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Spinning-in Fibres – a Quality Factor of Rotor Yarns

Abstract
The physical-mechanical properties of yarns, similar to those of other solid matters, are a function of their structure. Yarns are composed of fibres of different lengths and shapes, resulting in yarn spirals with varying radii, which can form kinks at intervals, and even project from the yarn surface. Therefore, it is not the overall length of the fibre that contributes to the yarn strength, but only the spun-in part of it. In this work, the spinning-in coefficient K_F was determined for carded and combed rotor-spun yarns, in accordance with the theory of spun-in fibres in yarns. Measurements have shown that the inner structure of cotton rotor-spun yarns, presented by the value of the coefficient, varies with the spinning system used. The K_F values for combed yarns show that most of the fibres were incorporated into the yarn, which gives better physical-mechanical characteristics. In carded yarns, this coefficient is slightly lower, indicating a greater number of looped fibres and fibres incorporated into the yarn with less than half their lengths.

Key words: *spinning-in of fibers, open-end rotor-spun yarn, carded cotton yarn, combed cotton yarn, rotor.*

Introduction

The physical-mechanical properties of yarns, similar to those of other solid matters, are a function of their structure. Therefore, many authors and reference works have described the structure of the yarns. By the end of the 1960s, along with the classical cotton yarns (carded and combed ring-spun yarns), the market saw the arrival of rotor-spun yarns [1]. These new yarns had different properties from the previous ones. In order to explain the specific properties and their origin, studies devoted to the inner structure of staple fibres in the yarn were intensified [2].

The yarn structure is a function of many factors, the most important among them being [3]:

- fibre character as the yarn structural component (length, fineness, cross-section and voluminosity) and its mechanical properties (tensile strength, stretchability, bending ability, elasticity, etc.);
- fibre distribution, i.e. the count and layout of fibres along the yarn cross-section (radial and square layout), the regularity of fibre distribution along the yarn (axial or longitudinal) and the distribution of individual lengths and forms of spun-in fibres within the yarn, i.e. the fibres' migrational properties.
- the relationship between the yarn structure elements, i.e. between the fibres (friction, various surface properties, number of contact points, etc.), determined by the spinning system, level of twisting, or subsequent chemical processing.

In their works, many authors [4-9] paid special attention to one of the characteristics mentioned above, namely the shape distribution of the structural (fibre) elements in the yarn.

The most important work for the development of new theories on the inner yarn structure was the work of Hearle et al. [10], wherein he presented his comprehensive report on the fibre migration in the yarns. To evaluate these migrations he introduced three parameterrs:

- the average position of the fibres, i.e. the position between the surface and the axis of the yarn:

$$Y = \frac{1}{l_n} \cdot \int_0^{l_n} Y \cdot dl = \sum \frac{Y}{n} \qquad (1)$$

where n is the number of measured positions over a yarn length l_n;

- migration amplitude;

$$D = \left[\frac{1}{l_n} \int_0^{l_n} \left(Y - \bar{Y} \right)^2 dl \right]^{1/2} = \left[\sum \frac{\left(Y - \bar{Y} \right)^2}{n} \right]^{1/2} \qquad (2)$$

- mean migration intensity.

$$J = \left[\frac{1}{l_n} \int_0^{l_n} \left(\frac{dY}{dL} \right)^2 dl \right]^{1/2} = \left[\sum \frac{\left(\frac{dY}{dL} \right)^2}{n} \right]^{1/2} \qquad (3)$$

According to Hearle, fibre migration in the yarns is a result of the interaction of two mechanisms: one is dependent on the difference in fibres tension, and the other on the sliver twist level. The tests have shown that the fibre tension is of utmost importance for spinning-in.

Theory of spun-in fibres in yarns

The study of fibre configuration has something in common with the theory of macromolecular substances. The macromolecular substances are comprised of macromolecules of different lengths and shapes, just as the yarns are also comprised of fibres of different lengths and shapes. The fibres are distributed in spirals with variable radii; they sometimes become entangled, and even protrude from the yarn. Therefore, the total length of the fibre does not contribute to the yarn strength, but only the part of fibre that has been spun in. For this reason, the spinning-in coefficient K_F has been introduced [11, 12].

