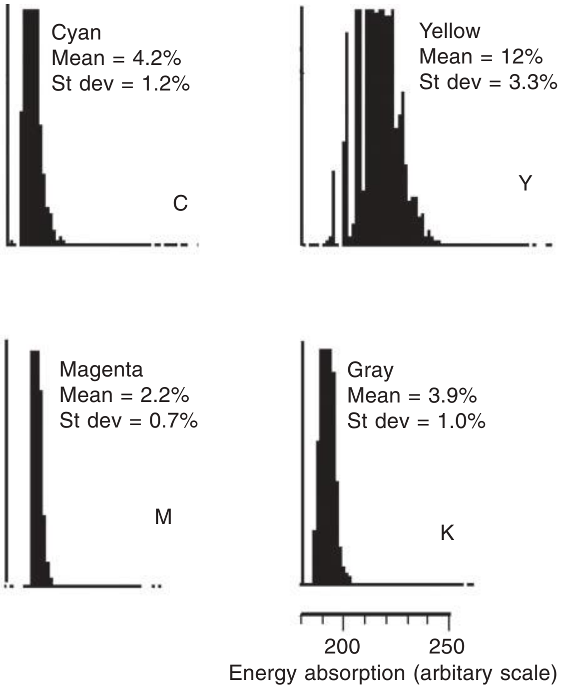


Fig. A7.8 Comparison of color components in sliver

applies to the color spectra as well as to the other attributes. It is possible to measure the color spectra fairly easily and this provides a useful view on the efficacy of blending.

The color spectrum of a fiber assembly may be expressed as color separations, such as those used in the printing of color photographs. One method is to use the cyan, yellow, magenta, gray (CYMK) system of color values and to quote the color depths of the textile material, such as that of some sliver as illustrated in Fig. A7.8, instead of the Hunter scale of +b.

Examination of scanned images of various sliver and yarn specimens indicates that there are micro-variations in yellowness, which are likely to arise from incomplete homogenization of the fibers within the blend. Even combed sliver shows striations in the yellow separation, which are not very visible in the other color components. More work is needed to comprehend the longer-term ramifications of such anomalies.

Reference

1. Beech, S R (Ed). Textile Terms and Definitions, The Textile Institute, Manchester, UK, p 114.

Appendix 8

Advanced topics VI: Drafting and doubling

A8.1 Theories of drafting

A8.1.1 Purposes of drafting

The purposes of drafting are to elongate the strand (a) to change the linear density, and (b) to improve the fiber orientation within the strand. Two types of drafting are common, namely roller and toothed drafting. Roller drafting will be dealt with first, but many of the remarks apply to toothed drafting as well. The combing roll used in rotor spinning typifies toothed drafting.

Roller drafting is known to create irregular fiber flows, particularly when there is a large variation in effective fiber length. Thus, errors are introduced into the output strand by the act of drafting. The means of control for this irregular flow include the use of aprons, pressure bars, and rolls. All of these control elements attempt to restrain the forward movement of the fibers within the draft zone until the last feasible moment. More detailed discussion of this is given in Chapter 3. The ideal control element acts to keep the floating fibers at the speed of the back rolls. It only permits the fibers to accelerate to the front roll velocity when the leading end nears the front roll nip. This means that the control element is in contact with some fibers traveling at the rapid front roll speed and some at slower velocities.

The manner of drafting in one stage affects the performance of the next. Consequently, there is a chain reaction along the stages of production, which can culminate in a very poor performance of the spinning frame. Poor performance at this point directly affects the efficiency of spinning and subsequent processes. It also adversely affects the quality of the product.

A8.1.2 Error wavelength and amplitude

A machine-created error is often sinusoidal (i.e. its amplitude and wavelength are characterized by a sine wave). An error wavelength is merely the distance along the strand between repeats of the sine wave. Amplitude is the size of the maximum error due to that sinusoid.

A8.1.3 Mechanical errors

In practice, errors from the early stages of drafting are elongated by the drafting and have long error wavelengths at the output of the final draft zone. Thus, there is a spectrum of errors of varying wavelength, components of which come from the various drafting zones. A repetitive error that is not sinusoidal can be expressed as a Fourier series of sine waves of different wavelengths, and harmonic analysis can reveal these various components. This is a valuable diagnostic tool for finding machine errors and it is extensively used in the textile industry. Furthermore, random errors typical of drafting waves caused by fiber-borne variations produce recognizable patterns on a spectrogram. It might be recalled that the spectrogram is a diagram that gives the error wavelengths and amplitudes.

Consider the effect of an eccentric front roll, where the roll is round but off-center. Assume that the remaining rolls are perfectly true, all the rolls are of the same radius (r), and the rotational speeds are ω_1 and ω_2 radians/sec for the back and front rolls respectively. Let the eccentricity be ε inches. At the extreme position (a), the surface speed of the roll is $\omega_2(r + \varepsilon)$, but at the other extreme position (b), the surface speed is $\omega_2(r - \varepsilon)$ length units/sec. The linear velocity, V_o, of the delivery varies cyclically between these extremes but the input velocity, V_i, remains constant; the result is that the draft, Δ, varies cyclically. This, in turn, causes the linear density to vary. For an eccentric front roll, the error wavelength is equal to the circumference of the faulty roll. For cotton spinning this is often about 5 inches. (Bad aprons also produce cyclic errors related to the length of the apron.)

$$\text{In position (a), the mechanical draft is } V_o/V_i = (\omega_2(r + \varepsilon))/(\omega_1 r)$$

$$= (1 + (\varepsilon/r))\Delta$$

$$\text{In position (b), the mechanical draft} = [1 - (\varepsilon/r)]\Delta$$

$$\text{Amplitude of the error} = \pm\,(\varepsilon/r) \times 100\% \qquad [\text{A8.1}]$$

The mechanical error is magnified because meshing eccentric rolls have a nip line that oscillates along the direction of the flow of fibers. This oscillation causes periodic drafting wave activity and the physical movement of the nip itself creates an additional error ‘spike’ in the spectrogram. If the faulty material is drafted again, the original error is further elongated. Drafting reduces the absolute error amplitude but the percentage value either remains constant or increases. The input error wavelength is increased by drafting in proportion to the draft ratio. The general case is:

$$\text{Error Wavelength} = \pi \times \text{roll diameter} \times \text{intervening draft} \qquad [\text{A8.2}]$$

Intervening draft is that draft which exists between the point of origin of the error and the point of measurement of the strand. If there is no drafting between these points, the intervening draft is 1.0. An error in the back roll of a drafting system produces an error in the strand, but the error is then elongated as it passes through the draft zone. The wavelength of the error in the material delivered by the front roll is equal to the circumference of the back roll multiplied by the draft ratio between the back and front rolls. Where several machines are involved, the appropriate draft is calculated by multiplying all the intervening drafts together before applying the result to Equation [A8.2].

A8.1.4 Fundamental theory of roller drafting

Much of the theory concerning roller drafting has treated individual fibers as long, thin rods lying parallel to the flow direction, the length of the rods being the only independent variable. The simple basis for the theory is that the fibers accelerate to the front roll speed out of phase with one another. This causes migration of the short fibers with respect to the longer ones [1]. Consider two fibers approaching a drafting zone, as shown in Fig. A8.1(a), and consider a worst case scenario. The long fiber approaching the input is of the same length as the roll setting and it is regarded as the reference fiber. The short fiber is of length *S* and its leading end is level with the reference fiber, of length *L*, as it passes into the back nip. The long reference fiber cannot accelerate from velocity V_i to velocity V_o until the leading end reaches the

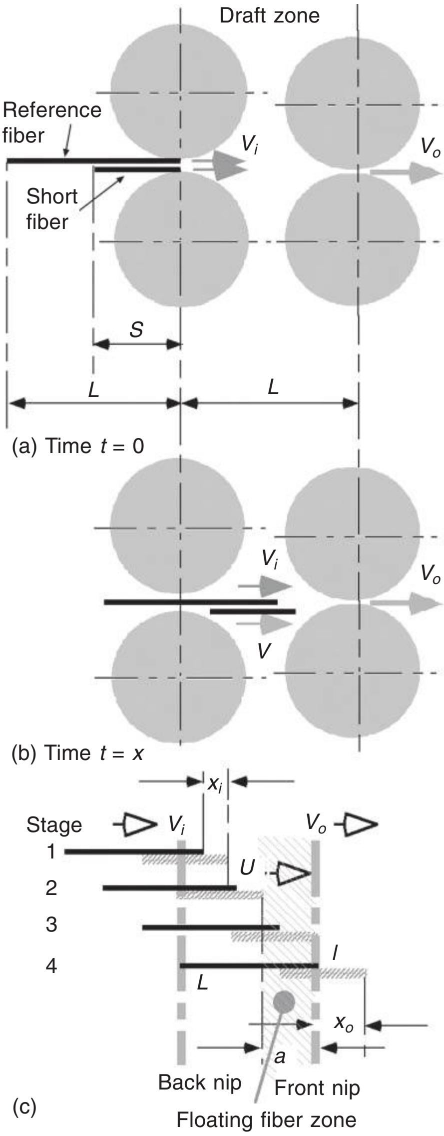


Fig. A8.1 Fiber flow in a drafting zone front nip, unless there is slippage between it and the roll surfaces. However, the short fiber can accelerate before this and the acceleration point can vary. The short fiber under these circumstances is called a ‘floating fiber’.

Figure A8.1(b) depicts the situation after the trailing end of the short fiber has left the nip of the back roller. The fiber travels at a velocity V that is greater than V_i, and could be as high as V_o, or somewhere in between (i.e. $V_i > V > V_o$). Fast moving fibers already nipped by the front rolls but also in contact with the short fiber just described, create a force tending to accelerate it (the short fiber). The more numerous fibers in contact with the back rolls try to restrain this acceleration. The accelerating force increases as the floating fiber moves towards the front rolls and the restraining reaction decreases. Thus, there is a point at which the floating fiber accelerates to the higher output velocity. From then on, until the leading end of the long reference fiber reaches the front roll nip, the two fibers travel at different speeds.[1] In the worst case, the short fiber travels a distance $(L - S)$ at velocity V_o after the acceleration. The long fiber travels $(L - S)$ at V_i, and the time for transit is $t = (L - S)/V_i$. Taking the draft ratio, Δ, as numerically equal to the velocity ratio, the short fiber moves:

$$V_o t = V_o(L - S)/V_i = \Delta(L - S) \tag{A8.3}$$

The long fiber moves:

$$V_i t = (L - S) \tag{A8.4}$$

Not all fibers migrate as much as this. The typical short fiber moves $k(\Delta - 1)\ (L - S)$ relative to the reference fiber, where k is a factor < 1.

Grishin [2], like many others, assumed that the fibers are straight and oriented in the direction of movement. Furthermore, he termed the longitudinal distance between the centers of the fibers as shear; also he pointed out that the shear increases as the fiber stream is drafted. Starting from the position of the leading ends of fiber, the shear changes from x_i (when both the short and long fibers are both gripped by the back roll pair) to x_o (when the long fiber passes from the control of one roll to the next).

The scheme is shown in Fig. A8.1(c), where the long fibers of length L are shown as heavy black lines and the short fibers of length l are shown cross-hatched. The zone in which the short fiber can accelerate is shaded in gray and is called the ‘floating zone’. Fibers change velocity from V_i to U in the shaded zone. Most theoreticians assume that $U = V_o$; the exact point where the events occur is open to interpretation but clearly not all fibers accelerate at the same distance from the back nip. Grishin assumed that $x_o = \Delta x_i$ and that the maximum deviation of $a(\Delta - 1)$ occurred at the front nip. Δ is the draft and a is the width of the floating zone. This implies a uniform probability distribution of the fiber acceleration point over the distance a. In this theory, a systematic displacement of all fibers of the same length plays no role in the unevenness of the strand delivered. However, deviations from the random do cause irregularity. Fujino and Kawabata [3] suggested that the wrongful acceleration of the fibers in this zone is influenced by the fiber speeds. They deduced that the probability distribution of the fiber acceleration point was an exponential function of distance from the front nip. Goto *et al*. [4] used a normal distribution. All

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[1] According to some authorities, the short fiber passes through several steps of speed change, perhaps sometimes accelerating during the intermediate stage, but, for the present purpose, a simple one-step model will be used.

these theories assume that the fibers are straight, aligned and act independently. Other authors recognize that fibers sometimes travel in groups. Whichever theory might be closest to the truth, it is evident that the smaller the value of a, the less chance there is for irregularity to develop. It is quite clear why a proper setting of the aprons has such a beneficial effect on the evenness of the strand. The main limiting factor in the use of aprons is the wear at high linear densities and high speeds. It is also clear that the magnitude of the draft plays a large part in determining the errors produced. Thus, one would expect that the ring frame would produce the largest errors because the draft there is the largest of the roller drafting systems used in a mill. Table A8.1 confirms this expectation.

Following Grishin's lead, let the fiber shear be defined as the average distance between the ends of various fibers denoted by X. Providing there has been no extra disturbance, shear after perfect drafting is ΔX. If a fiber accelerates earlier than it should, it becomes displaced relative to the others; it swims downstream because its average velocity is increased by the early acceleration. The relative movement of this fiber makes the strand thicker in the place to which it has swum, and thinner in the place from whence it has come. Hence, the displacement of any fiber from its proper position creates an irregularity of linear density. Such fiber migrations alter the shear in the output. There is always some irregularity in the positions of the fiber ends and the shear after drafting, X', may be expressed as:

$$X' = \Delta X + s \qquad [A8.5]$$

where X is the shear, Δ is the draft, and s is the standard deviation in shear. Shear may be regarded as a form of longitudinal fiber migration.

Consider two fibers traveling at the same time, one of the correct length and one shorter. The first travels through the draft zone at the back roll velocity until the leading end almost reaches the nip of the front roll. The short one accelerates early and travels distance y at the higher front roll velocity. The velocity difference during the time that the short fiber is passing through the front nip is $(V_2 - V_1)$ and the relative draft is $(\Delta - 1)$.

The scale of all the deviations is changed by the same factor.

$$\text{Standard deviation in shear} = (\Delta - 1)y \qquad [A8.6]$$

Johnson [5] used a computer to simulate fiber movement in a random sliver where the rolls were eccentric and the fibers were elastic. He also allowed the fibers to group. Lamb [6] claimed that use of this mathematical model produced a good result for wool processing. This demonstrates that, although the use of models using rigid rods as the moving elements might be deficient, the models suggest that grouping of the fibers might not be as important as some suggest.

Table A8.1 Typical changes in evenness of linear density due to drafting

	Card	**1st Draw frame**	**2nd Draw frame**	**Roving frame**	**Ring frame**
Yarn count N_e	0.14	0.15	0.18	2.0	60
Theoretical CV_{th}%	0.65	0.67	0.74	2.45	13.4
5% Uster values CV_{act}%	2.7	2.8	2.8	5.2	14.9
Irreg^y index = CV_{act}/CV_{th}	4.2	4.2	3.8	2.1	1.1

All the theories deal with the short-term errors, and even if some of these errors are elongated by successive draftings, they deal with only one aspect of the problem.

A8.1.5 Drafting using toothed components (Staple fibers)

There is another class of drafting in which the one or more pairs of rollers is/are replaced by moving toothed components. (A sketch of a typical toothed drafting system is shown in Fig. A8.2(a).) These components may have saw-teeth, pins or even just a roughened surface capable of gripping a fiber. The toothed components usually create a grip on the leading portions of the fiber elements being drafted and the trailing ends are often restrained by a roll and feed plate combination. Other combinations are possible. In this class of drafting, it is necessary to define the fiber element being drafted. The element might be a fiber clump of some size or it might be a single fiber.

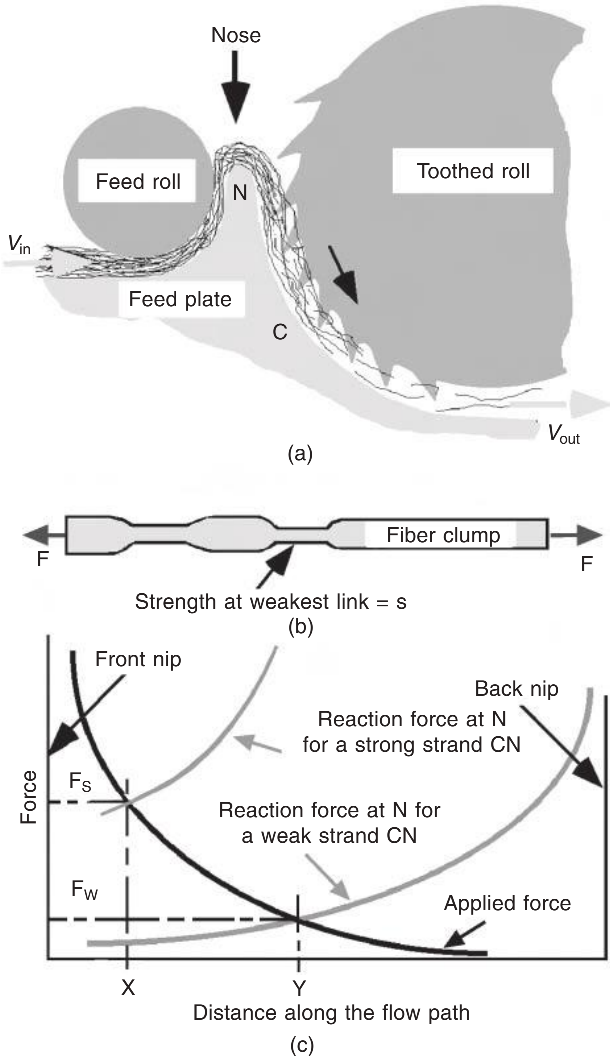


Fig. A8.2 Toothed drafting

Consider a sliver used in rotor spinning. There might be some very small fiber clumps embedded in a matrix of a larger number of single fibers. However, the average exit clump size nears that of a single fiber. In the opening line processes, the clump size is much larger. These clumps are also embedded in a matrix of fibers and it is difficult to characterize the clumps. Generally, the fibers within the clump have a greater mutual cohesion than that which exists between them and those in the surrounding matrix. The clump tends to retain its identity until sufficient force is applied to break it apart. As before, the material enters at velocity V_i and is delivered by the toothed element at V_o; the draft ratio is V_o/V_i.

Many theories of roller drafting relate to indivisible fiber elements, whereas with toothed drafting the fiber elements (i.e. fiber clumps) divide in the process. Theories of roller drafting assume that the length of element is virtually unchanged by the drafting, whereas with toothed drafting it is almost certain that the average length changes substantially. Consider a fiber clump being restrained by the rearward portions of the mechanism (such as N in Fig. A8.2(a)). The teeth in the forward part of the mechanism apply a force, F, to the leading portion of the fiber clump, which tends to stretch the clump. This force increases as the leading end of the clump approaches the virtual nip zone in the front of the drafting zone. As the clump moves forward, the force rises until either (a) the trailing end is released, or (b) the clump divides at its weakest point (Fig. A8.2(b)). One possibility is that, when the acceleration force, F, equals the strength, s, at the weak spot, the frontmost portion of the tuft accelerates to the delivery velocity. Later, a second weak spot might fail during the drafting process. Then a further portion of the clump might accelerate to be followed by the remainder when the new accelerating force and the reaction come into equilibrium. Alternatively, the second weak spot may not fail before the equilibrium between the accelerating force and reaction is reached, in which case the clump will have been divided only into two pieces instead of three. Other possibilities also exist. The statistical distribution of the daughter clump sizes differs from the mother distribution. Generally, drafting reduces the range of clump lengths. The length of the clump is always measured in the direction of flow.

Performance of the toothed system depends upon the design, among other things; the shape of the zone between the toothed roll and the feed plate is particularly important. An aggressive design tends to break down the clumps more quickly and to straighten fibers more, but at an increased risk of fiber breakage. The design and condition of the teeth or pins are also considerations.

In roller drafting, rule of thumb indicates that error wavelength of the major drafting errors is about three fiber lengths. If this were applied to toothed drafting, it would imply that the error wavelengths at the exit of the drafting system would be about three clump lengths. As the tufts get shorter, so would the distances that the tufts migrate due to the drafting process.

The greater the strength of the weak link, the smaller is the distance X in Fig. A8.2(c), since the leading end of the tuft has to penetrate nearer to the nip to accumulate a sufficient force. The strengths of the weak links that fail in drafting are variable and the value of X is also variable. The value is equivalent to the value $(L - S)$ in roller drafting. It controls the migration of the daughter tuft with respect to a reference one that does not divide. There is a distribution of fiber migrations and each component contributes to the irregularity of the fiber stream emanating from the draft zone.

The complex and varying interactions between clump lengths, longitudinal migrations and blending irregularities makes any deterministic solution extremely difficult. The distributions of these components are unknown and therefore only generalizations can be made. Fiber migration is determined by draft ratios (in the order of 100). Thus, it might be realized that relative fiber movements in the order of several yards are obtained at each stage. After the various drafts of intervening machinery are taken into account, cumulative relative motions in the order of 100 yards in card sliver are possible. Such migrations might be significant when the blend is irregular.

A8.2 Roller drafting

A8.2.1 Draft distribution

The simplest practical roller drafting system is a ‘three-over-three’ system. Too small a break draft does not fulfill its function of breaking down fiber clumps in the input material and too great a break draft introduces unacceptable error in the first stage. More attention to the quality of the input material pays a larger dividend than ultra fine tuning of the break draft value. SKF [7] recommended that the break draft should be between 1.1 and 1.4 for a total draft between 12 and 25; for higher total drafts the break draft could be higher. Values up to 4 were suggested.

A8.2.2 Roll setting

There is always a margin allowed over the theoretical setting of the rolls. The exact margin depends on the linear density of the strand and the variance in the length of the fibers. For sliver, the setting can be as much as 10 mm more than the upper quartile length (UQL) for cotton fibers. For finer strands, the margin is reduced. However, other factors intervene and many machine manufacturers recommend settings that are 1 or 2 mm less than the UQL. This is because natural fibers have only a small percentage of long fibers; the majority of them are short. The breakage of a few long fibers is regarded as a worthwhile sacrifice to obtain a better performance with the bulk of the fiber population. Even with man-made fibers, there are fibers shorter than the original cut length because of breakage and fiber convolution. Also, there are a few that are longer due to stretching during processing. An example of the effect of varying the setting for a drawframe when drawing polyester sliver is shown in Fig. A8.3(c). The machine maker’s recommendation was for a setting of between 35 and 37 mm. The example was chosen because there is less variation in fiber length with a man-made fiber than with cotton. When the setting was reduced below 27 mm, the evenness of the sliver deteriorated sharply and it became progressively more difficult to run the machine as the setting was further reduced. In theory, the relationship between the setting and the fiber length is important. The settings theoretically should be changed to match the fibers being run, otherwise the evenness of the output strand suffers. However, in practice, it is rare for changes to be made in the mill except for merge changes and during maintenance.

A8.2.3 Errors in drafting

Each draft zone produces its own error, which is superimposed on the errors already present. Short-term periodic errors produce moiré effects, and cloudiness in a fabric if the errors are non-periodic; long-term errors produce streakiness and barré.

In roller drafting, the top rolls are covered with a rubber material and, if the load

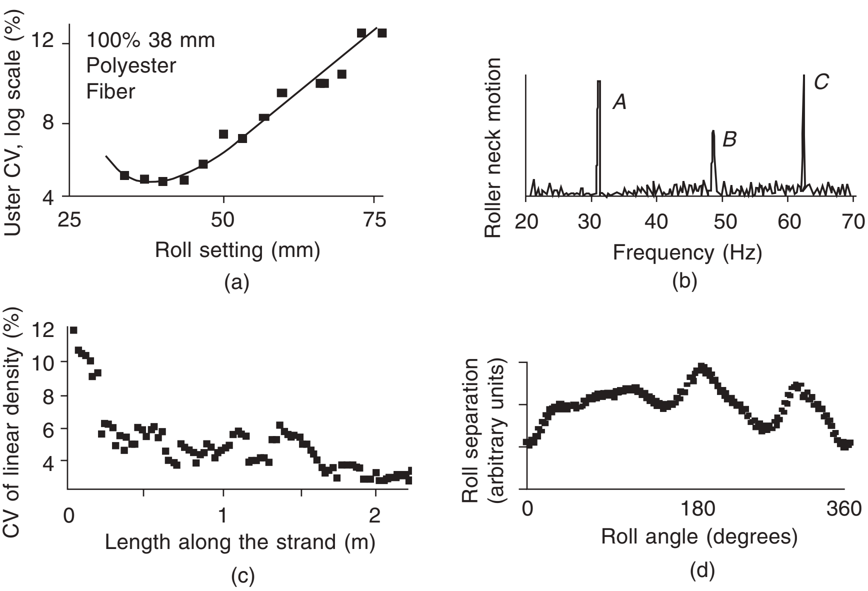


Fig. A8.3 Some drafting errors

is left on while the machine is still, flats develop because the rubber is visco-elastic. These cause periodic errors, which were a function of the ratch setting as in Fig. A8.3(a).

It is common for top rolls to have several minor flats and Fig. A8.3(b) shows a periodogram of the results found with a damaged top roll meshing with a true bottom roll. The several peaks in the profile can be seen. When the data is expressed in CVs as in Fig. A8.3(c), it is evident that the value of CV is considerably higher at start-up than after a few seconds of running. Changes occur as the rubber of the top rolls warms up. The variations in roll separation are closely tied to the irregularities in the strand. A frequency of just over 30 Hz corresponds to the front roll speed (Peak A) and Peak C corresponds to the second harmonic. Peak B comes from elsewhere. When the separation of the rolls was plotted against angle of rotation of the bottom roll for a very large number of rotations, there was a unique pattern dictated by the roll error as illustrated in Fig. A8.3(d). Clearly, mechanical errors can be made to show up distinctly, in contrast to the random errors (For more discussion see Section A8.2.6). An investigation by Keyser *et al.* [8] showed a linear relationship between yarn unevenness and roll eccentricity, as shown in Fig. A8.4. The data are old but the result clearly demonstrates the importance of roll eccentricity. The authors also found that yarn strength was diminished and the appearance of the yarn deteriorated. Foster and Tyson [9] carried out a similar experiment and found that the slope of the curve of standard deviation vs. roll setting was a function of draft. It follows that there is an interaction between what happens in the draft zone and the cyclic change in velocities. This aspect will be discussed later, but before that, other forms of error have to be considered.

All significant mechanical errors in drafting arise from poor maintenance or improper setting. Out-of-true rollers, rolls with uneven rubber hardness, and damaged roll necks (i.e. bearings), gearing, aprons, or other components can cause product errors. Slack bearings can also give problems. Cots or cushion rolls (rubber-covered top

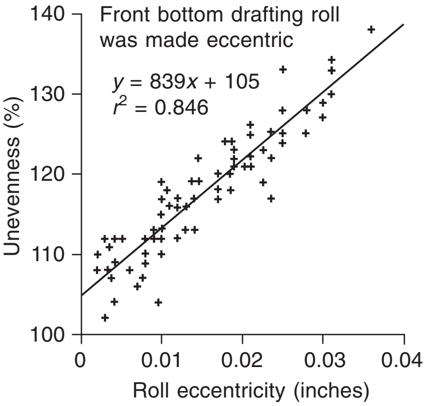


Fig. A8.4 Bottom roll eccentricity

rolls) must be buffed periodically to true them up; worn or damaged elements must be replaced when necessary. The combination of a good maintenance program with a proper quality control system to identify the sources of error is essential to the running of a modern mill.

A8.2.4 Pneumafil and reworked fibers

Production of yarn temporarily ceases when an end breaks in a ring frame. An end refers to the yarn emerging from the delivery rolls of the drafting system. Repair has to wait until an operator (or robot) gets around to it. During these times of interrupted production, the drafting system continues to deliver fiber, which is sucked away by a pneumafil system. The fiber removed is also referred to as pneumafil. The fiber removed is that which would have gone into the yarn, and has good characteristics of length and strength; but fiber crimp and elongation characteristics have been changed as compared to the virgin fiber. Nevertheless, the pneumafil waste is reused or 'reworked' because it is too good to throw away. The reworked fiber has to be blended with the virgin fiber very carefully so that the percentage does not exceed, say, 3% anywhere in the blend. Failure to control the blend leads to problems throughout the process line.

Besides the pneumafil produced during the time of an end down, there is a continuous loss of fiber from the twist triangle and balloon during spinning. This is only a fraction of a percent of the total volume being processed, but it is significant in terms of the amount of pneumafil produced. Consequently, there is not a unique relationship between the ends down rate (in breaks/1000 spindle hour), machine productivity (in lb/spindle hour), and the pneumafil production rate (in lb/spindle hour) as might be expected, although there is a rough correspondence. Mill trials produce a range of values depending on the product, machine, and operators. A very rough rule of thumb is that the percentage of pneumafil is about one-tenth of the end-breakage rate. Excessive deviations in the ratio between the pneumafil production rate and the theoretical value given below are a sign of inefficient repairs of the broken ends.

Theoretical pneumafil production rate, P_p, is given by

$$P_p = K + \{P_y \times (m_r/m_s)\} \qquad [A8.7]$$

where K = a factor dependent on the production of pneumafil created whilst the spindle is working

P_p = average production of pneumafil in lb/hr for 1 spindle
P_y = the production of yarn in lb/hr for 1 spindle
m_r = number of spindles idle in a set because of end-breakage
m_s = number of spindles in a set = (usually) the spinner's assignment.

A8.2.5 Hairiness

Errors exist other than changes in linear density or creation of thick and thin spots, slubs, and nep. If the surface of the yarn has a differing structure along its length, it can produce customer complaints because of shading, barré, and moiré in the fabric. Change in hairiness of the yarns is one of the factors responsible.

Variations in hairiness can come from several sources. One source is wear in yarn guides and other running surfaces, which rough up the yarn as it runs through the machine. Sometimes lack of careful maintenance will allow deep cuts to be produced on surfaces, especially when running with a fairly abrasive fiber such as polyester. A second source is in the twist triangle, where conditions leading to a ragged and varying construction can also lead to undesirable changes in the surface of the yarn. A third cause arises from varying quantities of short fiber arriving at the twist triangle which produce changes in the yarn surface.

A8.2.6 Continuous measurement of sliver properties

Grover [10,11] discussed the problem of dynamic measurements of linear density in a flowing sliver. Amongst many sorts of transducers assessed was a thermocouple device (which measured the temperature of the throat of the trumpet), a pneumatic system (which measured the pressure at the throat), and a force reaction system (which measured the drag force acting on the active part of the trumpet).

Compressed sliver sliding through the throat of the trumpet dissipates energy. Friction at the throat heats the sliver as well as the trumpet and it is possible to measure the sliver temperature. The time response is slow for the relatively massive machine components in the heat dissipation path. However, the speed of the sliver causes it to respond to the changes in the resistance of the sliver passing through the trumpet with a time response better than 0.05 sec. Significant differences in temperature even over just a few inches of sliver running in a drawframe could be detected. When running cotton, temperatures of up to 30°C were typical whereas with acrylic fiber the value would rise to the region of 40°C. Drawn slivers produced lower temperatures than carded ones. Figure A8.5 shows a series of scans with an infra red movie camera recording the temperature of the sliver as it left the trumpet. Each scan showed an increase in temperature as it passed over the sliver. About 70 mm of sliver passed during one scan cycle. The three-dimensional graph shown has x, y, and z axes; temperature is along the y axis, length along the sliver is along the x axis, and distance across the sliver is along the z axis. All three axes are mutually perpendicular. The temperature profile on each scan is an indication of structure of the sliver, and the distance apart of the shoulders is an indication of the sliver diameter (as shown in the diagram). Tests showed good results but the expense of the system was a problem. Until a cheaper means of measuring the radiated heat is available, the method is unlikely to be developed commercially.

Pneumatic trumpets are often used in which the air pressure at the throat of the trumpet is measured as a proxy for linear density. The flowing fibers carry air into the

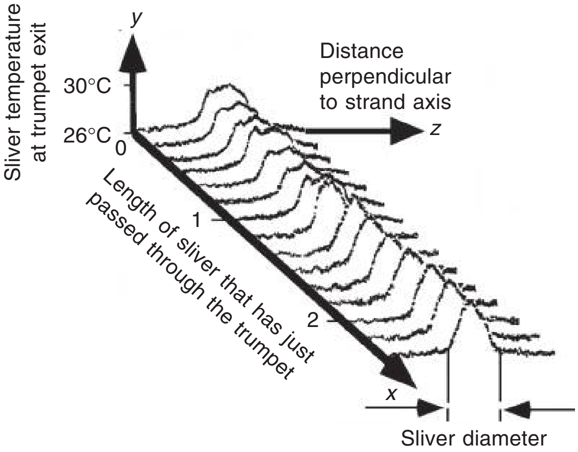


Fig. A8.5 Continuous sliver temperature measurement

trumpet and this creates a pressure in the throat. It also creates air turbulence due to backflow at the entrance to the throat. The relationship between the air pressure and the linear density depends on the bulkiness of the ingoing sliver and the speed at which it travels. Trials were made with a trumpet in which a sliver was run and pressure measurements were recorded. The sliver was cut into consecutive one-inch lengths of sliver, weighed and matched to the corresponding portions of output signal from the transducer. The comparison showed only a 0.64 correlation coefficient. Longer-term errors yielded better results, but it was clear that the pneumatic trumpet could not be relied upon to provide an accurate measure of very short-term error.

A trumpet was equipped with one or more diaphragms, each containing an orifice through which the sliver passed. In the simplest one, a single orifice was mounted on a diaphragm and strain gages were used to measure the reaction forces. A test with consecutive one-inch samples, similar to the one just described, was used, and this produced a correlation coefficient of 0.75. Although this was an improvement in performance in the measurement of very short-term error, there were problems with signal drift caused by uneven heating of the strain gage elements in a bridge network. (A Wheatsone bridge measures and compares the electrical resistance of the four arms; variations in strain or temperature of the material in any one of the arms will unbalance the bridge and give a signal.) This emphasizes the difficulty of getting a reliable signal to be used for control.

At a given roll pressure and a given fiber ribbon width, the linear density of the sliver is given by the separation of the rolls through which the material travels. A tongue-and-groove measuring system works on this principle and it is very successful in yielding accurate results providing the operating surfaces are true and clean. However, there is a tendency for the meshing of tongue and rolls to cut fibers that are not pressed into the groove. Grover [10] and Lord and Govindaraj [12] used drafting roll separation as a proxy for linear density of the ribbon of drawn slivers passing through the front rolls. The measurements were found to be sufficiently accurate to use as a control signal to adjust the ratch setting although some errors due to changes in density at the selvages of the ribbon became evident. Mechanical errors in the rolls came into sharp focus. The use of an encoder permitted the exact position of any flaw in a rotating roll to be identified without stopping the frame. It was also found that when a frame first starts up there are minor flats on the rubber cots but that these flats disappear as the rubber warms up in use. Thus, there is a temporary increase in the irregularity of the sliver when a machine is started after a certain rest time. The regularity of the sliver improves over the first minute of running.

Another approach by the researchers just mentioned was to optically measure the thickness of the fiber ribbon that passes through the draft zone of the drawframe. There are difficulties in getting access to the material because of the space taken up by the rolls. One of the conclusions from this phase of their work was that the input slivers retained their autonomy through the drawing process, each sliver behaving independently of the others. Traditionally, *m* input slivers are considered doubled before drafting, and the variance of the material input to the drafting process is expressed as (1/*m*)th of the average. The variance of the output material from the drafting process is then given as:

$$(\sigma_{\text{out}})^2 = (\sigma_{\text{in}})^2 + (\sigma_{\text{added}})^2 \qquad \text{[A8.8]}$$

where the variance due to drafting is added to the variance of the input material. However, if the slivers behave independently during drafting, it is more correct to say that the variance added by drafting is added to each input sliver and the doubling takes place after drafting. The equivalent relationships are then:

$$(1/m)\sum_{j=1}^{m}(\sigma_{\text{out},j})^2 = (1/m)\sum_{j=1}^{m}(\sigma_{\text{in},j})^2 + (1/m)\sum_{j=1}^{m}(\sigma_{\text{added},j})^2 \qquad \text{[A8.9]}$$

This may be interpreted as:

average of the output variances = average of the input variances
+ average of added variances

In this situation, drafting adds even more irregularities than is usually believed. Furthermore, the result implies that their neighbors influence fibers when the packing density is high, and that they behave as groups rather than as individual fibers. Hence, the theoretical CVs should be calculated on the number of fiber groups in the cross-section rather than the number of fibers.

A8.2.7 Automatic control of drafting errors

In 1962, Ishikawa and Shimuzu [13] proposed a device for sliver drawing in which the drafting force was used to generate a signal to control the draft ratio. It was found that the time constant of the system was an important parameter and that errors could be amplified at wavelengths shorter than dictated by the time constant of the system. In practice, they were able to control evenness down to about 3 inches (8 cm in the original paper) but instabilities at smaller wavelengths were troublesome. They succeeded in reducing the errors in their test apparatus but the importance of the paper was more in directing attention to the regions of stability in a control system than in developing a viable machine.

As mentioned previously, separation of the rolls in a drawframe has been used to provide a signal, which was used to control the ratch setting rather than the draft ratio. The idea was based on watching an expert set up a drawframe for minimum drafting wave error. These errors are caused by variations in fiber attributes that react with fixed roll settings. The expert first judges the drafting wave activity by the height of the hill on a spectrogram, then changes the roll setting, makes another test, re-judges and so on. This process continues until the setting is optimized for minimum drafting wave activity.