The probability that a fibre will be spun-in depends on the ratio of the fibre elemental length, Δl_i, and the actual fibre length, l_F. The probability P of the fibre being incorporated into the yarn, can be presented as:

$$P = \sum \frac{\Delta l_i}{l_F} \qquad (4)$$

Based on this equation, we can come to the following conclusions:

a) If the fibre is straightened, and the full length of the fibre is spun in, then:

$$\sum \Delta l_i = l_F ; \quad P = 1 \qquad (5)$$

b) If the full length of the fibre is outside the yarn structure, then:

$$\sum \Delta l_i = 0 ; \quad P = 0 \qquad (6)$$

c) If part of the fibre length is spun in and the rest protrudes from the yarn, then:

$$\sum \Delta l_i < l_F ; \quad 0 < P < 1 \qquad (7)$$

The probability distribution corresponds to the Gaussian distribution because of the randomness of the individual fibres' spinning-in. In order to avoid any later confusion between the probability for different types of fibre configurations and the probability of fibre spinning-in, the fibre spinning-in coefficient K_F was introduced. The physical character of the K_F coefficient is obtained from the following:

$$K_F = \sum^{n} \frac{K_{F_i}}{n} \tag{8}$$

where:
K_{Fi} – the fibre spun-in coefficient for the given fibre (i), and
n – the number of fibres tested.

The fibre spun-in coefficient in the yarn K_{Fi} represents the relation

$$K_{F_i} = \sum \frac{\Delta L_i}{L_F} \tag{9}$$

where:
ΔL_i – the yarn length into which the fibre is spun in (incorporated into the yarn), and
L_F – the length of the straightened fibre.

Based on this, the possible values of the coefficient fall within the limits:

$$0 \leq K_F \leq 1 \tag{10}$$

The practical determination of the spinning-in coefficient is limited by the testing methods and the time necessary for the testing. The problem is to determine the exact length of the fibres incorporated into the yarn.

An approximate value of K_F is more easily obtained by using the projected elemental fibre length, L, instead of the actual fibre length, L_F, whereby it is obvious that $L_F > L$. In the same way, we can project to the yarn axis and the spun-in fibre length:

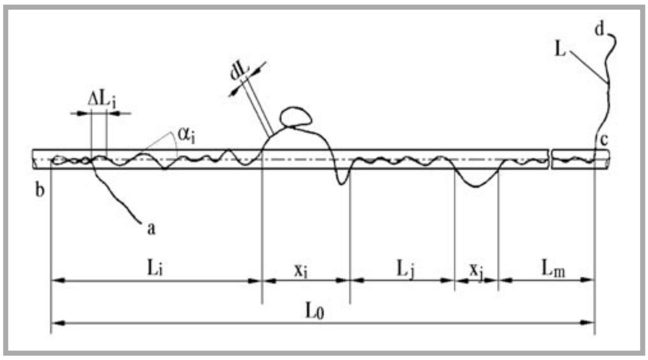
$$\sum L_i = \sum \Delta L_i \cdot \cos\alpha_i \tag{11}$$

The spun-in fibre length can be measured by a tracer on an enlarged photo of transparent yarn into which a dyed fibre has been spun-in. The equation given below shows the fibre spinning-in coefficient calculation method for the fibre shown in Figure 1.

$$K_{F_i} = \sum^{m} \Delta L_i \cdot \frac{\cos\alpha_i}{L} = \sum^{m} \frac{L_i}{L} = \frac{L_0 - \sum^{m} x_i}{L} \tag{12}$$

where:
ΔL_i – part of the fibre incorporated into the yarn,

__Figure 1.__ Photo of a fibre spun into the yarn body with the data for the spinning-in coefficient calculation.



L_i – part of the yarn comprising the spun-in fibre,
α_1 – the angle between the elemental length and the yarn axis,
x_i – the yarn length from where the fibres are protruding,
L_0 – the total yarn length between the beginning and the end of the fibre,
L – the total fibre length.