In the automatic control system, the middle and rear pairs of drafting rolls were mounted on a platform, the rolls were driven by stepping motors, and the setting of the front drafting zone was also controlled by a stepping motor. A computer program was written that sampled the output from the roll separation transducer within a specified error waveband, which included a typical drafting wave. If the magnitude of the signal was outside a control zone, the ratch setting was adjusted by 1 mm and the error was sampled again. If the error was still out of control, the process was repeated, but if it was now in control, the process ceased until the signal went outside the control limits again. Roll errors made sharp peaks enclosing only a small error in a periodogram whereas the drafting waves made a diffuse spectrum that encompassed a considerable variance. The system performed satisfactorily and could be seen to change settings from time to time as the fiber population changed. A cotton sliver was spliced to one made of longer polyester fibers and, as the splice passed through the system, there was a permanent adjustment to the new fiber length. Despite this, the system was not successful because it was so slow in reacting to changes.

A8.3 Avalanches in roller drafting

A8.3.1 Slub production

As stated earlier, a short fiber in the draft zone not being nipped by either set of rollers is called a floating fiber. The floating fiber is under the influence of others in contact with the front and back nips but it is not directly controlled by either set of rolls. Consider what happens just before and after the acceleration of the floating fiber.

Just before the acceleration, the subject fiber may be in contact with other floating fibers. For explanation purposes, assume the following. Three fibers in contact with the subject floating fiber are completely controlled by the back nip. Two are adjacent floating fibers traveling at the speed of the back nip but they are not directly connected to it. Another fiber is completely controlled by the front nip and is also in contact with the subject. No other fiber controlled by the front roll is in contact with the subject. If, at that moment, the fiber in contact with the front roll generates not quite enough force to overcome the frictional resistance between the subject and those in contact with the back roll, the subject will not yet accelerate. If, however, one of the three which had been in contact with the back roll is later released, and accelerates, it might cause the subject also to accelerate because there is now one fiber less restraining it. If the subject does accelerate, there is a possibility that the other floating fibers in the vicinity will be induced to go with it. A small avalanche has been created. Obviously, larger avalanches are possible, especially where the subject fiber and neighbors are nearing their normal acceleration points anyway. Where fiber clumps rather than single fibers are involved, the greater number of neighboring fibers can have a greater effect because the circumference of the clump is larger than that of a single fiber. Consequently there are differing chances of avalanches. The effect of such avalanches is to magnify the size of the defects and to undesirably increase the variability of output.

If a group of fibers accelerates early, then the population of fibers in the rearward section is depleted. Also, the group to be accelerated is not formed until Z inches of strand have passed. After drafting this becomes ΔZ. Concentrations of short fiber create weak zones, which are interspersed with good fiber. The body of the avalanche can become a slub, which carries a concentration of short fiber with it when it accelerates. These concentrations of short fiber are likely to cause more avalanches (and slubs) in later processing. After drafting, there are sometimes long portions of good material between the outbreaks of slubs (which are often processed without trouble). Under these conditions, there can be outbreaks of this type of fault in each of the drafting systems through which the concentrations pass. A steady concentration of short fiber can break up into pulses of short fiber; these, in turn, break up in subsequent drafting into intermittent bursts of activity. Relatively short lengths of yarn may be subject to heavy production of slubs and then there can be quite long periods without activity. The final slubs can be very heavy and the following thin spots are very prone to breakage in spinning. To minimize such effects, the roll settings must be properly controlled and high concentrations of short fiber should be avoided.

A8.3.2 Variations in fiber population

Lord *et al.* [14] point out that a fiber (or fiber clump) accelerates when the force exerted on it by fibers being pulled into the front nip exceeds the reaction from the more slowly moving fibers under the influence of the rear gripping medium. In roller drafting, this would be the back roll. The acceleration point is dictated not only by the relative speeds of the fibers, but also by the number of fibers in contact with the subject fiber (clump) and their degree of entanglement. This may lead to unstable conditions and avalanches [15].

Table A8.1 makes it clear that the actual CVs of linear density are much larger than the theoretical values for the draw- and roving frames where the strand cross-sections are large. It is not until the cross-section is reduced to the order of 100 fibers that the theoretical and empirical values approach one another. This suggests that the fiber flow in the first stages of the process line is not composed of independent fibers moving singly in relationship to one another; rather that fibers move in groups, and this causes a deterioration in the expectation of evenness.

It also suggests that the populations of fibers entering a machine may vary considerably along their length. If this is so, then there will be corresponding variations in drafting performance. Lord and Johnson [15] suggested a system of fiber population changes that would carry errors from one machine to the next in line, to make complex patterns of spinning performance. Grover [16] made many cross-sections of polyester/cotton yarns. The percentages of each sort of fiber were noted at one-inch intervals. The work gave CVs of about 20% in polyester content. The few gaps were filled by interpolation. The resulting time series (shown graphically in Fig. A8.6(a)) was subject to a fast Fourier transformation to give the periodogram shown in Fig. A8.6(b). The CV in the one component was considerably higher than that of the linear density (*c* 14%). There seemed to be a distinct probability that the main variability detected was from drafting waves in the roving frame. Since then, some work in measuring the characteristics of the cotton fiber delivered from the drafting system of a ring frame has shown a CV of linear density over 17% in long-term variability. The high CV probably arose from variations in the first drawframe. It is very difficult to measure the short-term variability except for short lengths. The

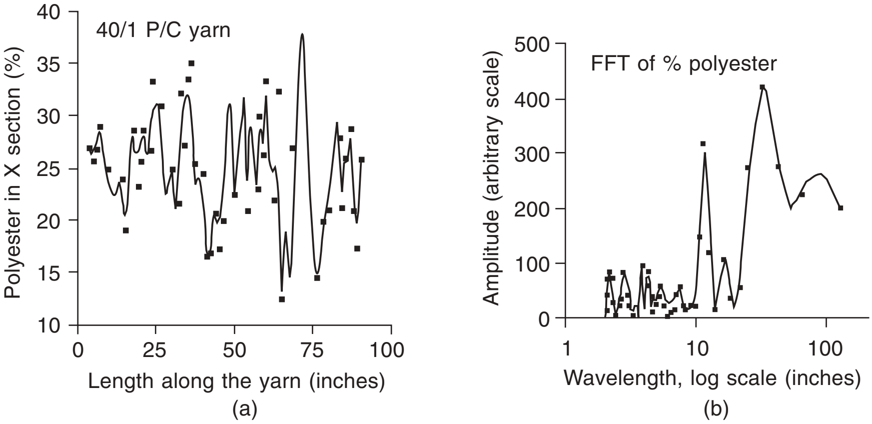


Fig. A8.6 Variation in polyester content

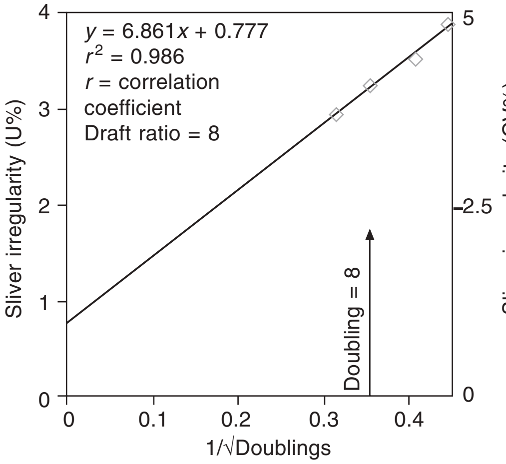
implication of this work is that changes in fiber population interact with the successive drafting zones to cause varying performance. The characteristics of batches of yarn might well be associated with these changes in fiber population. Changes in the attributes of the fiber passing through the system undoubtedly affect the CV of linear density of a yarn emerging from the front rolls of a ring frame. These effects might be even larger than those arising from changes in roll settings or machine condition. We finish this section on a practical note. Sampling the production and testing the CV gives a sample value that is good only for that time. A number of samples taken over an extended period needed to characterize a drafting system.

A8.4 Doubling associated with roller drafting

A8.4.1 Reduction of variance by doubling

Associated with many drafting systems is the idea of doubling. Several strands of input material are fed to the drafting system in an attempt to reduce the errors. A typical machine in which this occurs is the drawframe. Here it is not practical to use aprons; only the fixed control surfaces and the effects of doubling mitigate the irregularity caused by drafting. A quite usual assumption is that the variance in linear density among the strands is averaged. The resulting variance of the output is taken as $(1/m)$th of the variance of any of the m slivers used in the creel as input (i.e. m doublings). This neglects the variance added by drafting and the variations between the input slivers. An idea of this can be gleaned from an old study by Ozgur [17]. Data were re-plotted to give Fig. A8.7. Plotting the output irregularity in terms of $1\sqrt{m}$ and extrapolating towards zero, the irregularity does not reduce to zero. In fact, some studies have found that drawing more than about three times not only reduces sliver cohesion but also causes the regularity to deteriorate. Also, Bowles and Davies [18] showed that the improvement in CV due to doubling is reduced as the wavelength of error increases. No improvement will occur if the input error wavelength is much larger than the length of sliver in the supply cans. Very long variations can be induced by a poor bale laydown and doubling at drawing or elsewhere after carding might have little effect on these longer components.

Dyson [19] considered a model in which the variability of fiber extent was introduced.



NB Irregularity is a synonym for unevenness.

Fig. A8.7 Effect of doubling

(Fiber extent is the distance between the extremities of a crimped fiber.) The minimum irregularity, $\mathrm{CV_i}$, is then expressed as:

$$CV_\mathrm{i} = \{100/(mk)\}(1 + 0.0001\ CV_\mathrm{d}^2 + 0.0001\ \mathrm{CV}_\mathrm{k}^2) \qquad [A8.10]$$

Where CV_d is the CV of fiber linear density, $\mathrm{CV_k}$ is the CV of fiber extent, m is the number of fibers in the cross-section, and k is a factor. This assumes that fiber fineness and fiber extent vary independently of one other.

Dyson quoted work by other authors yielding $k = 0.95$ for carded cotton ring spun yarns and $k = 0.8$ for rotor yarns. With $k = 0.95$ and 0.8, the equations simplify to $109/\surd m$ and $119/\surd m$, respectively.

One way of expressing irregularity is by using an index, which relates the actual CV to the theoretical value. Experience shows that the index of irregularity decreases as the material moves down the process line, with the index varying from roughly 4 at the card to about 1.1 at the ring frame. Lamb [6] argues that doubling does not affect the index because both the denominator and numerator are affected by the factor $\surd m$. Undoubtedly, the movement of aggregations of fiber rather than single ones has an effect.

A8.4.2 Effects of between-stream variance

Passing reference was made earlier regarding the need for similarity in the means and variance in the streams of material being doubled. An example in staple yarn production illustrates how the between-stream variance can be included in the estimate of the expected total variance or CV.

Figure A8.8 illustrates how variations in the means of strands A, B, and C broaden the probability distribution of the combined strand shown as D. The means are a, b, and c; and the total unevenness in the product stream is calculated by adding variances between the means to the variance within the samples. In symbols:

$$CV_\mathrm{t} \approx \surd(CV^2/m + CV_\mathrm{b}^2)/100\% \qquad [A8.11]$$

where CV_b is between the means, CV is the mean of the components, and m is the

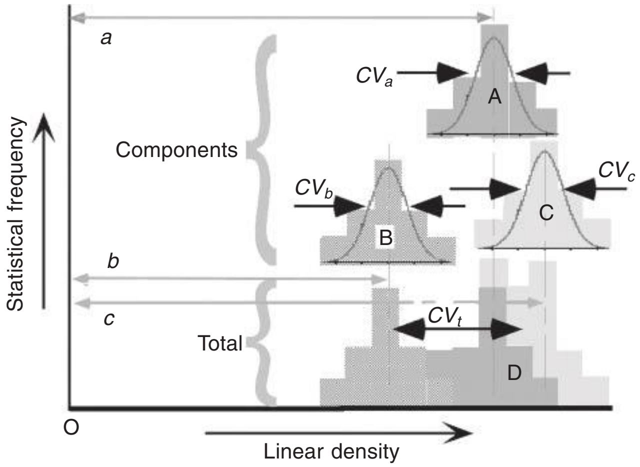


Fig. A8.8 Variability caused by differences in means

number of strands. Doubling of periodic errors can present problems, particularly if the error frequencies are similar for all input strands. The relative longitudinal positions of the streams then play a part in determining the error. Any such difficulties in this respect can be avoided by making sure that the equipment is in good condition and does not produce periodic error.

A normal drawframe has input slivers of varying mean values of linear density. Thus, finisher drawn slivers provide variations in yarn not only from the variance within each sliver and the variance produced by spinning but also from the variance between the slivers.

A8.4.3 Doubling mass constant

As discussed elsewhere, the flow of material through a mill is not really continuous; rather batches of material are processed in sequence. When traditional doubling is used, it is within a batch. Thus, for example, when we double sliver in a drawframe, we double within the batch defined by the mass of fiber in the creel. This mass may be thought of as a mass constant. The system is not able to significantly reduce error for wavelengths greater than that represented by about twice the mass constant of the machine involved.

A8.4.4 Effects of overdrawing

Whilst drawing sliver improves the orientation of the fibers and applies some doubling, too great a number of drawframe passages can adversely affect the product. Sliver tenacity falls off rapidly with multiple drawings. Klubowicz [20] determined the effect of multiple drawings (up to 36 drawings) on the yarn strength and strand evenness. He found that the yarn strength reached an optimum at somewhere between four and eight drawings, but then decreased with further drawings. The strand uniformity and yarn appearance improved with increased number of drawings, while the yarn elongation decreased. There was difficulty in handling overdrawn sliver because of the low sliver cohesion. This makes it clear that there is a limit to the benefits derived from drawing and doubling. Improvements in fiber orientation are similarly limited.

Many of the simple ideas of doubling and drafting are insufficient to explain the whole set of problems.

A8.4.5 The combined effects of drafting, doubling, and twisting

Cavaney and Foster [21] found, from empirical studies, that the variance of the output strand from a drafting system was:

$$(AN_e(\Delta - 1)/m] + b \tag{A8.12}$$

The factor A was a figure of merit but was not a constant and the factor b was almost zero; m was the number of ends fed to the system. Speed of the frame was found to have little effect. They recognized that fibers did not necessarily travel through the draft zone independently; they commented that the variance depended, in part, on the number of fibers in the fiber groups involved. Further, they pointed out that twist in a strand had a stabilizing effect on drafting. The performance of a roving frame may also be expected to differ from that of a drawframe on that account.

A8.5 Doubling and toothed drafting

A8.5.1 Opening line and carding

The process of dividing fiber clumps, which is a form of drafting, was described in some detail in Chapter 5. As outlined in Section A8.1.5, the basic ideas are fairly clear but the idea has not been widely recognized. There are large drafts applied to fiber clumps and the division of the clumps is irregular. Draft is applied to the whole stream, and the flow becomes irregular. However, few attempts have been made to assess this irregularity because (a) it is difficult to do so without impeding the operation, and (b) the effect of the irregularity is obscured by the massive doubling that occurs in devices like mixers and chute feeds. Perhaps someone will realize that there are potential gains in better controlling the fiber flow in the opening line, and then we shall see a further step in the continuing trend of improved yarn quality.

A8.5.2 Rotor spinning

Separation of fibers in a strand supplied to an open-end spinning machine is the essence of the process. It is necessary to separate the fibers almost into separate entities to make the system work. Open-end spinning, in the form of rotor spinning, has become very successful. Toothed drafting is an essential part of that success. Damage to the feed and combing rolls produces periodic errors as one might suspect and that sort of error can be detected by conventional testing and corrected by proper maintenance. Random variation in the fiber stream delivered to the rotor is reduced by the massive doubling that occurs when the many layers of fiber are laid inside the rotor to build up the necessary linear density of yarn (see Sections 3.4.1 and 7.2). Short-term random errors are low in rotor spinning. Perhaps the main lesson to be learned is that adequate doubling reduces the *random* errors. For this to be effective the mass constant must be large enough and, of course, there must be a sufficient number of doublings.

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Appendix 9

Advanced topics VII: Yarn balloon mechanics

A9.1 General observations

The whirling length of yarn between the pigtail guide and the bobbin produces yarn tension. Too high a tension above the pigtail guide leads to a high frequency of end-breaks, which reduces spinning efficiency and yarn quality. Too high a tension below the traveler makes unwinding at the next process stage more difficult and increases the number of interventions in winding, which reduces both winding efficiency and yarn quality. Too low a yarn tension in the balloon leads to collapse that produces similarly undesirable results. The behavior is usually analyzed by considering the forces involved, but there is also the possibility of using energy balances as a means of description. Forces are vector quantities whereas energy is a scalar quantity and this provides some relief from the mathematical rigor needed for acceptable solutions. An explanation can be derived from a consideration of the energy dissipated, stored, and/or transformed at the various parts of the rotating system. We will look at both approaches.

Technicians observe the balloon shape as a measure of the yarn tensions. Sophisticated means of measurement are rarely available in a mill and the normal means of judgment is whether the balloon is long and thin, whether it is fat, or whether it is bottle shaped. What is being observed is the surface area swept by the rotating yarn. Theoreticians have used vector mechanics to explain the complex phenomena and a reference point frequently used is the node formed at the pigtail guide. However, the energy to sustain the balloon derives from the bobbin, which is rotated by a mechanical drive system.

As far as the present discussions are concerned, the subject will be divided into several divisions. These will deal with various aspects of ballooning, and then go on to discuss (a) the lower zone between the traveler and the winding point, (b) the central zone, and (c) the upper portion above the pigtail guide. The central zone is a powerful tension producer but it is the reactions at the traveler and pigtail guide that produce the consequences.

A9.2 A rotating plane balloon – a very simplified case

As matters of definition, let the surface swept by the generator OBP (Fig. A9.1) be called the balloon and that swept by the more or less horizontal generator QP be called the base. To introduce the ideas, first consider the problem at the lower of two levels of simplification; the simplifying assumptions reduce the obscurity of the topic without enormously affecting the central idea. In this simplified case, the yarn rotates in a vacuum about an axis OQ, as shown in Fig. A9.1. This involves a rather unrealistic assumption that the plane OPQ rotates about the axis OQ at a speed of ω radians/second and that the yarn is confined to this plane. The theory ignores the effects of bending and torsional stiffness of the yarn. The yarn is treated as a string of beads, each element of which is δs units long. The action of the distributed centrifugal force and the restraints at O and P cause the yarn to become curved similarly to a hanging cable. Several radii may be defined. The radius with respect to the spindle axis at any height is denoted by r. The maximum value (r_e) is at the equator at B. The radius r_g is that at which the mass of the yarn length OBP may be considered to be concentrated (i.e. the distance to the centroid G). The length of yarn in the balloon (S) above the traveler may be estimated by calculating the length of the line OBP. The mass of yarn in that length is Sn (where n is the linear density of the yarn) and the centripetal acceleration acts on that mass through the centroid G. During a single chase, the length S might change by up to 10% but, in this rough analysis, the change will be ignored. (The meaning of the word chase is defined in Section A9.3.2.) F_t and F_{ho} are the horizontal components of the forces acting on the yarn at the traveler and pigtail guide, respectively. F_t includes the centrifugal force acting on the traveler. The centrifugal force $F_{cf} = n\omega^2 r_g S$.

Horizontal force components must balance and the moments within the plane should also balance. Taking moments about O,

$$F_{cf} \times h_g = F_t \times H \qquad \text{[A9.1]}$$

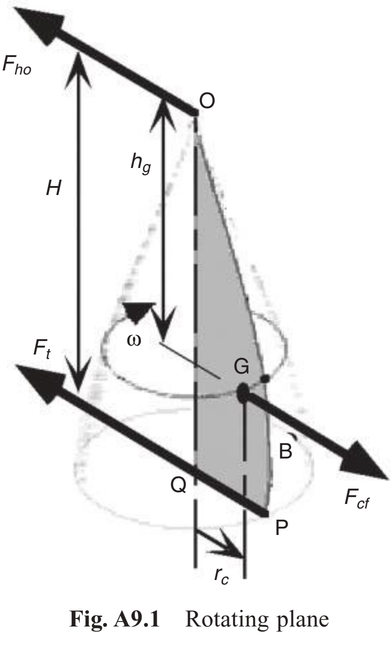

Fig. A9.1 Rotating plane

F_t is equal and opposite to the difference between the horizontal components of centrifugal force acting on the traveler and the reaction of the traveler with the ring. Distribution of the forces between O and P also alters with the position of the centroid, which changes during the building of the bobbin. The centrifugal force acting on the yarn changes with the radius of the centroid, r_g. The effect of these important reactions will be described later. A force of F_{cf} acting on an element δS is $\omega^2 rn\delta S$. The total force acting on the portion OP is the summation of all such elemental forces between O and P. If the length of the yarn between these limits is S, then

$$F_{cf} = \sum_{o}^{s} \omega^2 r n \delta S \qquad [A9.2]$$

This force is divided as in Equation [A9.1] to give the reactions at the ends. The vertical components of force for the simplified model are shown in Fig. A9.2. A force acting along the yarn is called yarn tension, T, and a force in any other direction is denoted by F. In a portion of the yarn at the equator B, the downward tension is F_v and the upward reaction at O is F_{vo}. For vertical equilibrium, $F_v = F_{vo}$.

A similar argument can be made if the yarn had been cut at U. The vertical component of T at that point also equals F_v for equilibrium. Thus, in the oversimplified model, the vertical component of tension in the yarn balloon does not vary at all as a function of height; it is solely determined by the end conditions. In ring spinning, the forces at the traveler and the pigtail guide determine the end conditions. The resultant forces at these points press the yarn against metal and friction creates tension gradients across these items. The frictional forces cause the tension below the pigtail guide to be more than that just above it because the yarn moves downward. The tension in the yarn leaving the traveler is higher than that just above it because there is a tension gradient due to friction. These effects will be further discussed later.

These rough analyses set the scene and establish how the distribution of the applied force alters the reactions at the end points. Even when the balloon is considered in

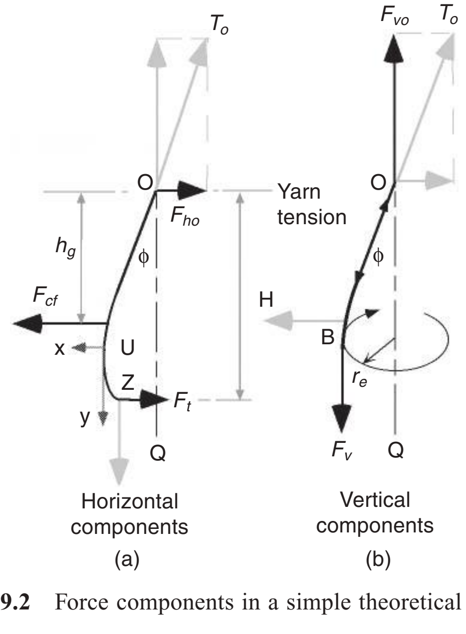

Fig. A9.2 Force components in a simple theoretical balloon three rather than two dimensions this is still true, although the analysis becomes more complex.

A9.3 Energy distribution in the balloon

A9.3.1 Energy taken from the bobbin

Figure A9.3(a) shows a compound view of the yarn between the bobbin and the

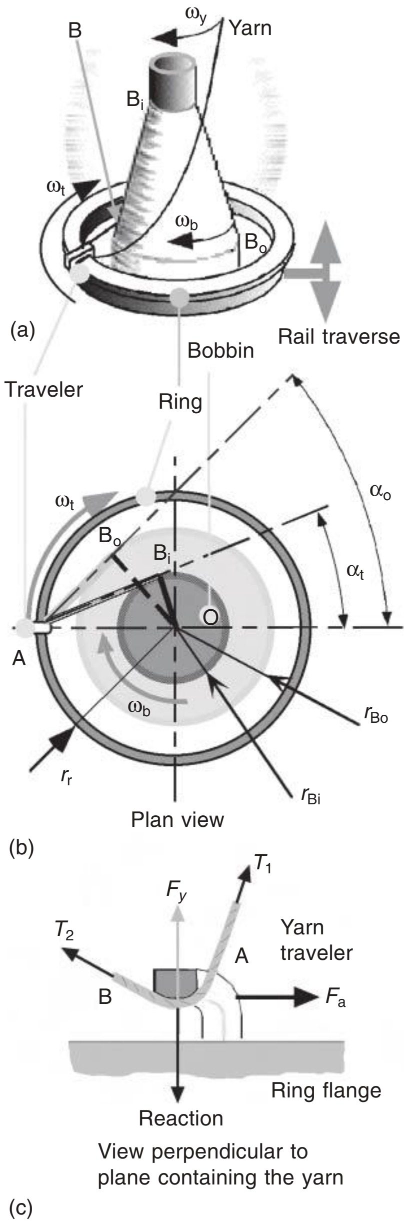

Fig. A9.3 The lower portion of the balloon traveler. The torque supplied to the rotating yarn system is the mathematical product of the horizontal component of yarn tension at B and the winding radius. The energy supplied is torque × rotational speed.

Let this energy be designated E. Conservation of energy dictates that the energy available at B is absorbed or dissipated by (a) kinetic energy of the yarn between the pigtail guide and the point B in Fig. A9.3, (b) kinetic energy of the rotating traveler, (c) strain energy stored in the yarn under tension and torque, (d) losses due to airdrag acting on the yarn, (e) friction losses caused by the traveler sliding on the ring, and (f) energy arising from forces generated by balloon instability. Potential energy changes are negligible; energy changes due to balloon instability are ignored.

A9.3.2 Energy balance in the base

The first component to consider is the more or less horizontal portion of yarn lying between the bobbin surface and the traveler. Figure A9.3 shows oblique and plan views of the ring and traveler system. The plan view at the bottom shows only the yarn departing from the traveler on its way to the bobbin and does not show the yarn arriving. This is to make it clear that the angles between the center line and the yarn change. As the winding point reciprocates between the lay point on the bare bobbin at B_i and that of the full bobbin radius at B_o, the angle changes from α_i to α_o. Due to this motion, vector components of the yarn tension acting along OA vary from $T_{Bo} \sin \alpha_o$ to $T_{Bi} \sin \alpha_i$, as the chase moves from bottom to top. (The chase describes the reciprocating movement of the lay point of the yarn onto the conical portion of the yarn already on the bobbin. The lay point, or wind point, means the point on the bobbin surface where the yarn is laid.) Periodic changes in geometry of the yarn, as the winding point moves through the chase, are reflected in the yarn tensions.

Kinetic energy stored in this portion of yarn is:

$$E_{k1} = I_1 \omega^2/2 \tag{A9.3}$$

where I_1 is the second moment of mass of yarn in the base about the axis of the bobbin and ω is the rotational speed in radians/second. The subscript ‘k’ refers to kinetic energy and ‘1’ refers to the base.

The winding radius changes cyclically through B_0 and B_1 as the ring rail moves through the chase motions. Further, the length of yarn changes cyclically through AB_0 and AB_1 (Fig. A9.3(b)); consequently, the kinetic energy in AB changes cyclically because of alterations in length, mass, radius of gyration, and winding radius. E_{k1} is a factor that depends on the geometry and mechanical arrangements of the short-term ring rail motion (or chase). The torque available changes cyclically in sympathy with the rail movement.

The kinetic energy of the traveler $E_{kt} = I_t\omega^2/2$, where I_t is the second moment of mass about the spindle axis. Since $I_t = M_t k_t^2$, where M_t = mass of the traveler, and k_t is its radius of gyration (note: radius of gyration is a special term used in mechanics to describe not only the position of the mass, but also its shape and size). The subscript ‘t’ refers to the traveler and ‘kt’ to the kinetic energy of the traveler.

$$E_{kt} = M_t k_t^2 \omega^2/2 \tag{A9.4}$$

The elongational strain energy is $T\varepsilon/2$, where T is the yarn tension, and ε is the elongation of the length of yarn involved. Yarn is visco-elastic and thus there is also a non-recoverable energy loss associated with the extension which is proportional to the length of the yarn segment concerned. However, the length of yarn in the segment now being considered alters. Consequently, the strain energy (E_{s1}) changes in sympathy. Thus, it follows that the energy level has a component, which is affected by the chase motion, but the changes are small and may be ignored.

Among other factors, airdrag depends on the length of yarn in the airflow. The fact of changes in length of AB means that there is a cyclic change in airdrag on the particular segment of yarn that is synchronous with the chase movement. Consequently, the energy dissipated ($E_{\mathrm{a}1}$) has a dependence on the chase similar to those just discussed. The subscript 'a' refers to airdrag. Airdrag losses in this segment of yarn are minor compared to the kinetic component; there is no need to complicate the analysis further. There is also a yarn–metal frictional energy loss at the traveler, but the sliding velocity is so low that this item, too, may be neglected.

The total energy absorption between A and B (which we may denote as E_1 where $E_1 = E_{a1} + E_{s1} + E_{k1}$) has a cyclic component that is dependent on the chase motion. Thus, the energy available to the traveler and the yarn above it is $E - E_1$. It might be realized that E is a variable by virtue of the changes in yarn tension and, as has just been discussed, that E_1 has a component related to the cyclic chase motion.

A9.3.3 Friction between ring and traveler

The traveler is pulled round the ring by the yarn. Drag on the traveler due to the friction between it and the ring causes the yarn in the balloon to rotate slower than the bobbin. The difference in speed causes the yarn to 'wind on' the bobbin. Referring to Fig. A9.3, the relative rotational speed of the bobbin in relation to the traveler is ($\omega_{\mathrm{b}} - \omega_{\mathrm{t}}$), and the relative linear winding speed is $(\omega_{\mathrm{b}} - \omega_{\mathrm{t}})r_{\mathrm{b}}$. The rotational speeds of the yarn and traveler are the same except for occasional local excursions in portions of the yarn above the traveler. The fiber is delivered to the system at constant linear speed and the winding system adjusts itself accordingly. Movement of yarn along its own axis proceeds at constant velocity, V_{y}. Values of ω_{b} and V_{y} are fixed, but r_{b} changes with the position of the winding point within the chase. Thus, the rotational speed of the yarn, ω_{y}, changes with ring rail position within the chase but it is normally marginally less than the bobbin speed. Microwelds between the ring and traveler, unstable air conditions, and perhaps some other causes result in occasional deviations from the normal cycle of events.

Figure A9.3(c) shows portions of the traveler and the sliding track on the ring; the traveler is shown cut at the level of yarn contact for clarity. Components of the yarn tensions in contact with the traveler (T_1 and T_2 in Fig. A9.3(c)) produce a resultant F_{y}. The tension at A is not the same as at B. A component of F_{y} tends to hold the traveler away from the ring. Centrifugal force acting on the traveler (F_{ct}) acts horizontally along a radius centered on the spindle axis and it tends to force the traveler into harder contact with the sliding track on the ring (i.e. in a direction roughly opposite F_{y}). Forces F_{y}, F_{cf}, and F_{a} adjust themselves to provide equilibrium by causing the traveler to tilt as necessary. The force normal to the sliding track, F_{n}, is the vector sum of the appropriate components of these and the tangential friction force along the sliding track is μF_{r} (see Section A9.5.5 for the full analysis of forces.) The energy dissipated is $E_{\mathrm{ft}} = \mu F_{\mathrm{r}} \times \omega r_{\mathrm{r}}$, where the subscript 't' refers to the traveler and 'f' to friction. Since ωr_{r} is virtually constant, the energy loss depends on the coefficient of friction, μ, and the normal force, F_{n}. The coefficient of friction is affected by the lubrication, or lack thereof; for cotton, lubrication is largely from crushed fiber debris deposited on the track on the ring.

The coefficient of friction depends on the state of wear of the sliding surfaces and the reaction force depends on the attitude of the traveler, yarn tensions, and centrifugal forces. Wear on the traveler alters the position of the center of contact area on the traveler. Also, the magnitude and directions of the yarn tension vectors vary. This is important because, not only do the forces applied to the traveler have to balance, but so do the first moments. Thus, if the direction and magnitude of F_y alters, the traveler tilts to correct the imbalance. This results in a modified value of F_n and a change in the energy absorbed in friction. In other words, there are reactions to changes in the system both above and below the traveler. There is also a long-term variation caused by wear in the components. In the case of the traveler after the initial break-in, this long-term change is measured in days, whereas the corresponding change to a properly run-in ring is measured in months, or even years.

The kinetic energy of the traveler, E_{kt}, $= I_t\omega^2/2 = M_t k_t^2 \omega^2/2$, where the second moment of mass about the spindle axis $= I_t$, the mass $= M_t$, and the radius of gyration of the traveler $= k_t$. Thus, the mass of the traveler is an important factor in determining the yarn tension since $k_t\omega$ varies but little.

Thus, summarizing:

$$E_{ft} = \mu F_n \times \omega r_r \qquad [A9.5]$$

and

$$E_{kt} = M_t k_t^2 \omega^2/2 \qquad [A9.6]$$

A9.3.4 Yarn above the pigtail guide

Rotation of the balloon induces torsion in the yarn above the pigtail guide and this stores some energy as torsional strain energy; it dissipates some of this due to frictional losses. There is also a small amount of tensile strain energy involved. The strain energies E_s reduce the energy available to the main balloon, but the quantity involved is small and may be neglected.

A9.3.5 Energy available to the main balloon

The energy available to the yarn above the traveler is $(E - E_1 - E_{kt} - E_{ft} - E_s)$. Changes in the chase motion, the mass of the traveler, and the effects of wear are now seen to affect the energy available to the main yarn balloon. As before, the energy available is distributed over categories similar to those already recited. Kinetic energy of the upper yarn depends on the mass of yarn involved and its radius of gyration; strain energy depends on the length of yarn involved. Of these factors, kinetic energy is the most important and the integration implicit in the factors for airdrag[1] may be left for later. Let E_{a2} be the airdrag of the yarn in the balloon between the pigtail guide and the traveler. The subscript '2' refers to the main balloon. The kinetic energy now available to the main balloon is:

$$(E - E_1 - E_{kt} - E_{ft} - E_s - E_{a2}) = E_{k2} \qquad [A9.7]$$

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[1] Airdrag on an element of yarn may be taken as proportional as to $C_d\, \alpha \sqrt{n}\, (\omega r)^2 \delta$, where C_d is the airdrag coefficient, α takes into account the attitude of the yarn element, n is the linear density of the yarn, ωr is that linear velocity which is tangential to the circular locus of the yarn element and δ is the length of the yarn element.

Let E_{k2} be the kinetic energy, n the linear density, S the length of yarn, and k the radius of gyration; each term referring to the yarn in the balloon rotating about the spindle axis, and the yarn referred to is between the pigtail guide and the traveler. Equation [A9.1] may be modified as:

$$E_{k2} = nSk^2 \omega^2/2 \qquad [A9.8]$$

Where E_{k2} is the kinetic energy, n is the linear density, S is the length of yarn, and k is the radius of gyration; each term referring to the yarn in the balloon rotating about the spindle axis. The yarn referred to is between the pigtail guide and point B.

The radius of gyration is related to the maximum diameter of the balloon; the normal speed is assumed to be so slightly different from the spindle speed that it can be regarded as constant. Thus, if ω and n are treated as invariable, the changes in energy available must cause changes in S, or k, or both. In other words, the size and shape of the balloon changes with the energy available. The length, S, changes significantly as the yarn on the bobbin builds up from base to tip; also there are changes in k. The yarn spirals in the balloon depending on the airdrag and this can cause significant changes in length; there is no unique relationship between length and diameter. These changes in E_{k2} are superimposed upon those arising from the right-hand side of Equation [A9.7]. Whatever combinations of these factors exist, there is a change in energy level that is distributed over the time it takes to spin a bobbin full of yarn.

A9.3.6 Instabilities

It is possible for the traveler motion to become unstable. At these times, the attitude of the traveler oscillates and imposes an additional energy variation on the main balloon, which is reflected in the tension variations.

If the yarn tension at the wind point drops below a certain level, there is insufficient energy available to maintain the normal, single-noded balloon. The balloon will then change such that the length of yarn is accommodated in a different shape, which permits the radius of gyration (or, approximately, the distance of the centroid) to be reduced. Sometimes the change in shape involves wrapping part of the yarn around a revolving support; when this happens the unsupported length and the radii of gyration are reduced. There are then extra frictional losses. The balloon is said to collapse because of the reduced diameter. One cause of such an event is the use of a traveler of too low a mass. This will be discussed later.

It is possible that subsidiary oscillations in the main balloon could absorb energy that would be subtracted from that available to shape the mean path of the yarn. There could be resonant vibrations at surprisingly low frequencies because the yarn in the balloon is restrained at the ends like a suspended cable; the effective modulus of elasticity of the system is low. Energy losses due to such vibrations would be one of these subtractions. Vibrations of this sort might be excited by intermittent slippages of torque and tension at the pigtail guide, mechanical vibrations, local air disturbances, etc. The system has a response time to force pulses imposed upon the balloon. Micro-welds between the ring and traveler can create such pulses, particularly if the ring is not properly run in. Recovery of normal running conditions after such occurrences is dependent on the response time.

A9.4 Yarn tension gradients

A9.4.1 Tension gradients as a connecting factor

A factor that appears in nearly all the energy items mentioned in the previous sections is yarn tension. There is a progressive change in yarn tension from the bobbin to the fiber delivery system, which is situated above the pigtail guide. A change in one segment affects all the rest; thus, the factors discussed earlier are mutually dependent and some discussion about yarn tension is necessary.

A9.4.2 Dynamic and passive yarn tension gradients

Tension gradients in the yarn may be classified into two categories. One has been called *dynamic*, because it arises from the centripetal accelerations acting on the yarn. The other has been called *passive*, because it does not depend directly on the rotation of the yarn about the spindle axis. Figure A9.4 illustrates one case and demonstrates how yarn tension forms a connecting thread in the control loop of the system. Remembering that the winding tension helps determine the available energy for the system, it can be seen that the behavior of any one segment of yarn is dependent on the tensions generated elsewhere.