Based on the above equations and the figure, it can be concluded that the spinnsing-in coefficient is one of the most significant characteristics of the inner yarn structure.

The inner yarn structure cannot be determined by the shape and configuration of a single fibre, because the fibre can have a random position in the yarn. The yarn is represented as a statistical series of more or less randomly configured fibres, and, in order to obtain a representative character of an 'average' fibre, it is necessary to statistically process a series of data with a great number of measurements.

It would be very difficult to perform such a large number of measurements by taking photographs simultaneously. Therefore, for practical purposes, the comparative method was introduced. Based on a large number of measurements, the typical shapes and derived empirical coefficients are defined. From the mathematical definition of K_F coefficient (8), it follows that it may be composed of a number of partial components:

$$K_F = \sum^{n} K_{F_j} \cdot \frac{n_j}{n} = K_{F_0} \cdot \frac{n_0}{n} + K_{F_1} \cdot \frac{n_1}{n} + \ldots + K_{F_n} \cdot \frac{n_n}{n} \tag{13}$$

where:
K_{Fj} – the mean spinning-in coefficient for a given class (class j),
n_j – the frequency of measurements for that class.

In a way, this is analogous to the polydispersibility of macromolecules. The staple fibres, from which the yarn is spun, are polydispersive by their characteristics. Different spinning methods contribute to different configurations of fibre lengths and shapes within the yarn; in other words, the polydispersibility of the fibres is emphasised by spinning. As the polydispersibility of polymeric substances reflects their chemical and mechanical properties, so the inner structure of yarn affects its mechanical properties.

Measurements of empirical standards and determination of their K_F values [13] brought about a classification of standard fibre distribution for statistical analysis with 10 classes with associated spinning-in coefficient values (Figure 2).

The mathematical and statistical approach to the problems of the inner yarn structure, presented here and based on the fibres lengths utilised, enables the comparison of different types of yarns, and facilitates the study of the complex structure of the yarns spun from staple fibres.

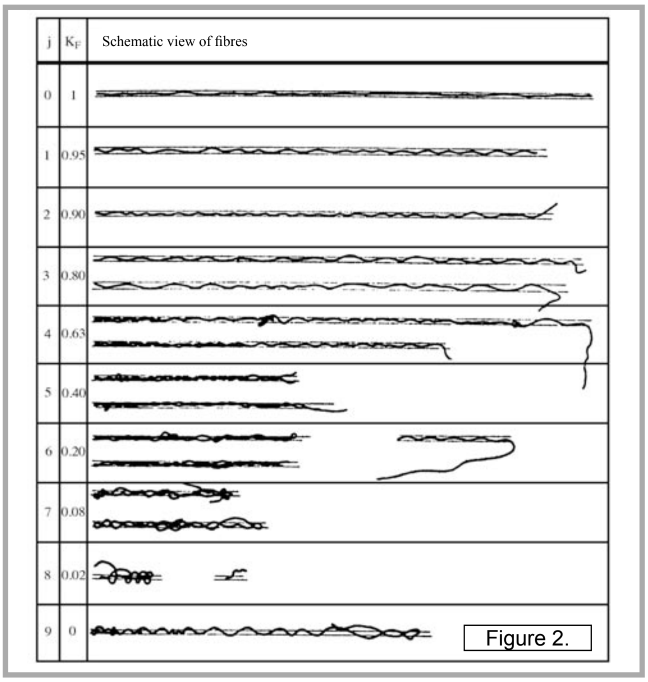
In Figure 3, more information is given on the yarn inner structure with the frequency distribution and cumulative frequency distribution spinning-in coefficients for individual types of yarns [11].