Yarn tension is at its highest at the winding point on the bobbin. The existence of a dynamic tension on the more or less horizontal portion of yarn sweeping the base means that the tension at the traveler is less than the maximum. Since the outer diameter of the balloon base is limited by the ring radius, this gradient does not vary much for a given spindle speed. Friction between the yarn and the traveler causes a passive tension gradient and the tension of the yarn entering the traveler is still lower. The yarn in the main balloon suffers dynamic tension gradients that vary along the length. A passive, frictionally induced tension gradient occurs at the pigtail guide with the result that the input tension to the twisting section is further reduced. In Fig. A9.4, the curve is shown for the simplest case, but the gradient can be multi-noded. When the balloon collapses, the lower end of the yarn might wrap around the bobbin (or crown, if one is used) and a further passive tension gradient will be introduced. It is also possible for the balloon generator to change from a roughly parabolic shape

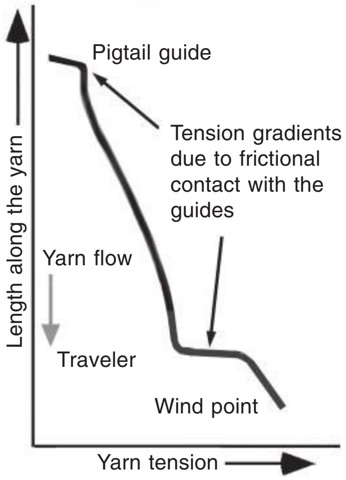

Fig. A9.4 Yarn tension profile

into a sinuous one with a number of nodes. In some sorts of unwinding from a bobbin, the balloon base, ring, and traveler no longer exist and these sources of tension gradient are removed from consideration.

A9.5 The real balloon

A9.5.1 The central section of the real balloon

When operating without balloon control surfaces (more about these later), any element of yarn is subject to the tensions and forces acting on it. The forces include airdrag, other frictional restraints, and the effects of electrical charging. Few of the forces arising from these phenomena act through a common point and thus there are moments that tilt, bend, and twist the yarn in the vicinity of the element. Figure A9.5 illustrates the forces acting on an element of yarn. The yarn in the balloon is curved; consequently the tensions acting on an element of yarn do not act along a common straight line; furthermore, the tensions differ from end to end. The forces acting approximately within a horizontal plane are shown with cross-hatched arrows. The light gray area represents the horizontal plane.

Let us take the roughly horizontal forces one by one. The airdrag is due to the relative motion between the yarn element and the surrounding air. It does not act along the same line as the velocity vector because of the airflows caused by the pumping action of the bobbin and yarn [1]. The centrifugal force acts along a line in the horizontal plane that passes through the center of rotation of the yarn element. This may or may not be congruent with the center of rotation of the bobbin. The

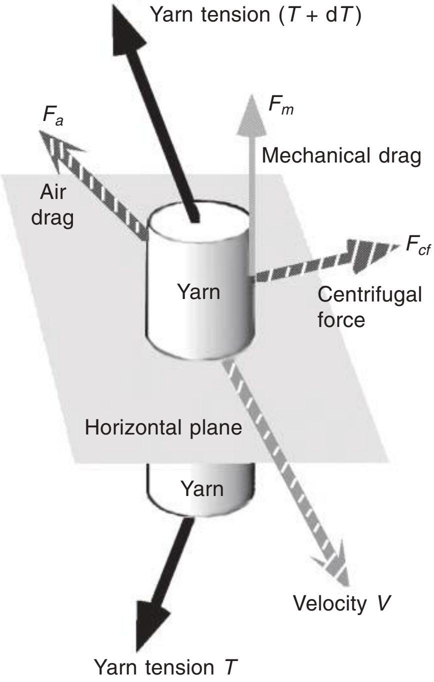

Fig. A9.5 The central zone of a balloon mechanical drag force, F_m, arises when the hairs protruding from the yarn element lash some machine part such as a separator plate, or when there is shear in the airflow. This produces minor periodic, false twist torques as repeated contact is made. The force system comprises components from the cross-hatched force vectors shown. The yarn element tilts and twists to balance the system, as sketched in Fig. A9.6.

Effects of tension, twist, and mechanical abrasion can change the condition of the yarn and alter the airdrag characteristics and perhaps the propensity to react to mechanical disturbances, such as contact with separator plates. The magnitude of these various components varies from one level to another because of the changes in radius, linear speed, airflow, and physical condition of the yarn. The shape of the yarn in the balloon is curved in three-dimensional space; also the gradients of tension, torque, and geometric attitude vary from level to level within the balloon. The varying population of fibers in the yarn being spun produces varying linear densities and amounts of hairiness, and there are long-term variations in airdrag that alter the tension patterns in the balloon [2]. These, of course, influence the end-breakage rates.

A real balloon is not confined to a rotating plane as was earlier assumed. The effects just discussed cause it to spiral, and if we use a rotating plane in any mathematical model, we can use it only as a reference. Thus, the real balloon rarely fits the simple theories; comprehensive equations of motion are needed. These give a better fit but they are not easy to manipulate without a computer and even these sophisticated programs do not completely account for all the vagaries of the balloon.

The next step is to consider events with such a reference. Plane OP*Tr* in Fig. A9.6(a) is assumed to rotate at the speed of the traveler about OP, and yarn in the balloon does not necessarily even touch it. (*Tr* is used rather than T to avoid confusion with tension.) Yarn streams behind the winding point due to the frictional forces and any element above the traveler lags. For example, an element at B lags the traveler by ϕ, with the yarn taking up an angle α, to a vertical plane OPBQ that passes through the segment being considered. Some drag may be from mechanical friction with

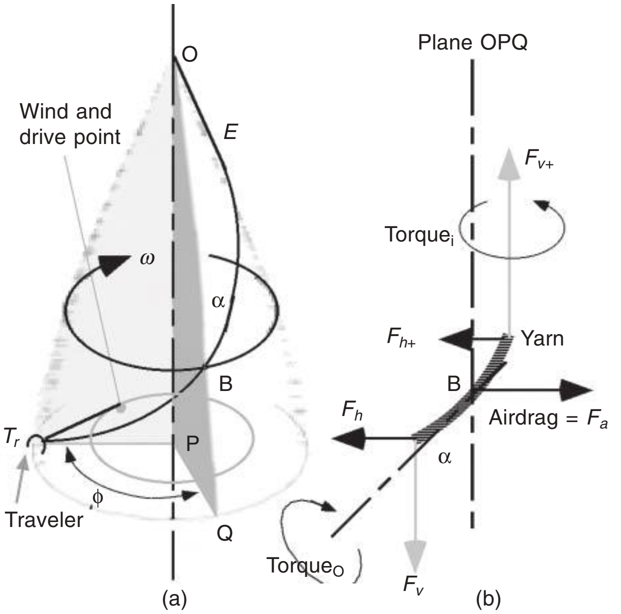

Fig. A9.6 A non-plane balloon

machine components, and there is an airflow caused by the moving parts. However, for the moment, we will deal only with airdrag caused by the motion of yarn through a fixed environment. Clearly there are three components in directions: (a) tangential to the locus of the element concerned, (b) vertical and parallel to OP, and (c) horizontal and parallel to QP.

A9.5.2 Airdrag

Airdrag is a function of fluid friction caused by the yarn moving relative to the air. McAdams [3] quotes the Fanning equation, which indicates that drag is proportional to the square of the relative linear velocity and is a complex function of Reynolds Number.[2] Figure A9.7 is based on McAdams' data which refers to flow in pipes but is often used for fluids flowing outside, but parallel to, the pipe axis. Our case involves hairy yarn and the hairs stream behind the main body almost like a comet's tail and affect the coefficient of airdrag. The relative airflow is usually neither parallel nor perpendicular to the comet's tail. The tail is oriented away from the line of motion because the hairs are subject to centrifugal as well as airdrag forces.

In calculating Reynolds Number for airplane wing sections and the like, the typical dimension normally used is the chordal width or length of the streamer rather than the thickness. Other researchers use results from flow perpendicular to the yarn, and the resulting graph has a somewhat similar shape but a different scale. The 'comet tail' of fibers is thought to have a significant effect on airdrag in ballooning. Some of the yarn near the top operates in the laminar region, with high drag coefficients. Other parts operate near the equator in the turbulent region with lower drag coefficients, and intermediate parts operate in the unstable region with variable drag coefficients. The point of the diagram is not the friction factor, but the range of operating conditions involved and the instability around 10^3 to 10^4 Reynolds Number. Fortunately, the highest drag coefficients occur at small radii and thus have only a small effect. Figure A9.8 demonstrates differences in the lag of the yarn due to airdrag. Not only do the theories give differing results for the portion of yarn below the equator, but experimental data show that considerable variation is possible. Most theorists assume the yarn to

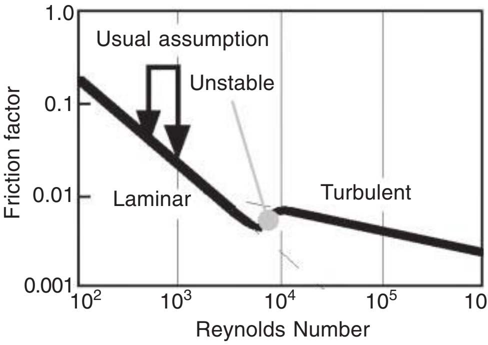

Fig. A9.7 Airdrag coefficient

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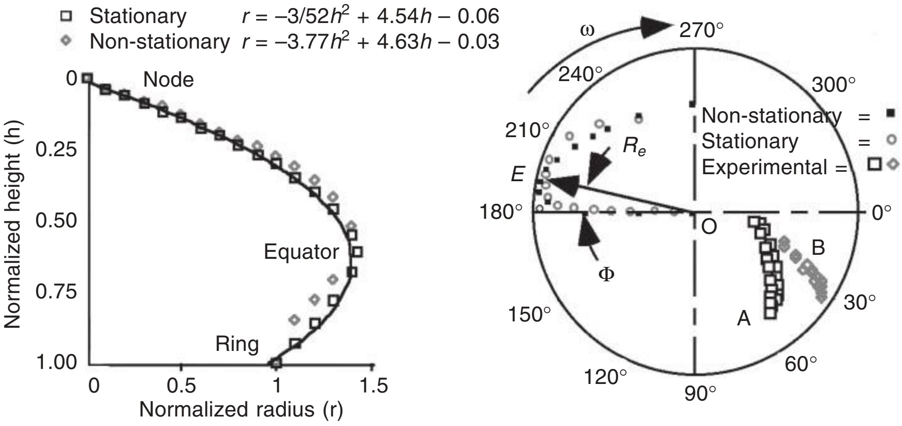
[2] Reynolds Number = $\rho VD/\zeta$, where ρ = air density, V = relative velocity, D is a typical dimension, and ζ is the viscosity of the air. It is the ratio of viscous and inertia forces; at a critical value, the flow changes from streamline to turbulent.



(a) Elevation (b) Plan view

Fig. A9.8 Radius profile of a balloon

be a thin cylinder of yarn of diameter d, and calculate Reynolds Number and drag coefficient (C_d) accordingly. If the length of the hairs streaming behind the yarn is used rather than the yarn diameter, the Reynolds Number spans a range that includes laminar, unstable, and turbulent regimes.

A9.5.3 Balloon theory relating to the central section

Batra *et al.* [4,5] quote the basic equations of motion of a quasi-stationary balloon, the adjective 'stationary' referring to the fact that they assumed the yarn was stationary relative to a rotating plane of reference. The plane of reference included the axis of rotation of the bobbin, and rotated about that axis. A balloon node was at the pigtail guide situated on the axis, and the center of the ring was also situated on the axis. The yarn in the balloon was treated as a quasi-stationary object with respect to the traveler and then the mathematical description was boiled down to a series of differential equations amenable to solution. The vector equation is:

$$\text{Absolute acceleration} = A_0 + A_r + 2\omega \times v_r + \omega \times (\omega \times s) + a \times s \qquad \text{[A9.9]}$$

Some of these terms can be eliminated and the following comments apply: (a) the acceleration of the origin at the pigtail guide is zero, (b) the first term (A_0) is zero, (c) the second term (A_r) is negligibly small, (d) the third term containing the Coriolis acceleration is negligible, and (e) the last term is assumed to be zero because it includes the factor a, which is the angular acceleration of the balloon. Thus, the equation reduces to absolute acceleration = $\omega \times (\omega \times s)$, which can be translated as centripetal acceleration acting along the radius of rotation of an element = $-\omega^2 r$. Furthermore, the rate of tension change along the rotating yarn is $-n\omega^2 r\mathrm{d}r$, where n is the linear density of the element, ω is the rotational speed in radians per second, r is the radius of the element, and dr is the incremental change in radius over the element considered. From this, Batra *et al.* say that the tangential component of air-drag is negligible and that the tension in the yarn in the balloon is:

$$T_o - T = n\omega^2 r^2/2 \qquad \text{[A9.10]}$$

As the yarn is made heavier, the balloon enlarges, the spindle is run at a higher speed, the traveler weight increases, or any combination of them, the yarn tensions increase. A curiosity is the resemblance to the equation met in rotor spinning (centrifugal force $= n\ \omega^2 r^2/2$); the yarn inside the rotor rotates within a plane and in a balloon it occupies a three-dimensional space.

The validity of using a stationary model is disputed by Lisini *et al.* [6] for cases where the balloon shape is subject to rapid variations. They point out that in ring spinning, the movement of the ring rail causes changes in traveler speed and this undermines the assumption of constant rotational speed of the inertial frame. The coil of yarn deposited on the bobbin forms a spiral rather than a circle. Relative motion between the traveler and the wind-on point is caused by changes in length and attitude of the yarn between the wind-on point and the traveler. These changes are related to the alterations in length in the yarn forming the balloon above the traveler. Consequently, the traveler speed tends to change cyclically, but the variation is small. Thus, it is true that an error is involved in using the traveler to anchor the inertial frame even if the effect is small. These authors favor the finite element method of calculation over the iterative Runge-Kutta solution. (The finite element theory assumes that the yarn is made up of very small straight segments.) A comparison of the two methods shows that they give similar results above the equator of the balloon, as shown in Fig. A9.8(a). However, the plan views in the top left quadrant of Fig. A9.8(a) make more visible the differences between the two theories relating to the yarn lying below the equator.

It is interesting to note that the shape of the elevation of the balloon is very near to parabolic, confirming the data of the present author. The angular lag of elements in the balloon relative to the traveler varies in the two theoretical cases. The use of stationary solutions greatly simplifies the analysis but at the cost of some accuracy. Theoretical models involve non-linear equations and a computer is required to obtain a solution in a reasonable time span. However, the solution is only as good as the assumptions made in respect of airdrag, coefficients of friction, and the flow of torque and tension in the system [2].

At point B back in Fig. A9.6, there is a system of forces that includes those shown, but there are others perpendicular to the plane of the paper. Curvature of the element results from the application of these forces. The normal to the yarn at B no longer intersects OP. The center of curvature is in space outside the balloon. Tension gradients across the yarn segment make the forces at the upper terminal of the segment differ from those at the bottom one; the segment is forced to tilt until the moments are in equilibrium.

At different heights above the traveler, the inclination of the yarn, α, changes with respect to the center line. The element of yarn shown does not lie in the plane of the paper but at an angle that varies. Yarn tension is the resultant of all the components acting on a segment terminal and as α alters, the yarn tension changes. There are sometimes multiple solutions to the equations under unstable spinning conditions. Instability is often the result of the use of too light a traveler.

Figure A9.8 also shows a plan view of some yarns in a balloon. As previously mentioned, the top left quadrant contains theoretical data based on the work of Lisini *et al.* [6]. An adjustment was made to the angular positions of the stationary and non-stationary curves to bring them as nearly as possible into congruence. It is interesting to note that there is little difference between the results for that part of the yarn that lies above the equator (which normally includes the majority of the yarn in the balloon). In the bottom right quadrant there are two sets of new experimental data gathered within a few seconds of each other, with the spinning machine running at constant speed and a fixed rail height. The data in the two quadrants should not be compared because different conditions prevailed, however curves A and B in the bottom right quadrant should be nearly identical but they are not. Obviously, variations in the yarn altered the shape of the balloon. One candidate for suspicion is the airdrag coefficient, which is normally modeled as a constant for a given yarn.

A.9.5.4 Balloon control rings

The purpose of a balloon control ring (see Fig. A9.9) is to reduce yarn tension; the device works for a range of conditions but it is not universally effective. Balloon control rings cannot be effective under the conditions of incipient collapse and they are rarely used for fine counts. From a practical point of view, the surfaces can become poisoned by accumulations of fiber finish or oligomer and these accumulations lead to difficulties in spinning. The control rings also impose an extra drag on the yarn that increases the spirality with effects similar to those discussed above. The control rings also tend to make the yarn more hairy.

As a first step, one can use a fairly superficial explanation of their mode of operation. The control rings reduce the surface area of the balloon. When the spiral angle of the yarn in the balloon is small, the yarn tension is roughly proportional to the surface area of the balloon. Thus, the control rings pinch the balloon to form a waist, which reduces surface area and thereby reduces the yarn tension. Mathematical models confirm that control rings reduce the tension for stable balloons and promote stability; the rings also reduce the destabilizing influence of slubs passing through the balloon.

The reduction in yarn tension permits the use of higher speeds, weaker yarns, or both. A higher speed improves productivity and permits the spinner to spread the fixed costs over a larger poundage, which reduces the cost/lb. The possibility of using

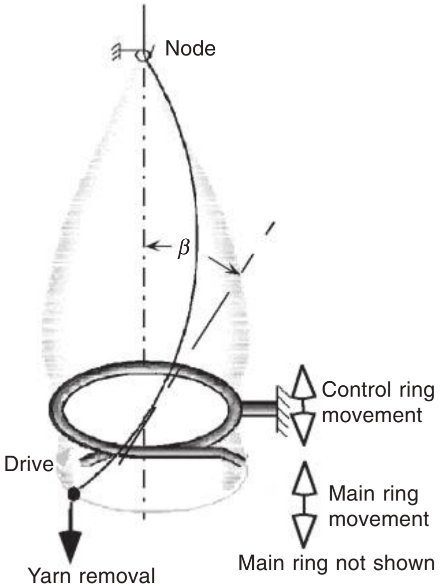


Fig. A9.9 Balloon control ring

weaker yarns means that, sometimes, lower twist can be used and this also increases productivity. Advantages are balanced by disadvantages. Summarizing the problems with balloon control rings: (a) they make the yarns more hairy, (b) they accumulate spin finish, (c) they add slightly to the cost of the machine, (d) they interfere with the doffing and piecing operations, and (e) they produce a torque in the yarn within the balloon. Of these, the first two are the most important.