Experimental

Testing methods

The following methods and apparatuses were used for testing of raw materials and experimental samples:

1. The testing of cotton fibres was carried out on a modern SPINLAB HVI 900A line for classification and quality assessment of cotton fibres, where the following parameters are studied:
   - fibre length, by the optical method (fibrogram), giving data on mean length, the mean length of the upper half of that length (UHML), and the percentage (%) of mean arithmetic length fibres in the cotton batch;



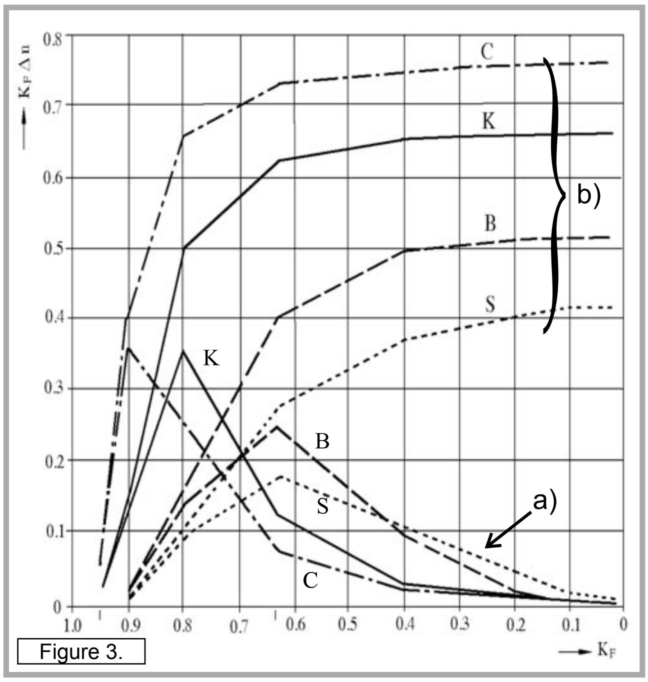


***Figure 2.** Standard fibres distribution for the statistical analysis of classes 0 to 9 for the spinning-in coefficient K_F.*

***Figure 3.** The spinning-in coefficient distribution curves for some yarn types; a) frequency distribution, b) cumulative frequency distribution; K_F - fibre spinning-in coefficient, $K_F \cdot \Delta n$ – weighted spinning-in coefficient (the product of K_F and the relative frequency of the spinning-in coefficient), C – combed yarn, K – carded yarn, B – rotor-spun yarn, S – rotor-spun yarn, old machine type.*

- strength, i.e. the breaking force and elongation at break, by the fibre sheaf breaking method;
- fibre fineness, i.e. microner-values by the flow of air stream through a fibre sample;
- content of impurities and micro-dust;
- colour of fibres; by measuring the reflected light the grade of yellowness is determined in accordance with the USDA cotton classification standard;

2. The linear density of the yarn fineness was determined on an Uster-Autosorter 3 apparatus with the standardised data processing method to ISO 2060;
3. The yarn twist was determined by the direct counting method (ISO 2061);
4. The yarn irregularity and hairiness were determined with a computerised Uster Tester 3 with additional hairiness measuring sensor;
5. Mechanical characteristics of the yarns were determined with an automatic Uster-Tenso Jet apparatus (DIN 53384 and ICS 59.080.20).

Results and discussion

Carded and combed rotor-spun yarns were used as the test material. All the samples were made of the same raw material (Russian Class I cotton 31/32), in order to avoid the raw material quality affecting the quality of the tested yarns. The fibres' characteristics are given in Table 1.

All the yarn samples were spun on a R1 Rieter spinning machine with 30-mm diameter rotors for optimal d_R/l_{vl} ratio. That is, cotton fibres of 29.03 mm in length were used, giving the ratio d_R/l_{vl} = 1.031 in 30-mm diameter rotors, which is near to the optimal value for a stable spinning process (0.9 - 1.0) [14, 15].

All the yarns were spun at a rotor rate of 106 000 min^{-1}, thus achieving good spinning stability for all yarn counts (fewer than 200 breaks/1000 rotor hours).