A9.5.5 The traveler

The balloon size and shape vary as the yarn builds up on the bobbin, and this is associated with changes in yarn tension. Consider the forces acting on the traveler as depicted in Fig. A9.10. Centrifugal force, F_{ct}, acts through the center of gravity of the traveler and is balanced by the resultant yarn tension, F_y, also there is a reaction force, F_r, acting between the ring and the traveler. There is a sliding contact between the ring and traveler at A, and the friction due to this exerts a drag force which causes the traveler to lag behind the bobbin. The beauty of the system is that the speeds adjust automatically to the prevailing conditions; no mechanical complications are needed.

Sliding contact can cause serious wear on the traveler and the life of the traveler is then measured in days. A normal practice is to judge the wear of the travelers by the number that are burned. According to Grishin [7], every 10% of burned travelers in the population increases the ends down rate by 5 per 1000 spindle hours. There is also some collateral damage to the ring and, over a much longer time, the ring too becomes unserviceable. For no damage, the vector sum of F_y, F_r, and F_{ct} should be zero, but if we were to run under those conditions there would be traveler instability.

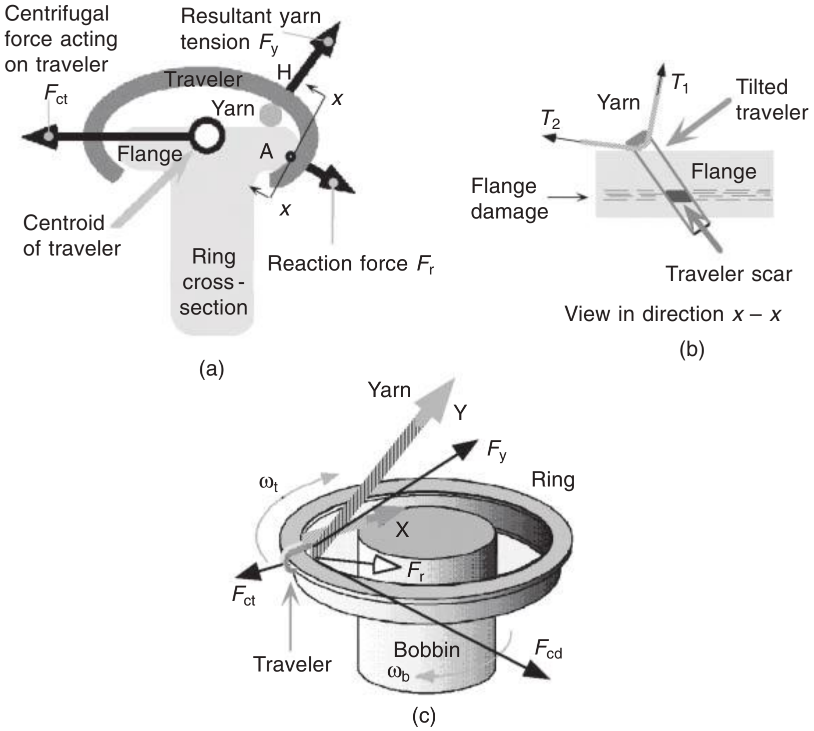


Fig. A9.10 Ring and traveler

F_y varies during the bobbin build and, if contact is to be maintained, the traveler weight has to be sufficient to control the tension over the whole range of conditions. The reaction force, F_r, is strongly influenced by the traveler mass, M, and consequently the tension, T_B, is also dependent on it. Traveler mass has to be changed as the yarn count is altered within the normal spinning range (M/n is usually kept constant). Adjustments also have to be made for changes in ring size and shape.

A properly run-in ring will last for years, whereas a traveler might only last, say, 10 days. The coefficient of friction between the two metal surfaces changes and this influences the drag force. The tensions T_1 and T_2 (Fig. A.9.10(a)) cause the traveler to tilt and the angle of tilt changes with balloon geometry. The reaction force is sufficient to cause transient metal to metal seizures of the poorly lubricated surfaces, although fiber debris and particles of fiber finish offer some lubrication. As a new traveler is put into use, there is a small contact area that runs at a high local temperature and creates fairly rapid wear of the surfaces. The damaged surface of the traveler is concentrated in a band and Fig. A9.10(a) shows a scar typical of a used traveler. Wear causes the area of contact to increase sharply at first, but the rate of wear then abates as the scar on the traveler grows. As the scar widens, the centroid of the reaction moves and changes the attitude of the traveler. Eventually, the tilt becomes sufficient to cause it to be thrown off. Before that happens, however, the yarn tensions become sufficient to cause a higher end-breakage rate than normal. It is important to change the travelers in timely fashion.

If moments are taken about A in Fig. A9.10(b), the moment due to the resultant yarn tension must balance the moment due to the centrifugal force acting on the traveler. Any change in the geometry of the traveler alters the position of the centroid and causes the traveler to adjust its angle with respect to the horizontal until balance is achieved. Various factors determine the forces described. For a given ring diameter, the centrifugal force acting on the traveler is determined by its mass and speed. The linear density of the yarn, the balloon geometry, the rotational speed of the balloon, and the reaction between the ring and traveler define the resultant yarn tension. For a given speed, the centrifugal force acting on the traveler is theoretically constant whereas the forces transmitted by the yarn vary as the bobbin builds. Thus, the angle of tilt taken up by the traveler varies cyclically. With a poor design of traveler, slip-stick conditions can lead to an unstable porpoising as it rides the flange and this either causes an end-break or throws off the traveler.

Because of constraints in mass and size of the traveler, there is little space available for the yarn and it could become trapped near H. Consequently, the shape of the traveler is important and each type of yarn not only needs a traveler that has the required mass, but one which provides adequate space for the yarn. The yarn can also become trapped if the traveler tilts too much. If the traveler is too heavy, the friction between the ring and traveler soon destroys the traveler and might damage the ring. If it is too light, the balloon can collapse and cause high tensions with all the problems described earlier. Stability of the yarn package becomes a problem if the winding tension (related to traveler weight) is reduced too much; soft-wound packages occupy too much volume and are liable to become damaged in subsequent handling.

Frazer [8] illustrated the instability of a balloon when the traveler is too light. At low traveler mass, there is an ambiguous tension at radius r, as indicated by the leftmost dark curve in Fig. A9.11. In that case, three tensions are theoretically possible at the lowest traveler weight shown. The other dark curves show stable relationships between the lay point radius and tension.

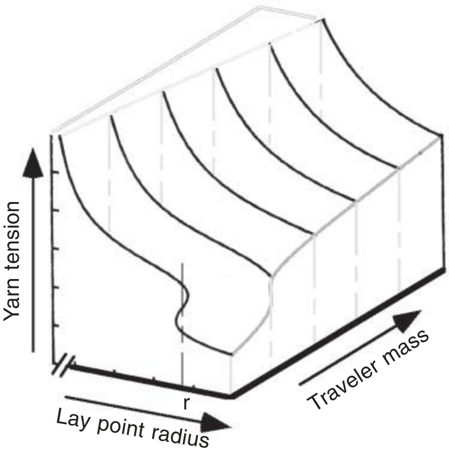


Fig. A9.11 Effect of traveler mass

A9.5.6 The lower portion of the balloon

The factors determining the resultant force (F_y) can be visualized in three dimensions as indicated in Fig. A9.10(c). It will be seen that F_y is the vector sum of the forces in the upward pointing section of yarn at Y and the roughly horizontal section shown at X. The resultant force is balanced by the system containing: (a) centrifugal force acting on the traveler (F_{ct}), (b) the reaction between traveler and ring (F_r), and (c) the drag force, F_d, acting tangentially to the ring. The drag force (F_d) is the result of the traveler sliding on the ring at a rotational speed of ω_t. The bobbin (shown in truncated form) rotates at ω_b. Reiterating previous statements, changing the mass of the traveler alters the yarn tensions. Indeed this is the only practical way a user can adjust the tension, given that the yarn count, balloon geometry, speed, and machine configuration are fixed by design or commercial considerations. The centrifugal force acting on the traveler is $F_{ct} = \omega^2 r_t M$, where M = mass of the traveler, r_t = radius of the locus of its centroid, and ω = rotational speed. The angles taken up by these portions of yarn are critical in determining the tensions T_A and T_B, which act at X and Y respectively. These tensions, in turn, help to determine the rest of the tensions in the balloon. There is a relationship between them that is dictated by the friction forces between the yarn and the traveler. Using Amonton's Law as an approximation, the relationship is:

$$T_A = T_B\, e^{\mu\Psi} \qquad \text{[A9.11]}$$

However, any assumption that the coefficient of friction is a constant is imperfect. The coefficient varies with yarn hairiness, finish, and possibly rh. Another source of possible error in Equation [A9.11] arises from the fact that the yarn is bent to a small radius of curvature when passing round the traveler. If the radius is too small, bending stiffness begins to play a significant part and the normal force between the yarn and the traveler will be higher than estimated (which results in higher drag force). Thus, one might expect deviations in winding tension from those predicted by some mathematical models. Also, the greater the energy loss in overcoming the drag force acting on the traveler, the less is the energy available to inflate the balloon.

During spinning, the yarn winding point is controlled by the ring rail motion. There is a fairly short oscillation period as individual cones of yarn are laid on the bobbin. Also, there is a much longer period as the bobbin is built from bottom to top, laying new cones over each of the previous ones. Each chase builds a new layer of yarn and requires a small change in mean height of the ring rail. The upwards rate of change of the rail position during the chase is usually different from the downward one; this is to create an interlocking yarn package structure.

A vector component of the tension along AB_o in Fig. A9.3 helps to balance the centrifugal force acting on the traveler. Let this force be $T_B \cos \alpha$ and let $F_d = k_b \mu F_r$ (where k_b is a factor to take into account the forces omitted and F_r is the reaction to the forces acting on the traveler). The appropriate subscripts should be added. If the yarn above the traveler is nearly upright, k is almost 1.0. Substituting for F_d and $\cos \alpha = r_{wo}/r$, we can write in functional form:

$$F_r/T_B = f\{(r_w/r_r), k_b, \mu\} \tag{A9.12}$$

The radius r_w varies from r_{B1} to r_{B0}; k and μ vary also. This relationship implies that as the ring rail moves, F_r/T_B changes. The tension T_B is related to the yarn tension above the traveler and it increases to a local maximum at the top of the chase where r_w becomes a minimum. There is a limiting size to the bobbin diameter. As stated earlier, the bobbin size is normally about 40% of the ring size, because winding yarn on smaller diameter bobbins creates excessive yarn tension. Also, the bobbins are slightly tapered. As the bobbin builds, the wind-on radius, r_w, is normally limited between about $0.4r_r$ and about $0.9r_r$.

For continuous control, $F_r > 0$ if undesirable instability is to be avoided. The energy available to the system = $T_w r_w \omega$, where the subscript w refers to conditions at the winding point. Except under the unlikely condition where tension $T_w r_w$ is invariable and ω changes significantly, any changes in r_w are associated with changes in energy available. Because of the changes in yarn angles at the traveler, the passive tension gradients can change markedly with changes in r_w. Under stable conditions, an increase in r_w is associated with a drop both in tension and energy available. The tension variations arising from the ring rail movement, which controls the chase, are measured at frequencies of less than 1 Hz.

A9.5.7 The upper zone of the balloon

Yarn tension between the node at the pigtail guide and the front rolls of the drafting system is a critical factor in determining end-breakage rates in spinning. The friction of the yarn running through the pigtail guide situated at O in Fig. A9.12 affects the tension and twist of the yarn. As mentioned earlier, $T_o \approx T_i e^{\mu\varepsilon}$. If the guide is off-center, or the yarn flow approaching the guide is not coaxial with the center line of the spindle, the angle ε varies within each revolution of the yarn in the balloon, with the result that T_i varies also. The point at which the strand is at its weakest usually lies in the twist triangle and T_i must be kept below that breaking strength. The term strand can mean either the yarn or the fiber flowing through the twist triangle. Not only is the value of T_o important, as previously discussed, but so is the angle ε because, if the variation is large, then $\omega^2 r_r$ has to be kept lower to compensate (r_y is the yarn radius in general). The tension variations from this source appear at the frequency of the rotation of the balloon (say, 200–300 Hz).

Not only is there a tension gradient in the yarn passing through the pigtail guide, but there is also a torque gradient. The normal force acting on the yarn at the contact point produces a friction drag force, which has components (a) along the yarn, and (b) tangential to a normal cross-section of yarn. The former produces tension and the latter produces torque. It can be argued that:

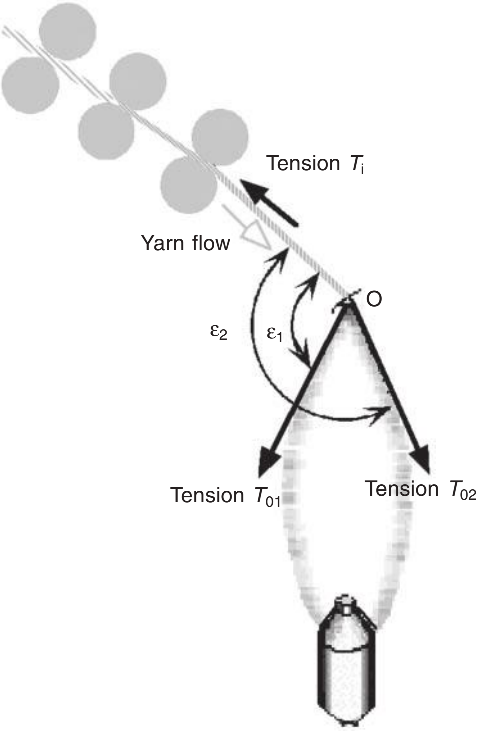


Fig. A9.12 Upper portion of the balloon

$$\tau_o \approx \tau_i e^{\mu\alpha} \tag{A9.13}$$

The symbol τ denotes torque and the other symbols have their previous meaning. If, for example, we assume that $\mu\varepsilon$ varies between the limits of 0.04 to 0.12 radians as the package builds up, then the ratio of torques would vary between 1.04 and 1.128. In other words, the average twist in the yarn above the pigtail guide would, in that case, be reduced by 4% to 13% compared to the value just below the guide. The twist is reduced in the very place where it might be an advantage to increase it. Attempts to use rotating guides to overcome the problem have not been successful; this is partly due to the extra costs involved and partly to the difficulties in piecing.

False twist in the yarn leaving the pigtail guide is of some importance. The resultant of the input and output yarn tensions on either side of the guide has a horizontal component that presses the yarn against the inside surface of the pigtail. The yarn might roll, as well as slip, on that surface and the rolling action would produce false twist between the drafting system and the pigtail guide. Total twist in this region is the sum of the real and false twists but the false twist above the guide is negative. The net effect is another small reduction in twist in the yarn coming away from the twist triangle. This component changes cyclically.

The twist triangle geometry is determined by the net twist, which affects a number of yarn properties such as hairiness and bulk as well as the end-breakage rate. If there are surges of twist at this point, then the balloon will be disturbed, the tension will fluctuate, and the yarn properties will vary accordingly. The surges are similar to those sometimes found in rotor spinning at the navel.

Evidence of such phenomena has been gathered by illuminating the balloon with horizontal thin sheets of light at different levels. The normal assumptions imply that the loci of the small segment of yarn are circular. In some cases seen in industry, the locus of the yarn elements just below the pigtail guide is badly distorted. Figure A9.13 shows a modest distortion arising from the pigtail guide, but it fades at distances remote from the guide. There are also distortions from other causes. The strata designated B through E were between the pigtail guide and the top of the bobbin. The stratum A was above the guide in the secondary balloon and the stratum F was below the top of the bobbin. The balloon control ring did not operate and the photographs were taken with the ring rail at a constant position in the chase.

A9.5.8 Stability of the speed of the yarn balloon

There is a torque generated tending to change the rotational speed of the mass of an independent element of yarn, δm, if it changes radius. As a first model, consider a yarn to consist of a series of contiguous elements like a string of beads and the length of yarn in the balloon, S, is $\sum \delta m$. If elements of yarn do not follow a circular locus, they must change speed to conserve momentum unless a pattern of forces restrains the change. Momentum of each element = $I\omega$ and $I = \delta m \times r^2 = n\delta s \times r^2$, where n is the linear density of the element. In a balloon, the elements of yarn are not independent, but a change of radius still produces a system of forces tending to change the speed of the element and of its neighbors. A reduction of radius causes the elements to speed up and an increase in radius slows them down. Another cause of change arises from the lag of one element relative to another due to drag. Any change in drag alters the transient speed of the element with respect to the lower portions of yarn in the balloon. Once the stability of the balloon is disturbed, transient changes in speed and shape of the balloon are inevitable. These effects are not normally large unless the balloon is in or near the unstable region.

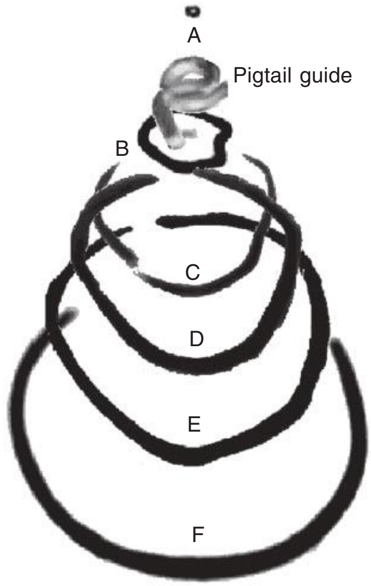


Fig. A9.13 Loci of balloon elements

A9.6 Balloon collapse

A9.6.1 Energy variation in the balloon

The relationships between the forces acting in a balloon are complex and distinctly non-linear. Most often, a perturbation causes an energy change that restores the system to its normal state, but under certain conditions the system is unstable. The system can go from one energy equilibrium state to another. Some of these energy states are stable within certain confines, but the operating zone can be induced to move from one local minimum to another. This is illustrated diagrammatically in Fig. A9.14, where the local equilibrium is illustrated as moving from B to A.

Consider an example. A perturbation in kinetic energy available to the yarn in the balloon usually leads to a change in radius of the centroid and the yarn tension changes in sympathy. If there is a change in mode, there is also a change in height between nodes. The yarn is no longer roughly parabolic but assumes a sinuous shape. There are a variety of balloon shapes in which the balloon contains the same amount of yarn but has a different position of the centroid. If the perturbation acts perversely, the effects permeate the system. If, for example, there is a decrease in yarn tension at the surface of the bobbin due to a change in yarn shape similar to that discussed, there is a reduction in energy available. If the reaction force between the ring and traveler increases because of the reduced tensions, more energy will be dissipated due to friction. This leaves even less available to the kinetic energy of the main balloon, which then causes the balloon to deflate. The reduction in balloon diameter further reduces the tensions and the system is seen to be unstable.

A9.6.2 Vector analysis

In standard ring spinning, where the machine designer does not intend collapse, the event causes difficulties. For example, when the balloon is long, a portion of it sometimes temporarily collapses on the top of the bobbin. When conditions verge on instability, the balloon collapses periodically as the wind-on point approaches the top of the bobbin. Often the result is that there is an end-break (which has economic repercussions) or there are periods of increased yarn hairiness while the balloon remains collapsed (which has quality repercussions). With coarse counts, the balloon may reach a size that is over double that of the ring diameter before collapse occurs. With a fine yarn, the balloon might collapse at a diameter roughly equal to the ring size.

Let a yarn consist of a series of small elements and, for the present purpose, consider the middle element in a chain of three. Figure A9.15 shows the forces acting

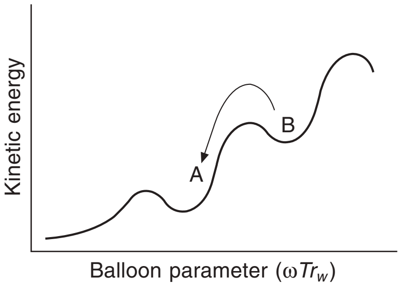
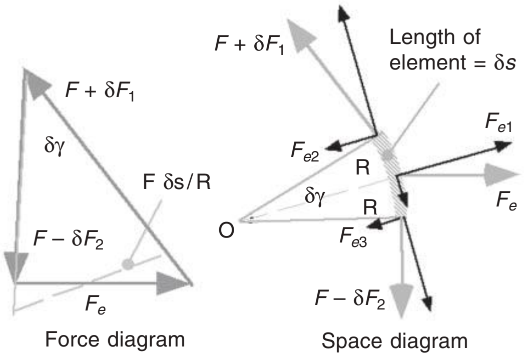
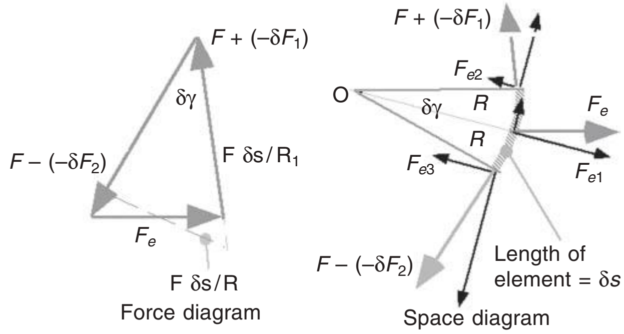


Fig. A9.14 Various energy states



δF and δγ exaggerated for clarity

(a) Case 1



δF and δγ exaggerated for clarity

(b) Case 2 for negative δF

Fig. A9.15 Forces on an element of yarn

on the subject element of yarn (shown shaded in gray). Before discussing the meanings of these, let the symbols be explained. For example, in diagram (a), a force of $F + \delta F$ is applied by the element immediately above it, and another force of $F - \delta F$ is applied by the element immediately below. This is regarded as a positive tension gradient. The radius of curvature of the element is R and the forces all lie in the plane of curvature, but they have been rotated about the element to make F_e horizontal in the diagram.[3] The vectors do not necessarily lie in the plane of the ring or in one including the spindle axis. The external forces acting on the element are almost horizontal. External forces are the centrifugal force acting on the element and the airdrag forces. The latter is true only if any secondary airflow produces negligible airdrag on the element. Thus by rotating the plane about a vertical axis to make F_e parallel to the resultant of the external forces, the element is brought into its correct attitude in the balloon.

In Fig. A9.15(b) the tension gradient is negative (the value of δF is negative) and the attitude of the element has changed in consequence. Resolve the principal

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[3] Constraints are (a) $F_{e1} = F_{e2} + F_{e3}$ and (b) the sum of the moments about any point on the element has to be zero (which implies that $F_{e2} \neq F_{e3}$). The moment arm about which F_e acts is not $\delta s/2$, unless F_e and F_{e1} are coincident.

components shown in gray. In the right-hand diagrams in the direction O–F_{e1}, the left facing components F_{e2} and F_{e3} (shown in black and facing leftwards) are unequal. Consequently, there is a moment tending to tilt the element, which should be balanced by the moment generated by the application of F_e. Thus, the tension gradient along the yarn within the balloon affects the attitude of the element with respect to its neighbors. Clearly, F_e is greatly influenced by any change in the radius of curvature. The behavior of the balloon is influenced heavily by changes in radius of curvature and tension gradient.

Equilibrium of the balloon occurs only when the outward forces balance the inward ones. The outward forces are a combination of the centrifugal and drag force acting on the yarn element. Drag forces are mostly tangential to the locus and have little direct effect on this balance when the balloon is fairly upright. However, collapse is initiated in the region just above the ring where airdrag causes the yarn in the balloon to incline almost to its maximum extent. A rough approximation in that zone is to treat the plane of curvature as the same as that of the ring, which implies that the radius of curvature is smaller than elsewhere in the balloon. The consequence is an increased tendency to reduce the radius of the locus in the lower regions near the traveler.

A9.6.3 Collapsed balloon spinning

It is fairly obvious that if the radius of the yarn balloon could be reduced as a practical proposition, the yarn tensions could also be reduced. In long-staple spinning this is an option, but in short-staple work it is not. Generally, collapsed balloon spinning is used for heavy, long-staple yarns that are capable of withstanding high tensions. The friction tends to make the yarns hairy. The winding tension in such cases is partly determined by the friction between the sliding yarn and the machine surfaces. It is also partly determined by the end conditions, which are determined by the traveler weight and other parameters already discussed. Lubrication of sliding surfaces is also a factor.

If the tensions are properly adjusted, it is possible to make the balloon collapse, or run at a reduced size, as shown in Fig. A9.16. Although the centrifugal component is much reduced by this, there is now a significant frictional drag as the yarn passes over the surface of the spindle or crown. The frictional drag may be calculated approximately from Amonton's Law using Equation (A9.13); this implies that the ratio of tensions is a function of the angle of wrap and the coefficient of friction. For the system to pay off, the increase in yarn tension due to friction by the above mechanisms must be less than the increase caused by allowing the balloon to inflate. Usually, a crown is mounted on anti-friction bearings on top of the spindle to reduce the frictional forces. However, the yarn still has to slide over the crown in a direction along the length of the yarn.

A9.6.4 Unwinding

The ring bobbins provide only temporary storage and the yarn has to be unwound from them in the so-called winding process as was described in Chapter 9. Winding machines usually pull yarn over-end from a stationary package. The package from which the yarn can be removed might be a ring bobbin, cone, or cheese, although the most common is the ring bobbin. The yarn is caused to balloon by the motion of the

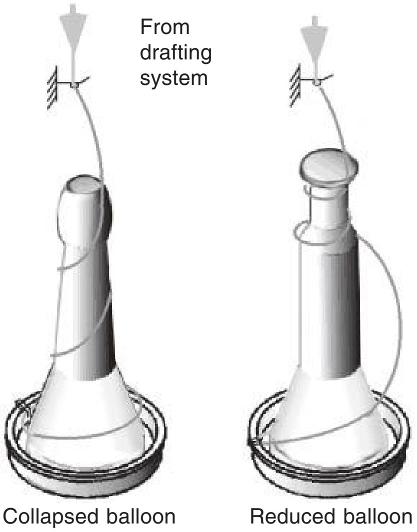

Fig. A9.16 Balloon collapse

wind-off point on the surface of the package. The take-off speed and the radius at which the departing element of yarn is removed from the bobbin determine the rotational speed of the balloon. Of necessity, the rotational speed is variable and the structure of the package causes the take-off point to oscillate rapidly. The balloon changes height, diameter, and shape as a result, and a chaotic balloon is created. There is usually no ring and traveler to help smooth out the fluctuations. Any instantaneous view of the yarn in the balloon shows a multi-noded sinuous shape rotating about the package axis.

The presence of ballooning forces is important because they hold the yarn clear of the surface of the package. This avoids the removal of neighboring coils of yarns that would result in tangles being formed. It also reduces the amount of hairiness created by the over-end unwinding process.

A9.7 Balloons in two-for-one twisting

A9.7.1 Tension control by the use of cylindrical surfaces

Two-for-one systems involve the high speed removal of yarn from large diameter packages stored inside the balloon. Consequently, the shape of the balloon has to be controlled to prevent the yarn just removed from rubbing the surfaces of the package(s). The tensions have also to be controlled because of the high speeds and diameters involved. Often there are two coaxial balloons involved and these have to be kept separate. For these reasons the balloons are frequently contained within cylindrical cans which act rather like balloon control rings.

A9.7.2 Tension control by friction devices

An absence of any frictional type of control leads to balloon instability and it is normal to use a spring-operated tensioner or a governor operated by centrifugal forces to help control the tension. Changes in yarn length within the balloon are accommodated by a disk designed to dynamically store limited amounts of yarn. An extreme and undesirable case is that of the chaotic balloon just described in Section A9.6.4, which lacks any such a control.

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Appendix 10

Advanced topics VIII: Topics in rotor spinning

A10.1 Brief history of open-end spinning

The idea behind open-end (OE) spinning is almost as old as history itself. Farmers twisted straw into binders for stooks of corn and wheat by continuously adding new straw to the end of the binder and twisting it into the existing structure to make it ever longer. The industrial revolution saw some clumsy attempts at a mechanical solution, but it was not until the twentieth century that elegant solutions began to appear [1]. Derivatives of two of the systems then envisioned have become established, namely air-jet and rotor spinning.

Early patents by Götzfried [2] disclosed the idea of using an air vortex to assemble fibers and twist them into yarn. Lord [3,4] worked on such vortex systems but fiber losses and yarn structure were unacceptable; the method was then commercially unattractive, despite the simplicity of the device. A design where the vortex was confined to the fiber assembly was offered for sale but did not achieve significant market penetration. It was left to Nakahara [5], Morihashi [6], and others to develop a system that used air-jets to twist but allowed the fiber assembly to be controlled by other processes. Although the idea started out as a sort of OE spinning, the successful system lost the essence of OE spinning because there was no longer an open end, merely a very ingenious way of manipulating twist and yarn structure. This was described in Chapter 10 and it is merely a matter of peripheral interest in this context.

The origins of rotor spinning were in the work of Berthelson [7] in 1937 and Meimberg [8]. In the early 1960s, VUB [9] in Czechoslovakia, the Shirley Institute [10] and UMIST in Manchester, UK, SRRL in New Orleans, USA, and perhaps others, were experimenting with rotor spinning. VUB produced a working prototype designated the KS200, which was the predecessor to the BD200, which was offered for sale in 1966 at $200 per spindle. Eventually, the Czech BD200 gained a good market share.

In the very early days, there seemed to be a limit of about 20 000 r/min in rotor speeds, because of bearing design. Also, calculations of that time suggested that a prudent speed limit might be about 25 000 r/min for a 3 inch (76 mm) diameter aluminum rotor with air pumping holes. (The pumping holes introduce stress concentrations that reduce the strength of the structure.) A number of experimenters found that rotors deformed or even burst when oversped. Somewhat later, Landwehrkampf [11], who was concerned with large rotors for long-staple rotor spinning, opined that plain 120 mm (4.75 inch) diameter rotors could run at 25 000 r/min. In a study by Wunsch [12] and Kerr [13], the energy consumption of a plain disk was found to be proportional to $D^{3.8}\ \omega^{2.5}$ and this implies that large rotors running at high speed will get very hot. Landwehrkampf published some curves that showed a 5.46 inch (138 mm) rotor running at 20 000 r/min required nearly 300 watts and approximately 1.5 inch (38 mm) rotors required about 120 watts to run at 80 000 r/min. However, by the time losses are included, a frame of 100 large rotors running at 20 000 r/min seemed to require well over 30 kW. The data of Landwehrkampf did not fit those of Wunsch and Kerr but that was not surprising because of the differences in shapes of the rotating member. For various reasons, the long-staple rotor spinner did not succeed commercially and it was the short-staple version that made a remarkable impact on the industry. From a consideration of the foregoing, it was estimated in the 1970s that a machine of 300 rotors of 1.5 inch (38 mm) diameter running at 100 000 r/min would require some 60 kW. This is a very large power demand and it was clear that the rotor size had to be reduced. The size of 38 mm had been picked on the basis that the diameter of the rotor ought not to be less than the fiber length for quality reasons. This idea was proved wrong as it turned out. In 1997, 28 mm rotors could be run at 130 000 r/min (the power consumption is not known to the author) and commercial speeds ranged between 85 000 and 110 000 r/min. The reduction in rotor size has continued over two decades and it certainly has been connected with the rising power demand at the ever higher speeds. In the modern rotor machine, the temperature of air leaving the rotor is very high. How much further these trends can go is another matter.

The early experiments at UMIST [14] indicated that rotor spun yarns were weak in comparison to ring yarns. One reason was the incidence of bridging fibers that caused an enlarged population of hooked fibers in the yarn. For this reason it was concluded (wrongly) that, to make the yarn attractive to spinners, the circumference of the rotor had to be many times the fiber length, in order to reduce the proportion of bridging fibers. The elegance of the tapered rotor sliding wall, which conserves space for the assembling of fibers, was not appreciated then.

The history of ring spinning shows the difficulties of getting a new process accepted, and one can find old articles opining that ring spinning would never replace the mule. Similarly, rotor spinning took time to become established and yarn weakness was one of the reasons for the reluctance. The market then began to accept the yarn for what it was, but it still took many years before it was fully accepted [15,16]. The relatively low cost of operating rotor spinning has always been one of its main attractions although the capital cost per rotor was initially four or five times that of a comparable ring spinning machine position. Consequently, the rotor had to be run faster to reduce the capital cost/lb of yarn produced to competitive levels. It is the history of this pursuit of speed that is so fascinating. Small rotors, new alloys, protective treatments to withstand wear, and new drive systems all made their contributions. The driving force behind this was to reduce the capital cost/lb of yarn by increasing rotor speed. It was necessary to increase productivity faster than capital cost in order to achieve this. Many of the doubts and reservations of the time are well expressed in a review of rotor spinning made in 1978 [17].

A10.2 Yarn evenness

A10.2.1 Number of doublings inside the rotor

Fibers are laid into the vee-shaped collecting surface inside the rotor, and enter as a thin stream of fibers. It takes many layers of fiber to make up sufficient linear density; in other words, there are many doublings. These doublings tend to even out any short-term irregularities in the yarn and OE yarns tend to be surprisingly even. Also, there are no errors carried forward from a roving frame, and many errors created by the combing roll drafting system are smoothed. However, longer-term errors arising from the sliver still remain, and these are usually neither worse nor better than with ring yarn.

Referring to Fig. A10.1, let n = linear density of the fiber, V = velocity, M = mass flow, m = number of fibers in the cross-section, and the subscripts f and y refer to fiber and yarn, respectively. Also let ω = rotational speed in rad/sec, r = radius of collecting surface of rotor, and τ = twist/unit length of yarn.

$$\text{Mass flow/unit time at input} = M_\text{f} = m_\text{f}\, n\, V_\text{f}$$

$$\text{Mass flow/unit time at output} = M_\text{y} - m_\text{y}\, n\, V_\text{y}$$

But

$$M_\text{f} = M_\text{y},$$

from which:

$$m_\text{y}/m_\text{f} = V_\text{f}/V_\text{y}.$$

If $V_\text{f} = \omega r$ and $V_\text{y} = \omega/2\pi\tau$, then

$$m_\text{y}/m_\text{f} = 2\pi r\tau \qquad \text{[A10.1]}$$

$$= \text{number of internal doublings in the process}$$

Thus, for a 30 tpi yarn running in a 1.5 inch diameter rotor, there are approximately 140 doublings in the rotor groove. This, then, is why the short-term unevenness is so good in comparison to ring yarns.

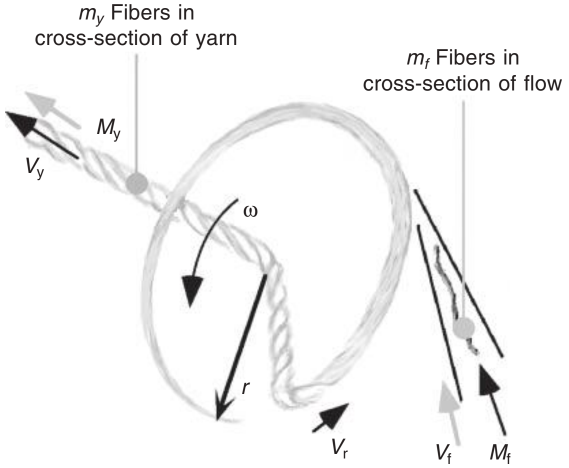

Fig. A10.1 Conservation of mass flow in the rotor

A10.2.2 Short-term blend evenness

Multiple doublings inside the rotor improve the short-term evenness and the intimacy of the blend [18]. In theory, the per unit CV of linear density of the yarn should be $\sqrt{(m_y/m_f)}$ for lengths up to $(m_y/m_f) \times$ rotor circumference. Figure A10.2 is from the work of Deshpande [19], who blended dyed viscose rayon with polyester fibers at a single passage of drawing, before spinning the blend on an OE machine. The machine used is now obsolete but the work shows that the multiple layering inside the rotor ensures a good blend. However, careful examination of Fig. A10.2 shows several spots where there are concentrations of similar sorts of fiber, and the homogeneity is not as perfect as might be hoped. Good dispersion of the components requires that the slivers be properly prepared and that the combing rolls in the OE machine be maintained and operated correctly.

A10.2.3 CV of linear density

With staple yarns, the number of fibers in the cross-section can vary considerably. If we assume that there is a Poisson distribution in this number, m_{av} is the average number of fibers in the cross-section, m is the actual number, and s is the standard deviation then:

$$CV = s/m_{av} \qquad [A10.2]$$

The standard deviation for this type of distribution is estimated to be a function of m; hence, if the value of CV is not too large:

$$CV = 100/\sqrt{m}\ \% \qquad [A10.3]$$

But m is related to the linear densities of yarn and fiber. Thus it will be realized that the CVs of blend, strength, and count vary with linear density. A 36s cotton yarn made from 4.5 micronaire fibers only has about 93 fibers in the cross-section and we

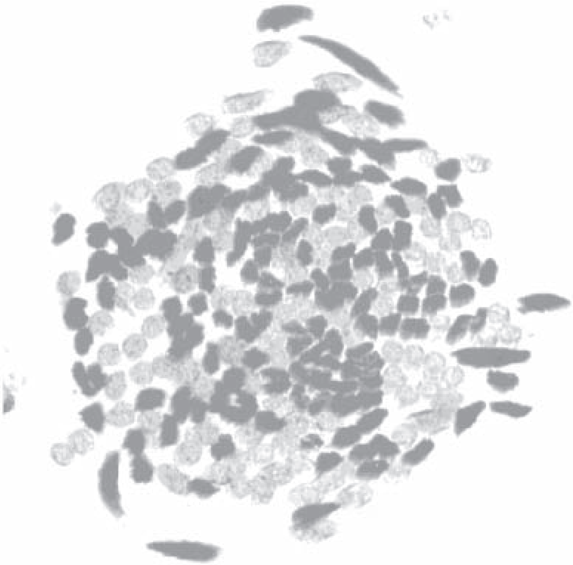

Fig. A10.2 Cross-section of a blended rotor yarn would expect 10.4% CV due to randomness of the fibers. If the yarn had been made of 2.5 micronaire cotton, the number of fibers would have increased to about 167 and the CV would reduce to 7.7%.