During the preparation of the drafted fibre for spinning combed rotor-spun yarns (Ricofil) [16], the combing phase is preset in such a way as to eliminate 12-13% of short staples; in comparison to the combed ring-spun yarns they represent normally combed yard, wherein 12-25% of short staples are eliminated. The spinning machines have a built-in Ri-Q-Box for the additional elimination of remaining impurities, which increases the stability of the spinning process.

The results of testing the carded and combed rotor-spun yarns' physical and mechanical properties are given in Tables 2 and 3.

It is well-known that the strength, i.e. the breaking strength of the yarn, is lower than the sum of breaking strengths of the individual fibres in the yarn cross-section, which is expressed by 'the coefficient of fibres strength utilisation in the yarn' (η):

$$\eta = \frac{Fr_y}{Fr_f}; \quad \eta < 1 \tag{14}$$

where:
Fr_y – the yarn's tenacity (cN·tex^{-1})
Fr_f – the fibres' tenacity (cN·tex^{-1})

The value of this coefficient is less than 1 (0.3 – 0.8), and it rises when the internal structure of the yarn is better. Therefore, this coefficient can be of use to a technologist as a measure for both the internal yarn structure assessment, and at the same time the assessment of the fibre processing technology procedure [17, 18].

***Table 1.** Cotton fibres used for the production of carded and combed rotor-spun yarns.*

Quality indices of the tested fibres	Statistical indices	
	$\bar{X}$	CV, %
Fibre fineness, in microns	5.0	2.45
Fibre linear density, Tt_f, dtex	1.97	-
Fibre length, l_f, mm	29.09	3.08
Tenacity, Fr_f, cN·tex^{-1}	21.8	3.14
Elongation at break, ε_P, %	6.0	2.72
Impurities, %	2.52	-
Moisture content, %	7.1	-

In his work, Rohlena [11] has determined the inter-dependence of the yarn inner structure and its mechanical properties.

Figure 4 shows the correlation between the fibre spinning-in coefficient and the fibre strength's utilisation coefficient, which is chosen to represent the mechanical properties of the yarn. The correlation coefficient between these two values is 0.97±0.02, which proves that the yarn strength depends to a great extent on the inner structure of the yarn.

From the known fibre spinning-in coefficient in the yarn for cotton yarns, the fibre strength's utilisation coefficient is calculated by the regression equation given below:

$$\eta = 0.83 \cdot K_F + 0.022 \qquad (15)$$

on the basis of which the yarn strength can be calculated as follows:

$$Fr_y = Fr_f \cdot (0.83K_F + 0.022) \qquad (16)$$

and vice versa, whereby on the basis of the known fibre strength's utilisation coefficient in the yarn, the fibre spinning-in coefficient can be calculated thus:

$$K_F = 1.138 \cdot \eta + 0.007 \qquad (17)$$

Figures 5 and 6 show the relation of these two coefficients (η, K_F), calculated for the carded and combed rotor-spun yarns by use of equations 14 and 17.

As is shown by the histograms in these figures, both coefficients (η, K_F) increase with the increase of the rotor-spun yarns' linear density. Comparing the values obtained for carded and combed rotor-spun yarns, it can be seen that the values are higher for combed yarns than for the carded ones. The measurements show that the inner structure of the cotton rotor-spun yarn, expressed by the fibre spinning-in coefficient K_F, changes when the spinning system is changed. The distribution of K_F values for the combed yarns shows that the prevailing part of the fibres is spun into the yarn, while with the carded yarns, more loops and fibres are incorporated into the yarn with less than half their length.

Considering that these two coefficients are correlated, we may state that this affects the physical and mechanical properties of the tested rotor-spun yarns, as shown in Figures 7-11 (see page 54). These results are given in numerical form in Tables 2 and 3.