Components due to organized errors arising from malsetting of the machines and variations in fiber properties should be added vectorially to these figures. The effect of doubling is to bring the actual CVs closer to the minimum values. Since the rotor doubles over a length equivalent to the rotor circumference, one can expect that errors shorter than, say, 6 inches (150 mm) will be sufficiently doubled and the short-term evenness should be improved. However, the actual short-term error is still significantly above the theoretical values predicted by Equation (A10.3) (but is normally better than with ring yarns). Some reasons for this are discussed in the next section. The long-term errors are little affected by the doubling in the rotor and are dependent on the doubling at the drawframe and other preparatory machines. If a single passage of drawing is used with eight slivers in the creel, there might be only eight doublings there. This is much less than is found within the rotor. The point being made is that preparation has a larger relative impact on long-term yarn evenness with OE yarn as compared to ring yarn. It will be recalled that poor preparation can induce high error production in ring spinning.

A10.3 Toothed drafting

A10.3.1 Combing roll clothing

Combing rolls pull fibers from the beard of a sliver that is continuously fed by a feed roll and plate system. The combing roll usually rotates between 500 and 9000 r/min, it is clothed with either saw-teeth or needles, and its function is to detach fibers from the advancing fiber beard. If the sliver is not well prepared, fiber breakage can ensue because the entanglement of fibers in a clump increases the withdrawal force per fiber and more are caused to break than is desirable. Some measurements were made with rayon fibers on an old OE spinning machine. Undyed rayon fibers can be made almost invisible in a bath of liquid methyl salicytate so that a dyed tracer fiber within the structure of the yarn can be seen among the surrounding fibers. Dyed tracer fibers were placed carefully in the sliver entering the OE machine and the yarn produced was studied under a microscope. In the yarn, the fiber extent (the distance between the extremities of a folded fiber embedded in a yarn) was greatly reduced as the fibers took up a variety of hooked and looped shapes. Sometimes the original fiber was found to exist in two or more pieces and often only a shortened piece of tracer fiber would be found. When the fiber placed on the sliver was greatly crimped or relaxed into a very convoluted shape, the fiber almost invariably broke. The condition of the combing roll wire, its speed and its shape, all affected breakage rates; it also affected the ejection rate for trash.

Siersch [20] showed that helicoidally arranged teeth on the combing roll split fiber tufts into roughly parallel fibers separated by contiguous teeth (Fig. A10.3). This beneficial separation was accompanied by cyclic fluctuations in fiber flux (number of fibers per unit area of flow) and yarn tension, which were related to the pitch of the tooth helix. CVs of the fiber flux in his experiments varied between 8.9% and 9.6%. This, then, accounts for one of the reasons why the short-term CV is greater than the theoretical value. The larger the number of tooth helices, the smaller was the variation, and the higher were the yarn strength and breaking elongation. Too fine a

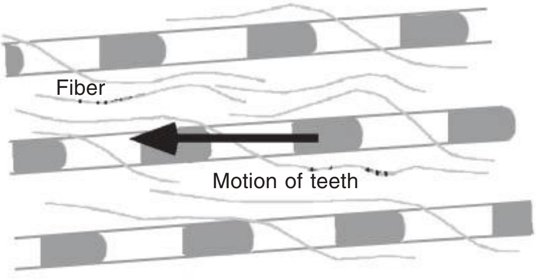

Fig. A10.3 Penetration of combing roll teeth into a fiber beard

tooth pitch (< 2 mm) created increased nep production with cotton fibers and a deterioration in yarn CV (Fig. A10.4). If the front angle of saw-tooth clothing (Fig. A10.4) was increased above about 20°, the drafting force increased and so did fiber damage. Various investigators have shown that combing roll damage produces yarn irregularity. The most usual damage is to the teeth; sometimes careless handling causes this, sometimes it is caused by large particles in the feed sliver, and sometimes by fiber jamming. The latter can be caused if a loop of sliver is lifted from the can and a double, or triple, thickness of sliver is ingested by the feed roll. A common time for this to happen is when a can is being emptied of the last length of sliver. However, it can happen when a sliver piecing has just been performed, or if a can has been damaged.

The life of the combing roll clothing is finite and the use of dusty fiber, or of fiber with abrasive fiber finish, increases the wear rate on the teeth. Consequently, not only are the metal surfaces hardened, but they are also surface treated to improve their wear resistance. Like card wire, the body of the tooth has to be tough to prevent brittleness; thus, despite the hardness of the cutting edge, the teeth can be bent. Bent teeth result in a loss of evenness in the yarn.

A10.3.2 Combing roll bearings

Combing roll bearings become damaged in service. Slippage in the tape drive can cause the bearings to become overheated, which causes the grease to fail. Typically, the grease hardens and blocks further lubricant from reaching the ball track.

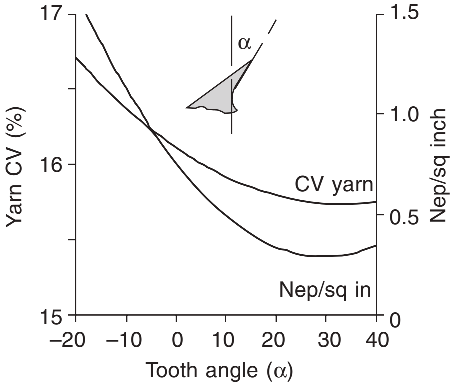

Fig. A10.4 Effect of comber roll tooth angle on yarn performance

Shock or overloading can cause the balls to indent the ball track. The race becomes noisy and consumes more power, which, in turn, leads to lubricant failure. Tests [21] using accelerometers to measure the vibrational accelerations at the combing roll bearing housings showed unusually high values for worn units. The use of an encoder driven by the combing roll enabled the vibration pattern to be resolved, and a sample is shown in Fig. A10.5. Cutting the bearing housings open revealed damage to the ball tracks.

A10.4 Fiber assembly – the formation of wrapper fibers

Once per revolution, the laying of the fibers on the collecting surface and the peeling of the yarn from the collecting surface interferes. Fibers laid at these times are called bridging fibers and, during removal, portions of these fibers become bent back and wrapped around the body of the yarn.

Consider Fig. A10.6(a). A fiber is shown sliding on the inside of the conical portion of the rotor. One end is already trapped in the yarn leaving the rotor groove. The peeling point is where the yarn leaves the rotor groove. As yarn is pulled from the rotor, this peeling point should move in the same direction as the rotor. The dotted line represents a sliding path of a fiber in the recent past. In Diagram (b), events occurring very shortly after the first are portrayed. A small amount of yarn has been removed, carrying the entrapped fiber with it; meanwhile, the trailing end of the fiber has slid nearer the rotor groove. Eventually, the trailing end must be folded back on the core of the yarn, as depicted in notional form in Diagram (c). However, the yarn rotates about its axis because of the false twist, and this causes the folded back fiber to become wrapped around the core of the yarn as indicated in Diagram (d). Variation in inclination of the fibers within the yarn is typical of the structure. Portions of the bridging fiber are wrapped around the outer surface of the yarn and carry very little load when the yarn is in the free state (i.e. not assembled into fabric). The remaining portions of the bridging fibers are buried in the yarn structure and, although they carry some load, they behave like short fibers. Consequently, the yarn is weaker than

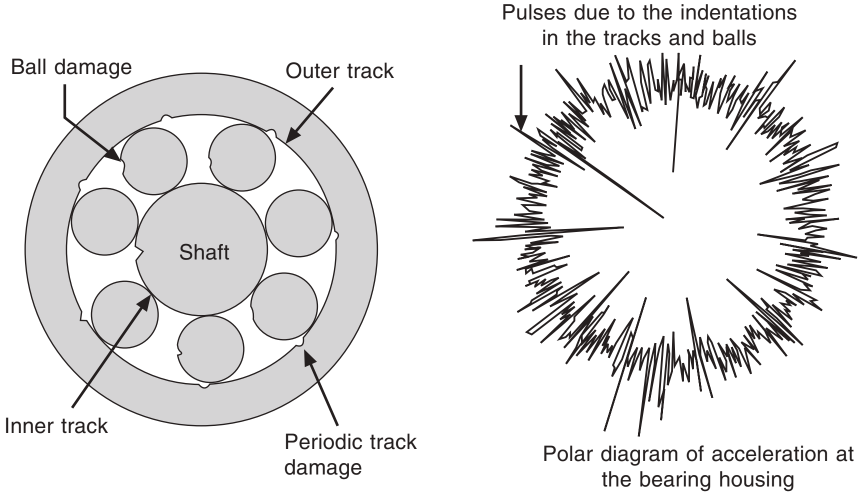

Fig. A10.5 Combing roll bearing damage

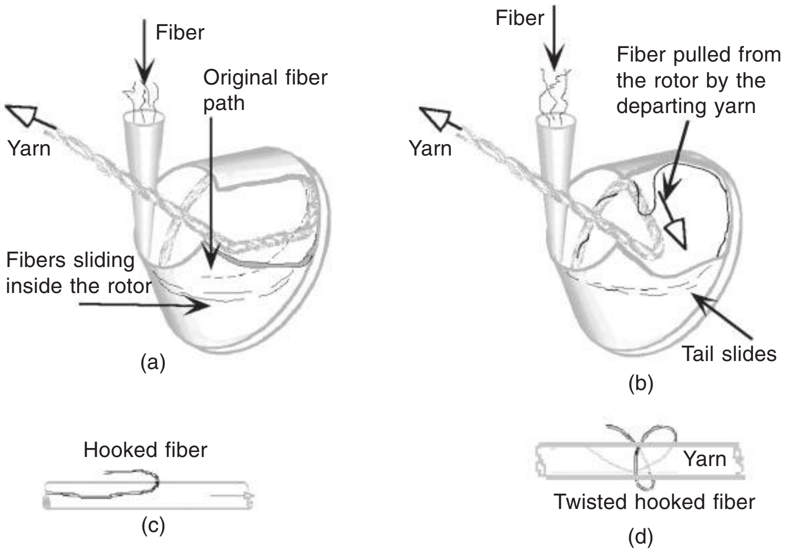

Fig. A10.6 Bridging fibers

ring yarn. Wrapper fibers increase the pressure on the enclosed fibers and this gives some local resistance to failure, although it produces an unwanted waisting in the yarn.

The chance of a bridging fiber depends on the rotor diameter and the projected length of the sliding fiber approaching the rotor groove. The term ‘projected fiber length’ must be explained. The fiber does not approach the rotor groove with its length parallel to a tangent of the rotor groove; rather, it approaches obliquely. Furthermore, the fiber may not be straight but might be convoluted in some way. Thus, if viewed perpendicular to the direction of slide, the distance between the extremities of the fiber is less than the real length. This distance between the extremities is referred to here as the projected length. To repeat, it is always less than the actual fiber length. Consider an example where the circumference of the rotor is 3 inches and the projected fiber length is 1 inch. In such a case, two out of every three fibers will be assembled inside the rotor groove without intersecting the path of the outgoing yarn. One in three will intersect the outgoing yarn and might be entrapped by it. The first, and larger, category of fibers becomes the core of the yarn and the second category become wrappers. The structures of the yarn are discussed in Appendix 5. Figure A10.7 shows some micrographs in which the core has been shaded to highlight the wrapper fibers. The wrappers are shown as dark fibers.

A10.5 Twist distribution

A10.5.1 False twist control by use of a rotating navel

Causing the navel to rotate can change the false twist created at the navel. Lünenschloss [22] showed that using a rotating navel increased the minimum TM at which one could spin (Fig. A10.8). He also showed that a soft yarn with a low twist could be spun. This was attractive not only because of the hand of the yarn but also because a low twist multiple gives a potential productivity increase. However, the rotating navel was an extra complication and it has not proved acceptable in practice.

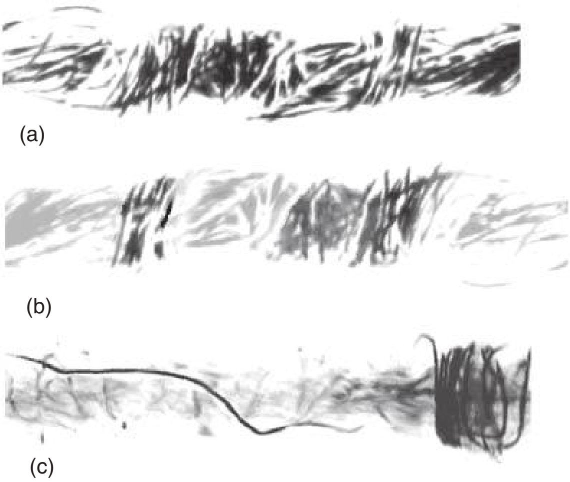

Fig. A10.7 Wrapper fibers

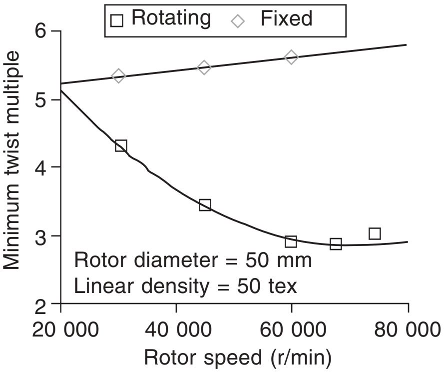

Fig. A10.8 Effects of fixed and rotating navels in rotor spinning

A10.5.2 False twist distribution in the rotor vee

The geometry of the navel affects the performance. As explained in the main text, the yarn rolls on the navel and creates false twist in the yarn inside the rotor. It should be noted that the twist of the yarn arm inside the rotor can be significantly higher than that in the emerging yarn. The torque of the yarn in the rotor vee is relieved at or near the peeling point of the yarn. A length of incipient yarn lying in the rotor vee adjacent to the peeling point has a varying level of twist, as indicated in Fig. A10.9. The shape of the rotor groove affects this twist propagation and a sharp vee tends to restrict the propagation more than a rounded one. An approximate distribution of twist in the incipient yarn lying in the rotor groove is:

$$T \approx T_o \, e^{k\mu\theta} \qquad \text{[A10.4]}$$

where μ = coefficient of friction, θ = angle subtended by the incipient yarn measured from the peeling point, $k = \omega^2 r^2 n/2 \sin \alpha$ and 2α = angle of the rotor groove. Thus, the groove angle has a strong effect on performance. If α is too small, the yarn jams in the groove.

The distribution of forces acting on the yarn lying in the rotor groove is shown in

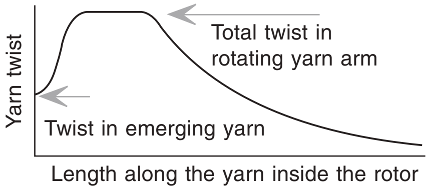

Fig. A10.9 Twist distribution inside a rotor

Fig. A10.10. A rounded groove gives a different distribution of forces, reduces the total lateral force acting on the yarn from F to F', and modifies the coefficient k. Wear can sometimes convert one shape of vee to another; this causes changes in yarn characteristics. In the 1970s, before adequate wear protection treatments had evolved, cases were known where the wear was sufficient to penetrate to the outside of the rotor. Build-up of dust and trash inside the rotor also changes the shape of the vee and affects the yarn characteristics.

A10.5.3 Twist surges

At very high speeds, difficulties begin to appear in retaining the twist in the rotating yarn arm. False twist can surge forward through the navel, leaving a transient depletion in twist inside the rotor, which causes an end-break near the navel inside the rotor. Twist traps in the yarn withdrawal tube become a necessity at high speeds, especially when spinning polyester or similar fiber. Many twist trap designs can be recognized by the cranked doffer tube, which causes the yarn to leave at an angle to the rotor center line. This is an important device in controlling the twist surges. The effect of such surges can be recognized by the presence of portions of yarn inside the rotor after an end-break. Without significant surges, there is only fiber and dust present because the failure under non-surging conditions occurs where the yarn is peeled

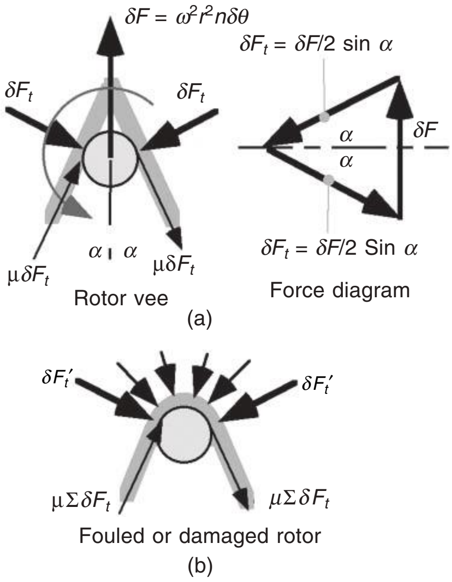

Fig. A10.10 Forces involved in rotor wear from the rotor groove. The angle of the cranked yarn withdrawal tube is important. Normally it is cranked at about 45°. The smaller the angle, the lower the spinning tension, but a torque-stop effect can be produced if the angle is increased. There are also other designs of twist trap to fulfill a similar function.

The design and condition of the navel, as well as the character of the fiber and the yarn count, play important parts in determining the nature of the yarn. The navel also plays a part in determining the effectiveness of the operation. Yarn tension creates forces between the orbiting yarn and the stationary navel. Normal forces between yarn and metal create friction; the frictional forces act tangentially on the yarn and produce torque. The mean tangential force is a function of the normal forces referred to and the coefficients of friction between the surfaces. The normal force is proportional to $\omega^2 r_r^2 n$, where ω is the rotational speed, r_r is the radius of the rotor, and n is the linear density of the yarn. The false twist depends on the fiber finish, the type of navel surface, as well as on rotor speed and size. An increase in coefficient of friction decreases yarn strength but improves end-breakage rates. The flare radius connecting the bore to the front surface of the navel plays a significant part in determining both the false twist and the properties of the output yarn [13,14,15]. With a large flare radius, it is possible to increase the false twist at the expense of the winding tension. Lünenschloss *et al*. [23,24,25] wrote that the output yarn tension can exceed the yarn strength when using a rotor diameter of 60 mm (2.36 inches) at rotor speeds above 70 000 r/min. This gives some idea of the problems at high rotor speeds.

A10.6 Conclusion

In high speed rotor spinning, attention to the design and condition of the combing roll clothing is needed to preserve yarn quality. Attention to the design and state of the rotors is important, not only to obtain high quality, but also to minimize the costs associated with unnecessary end-breaks, and the consumption of power. Cleanliness and maintenance are of great importance.

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Abbreviations
fil = filament
HOK = normalized productivity
ls = long staple
m.m. = man made
m/c = machine
r.h. = relative humidity
spg = spinning
ss = short staple

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