As seen from the distribution of the experimentally obtained values, all the

Table 2. *Physical and mechanical properties of the carded rotor-spun yarns.*

Yarn parameters			Yarn mark				
			I_1	I_2	I_3	I_4	I_5
Linear density, Tt, tex			17	20	22	23	25
Yarn twist, Tm, m^{-1}			850	850	850	850	850
Breaking force, Fa, cN		$\bar{x}$	238.1	282.2	322.9	376.8	403.5
		SD, cN	20.4	17.7	30.3	29.7	30.1
		CV, %	8.57	7.65	9.40	7.89	7.46
Tenacity, Fr, cN·tex^{-1}		$\bar{x}$	14.00	14.11	14.68	15.83	16.14
		SD, cN	1.20	1.08	1.38	1.25	1.20
		CV, %	8.57	7.65	9.40	7.89	7.46
Elongation at break, ε_p, %		$\bar{x}$	4.62	4.69	4.92	5.02	5.08
		SD, cN	0.36	0.33	0.36	0.34	0.34
		CV, %	7.93	7.00	7.41	6.79	6.74
Breaking work, A, cN·cm		$\bar{x}$	308.9	366.4	380.8	429.4	486.8
		SD, cN	42.0	53.0	51.5	60.4	69.03
		CV, %	13.59	14.48	13.53	14.06	14.18
Irregularity 'Uster'	Um, %	$\bar{x}$	13.07	12.67	12.21	12.02	11.78
		SD, cN	0.106	0.155	0.043	0.14	0.26
		CV, %	0.81	1.22	0.35	1.16	2.24
	CVm, %	$\bar{x}$	16.52	16.02	15.38	15.20	13.54
		SD, cN	0.152	0.202	0.054	0.18	0.23
		CV, %	0.92	1.26	0.35	0.69	1.75
Thin places (-50%), km^{-1}		$\bar{x}$	115	67	34	26	16
		SD, cN	15.06	12.19	6.63	7	6.97
		CV, %	13.1	18.2	19.5	26.9	43.6
Thick places (+50%), km^{-1}		$\bar{x}$	182	152	86	68	34
		SD, cN	34.94	25.08	4	10.67	16.69
		CV, %	19.2	16.5	4.65	15.7	49.1
Neps (+280%), km^{-1}		$\bar{x}$	84	62	29	16	9
		SD, cN	27.72	20.03	5.74	4.18	6.27
		CV, %	33.0	32.3	19.8	26.1	69.7
Hairiness, H, -		$\bar{x}$	4.11	4.22	4.24	4.31	4.93
		SD, cN	0.066	0.057	0.068	0.15	0.04
		CV, %	1.62	1.35	1.60	3.48	0.98

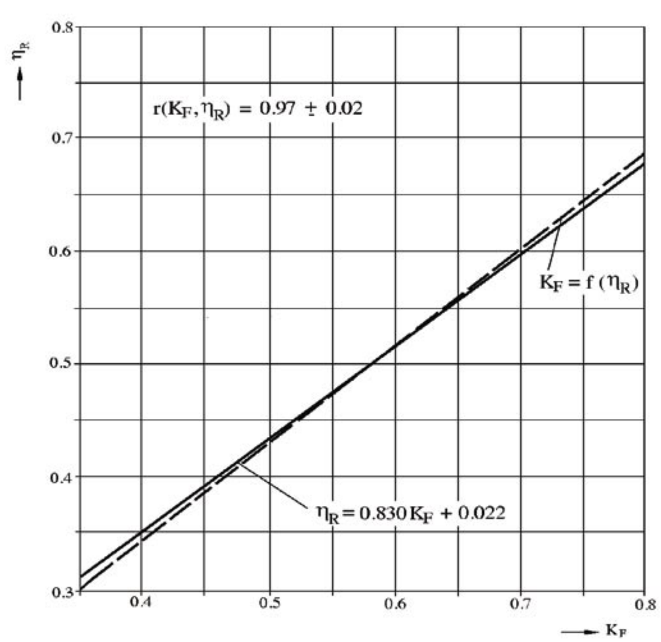


Figure 4. *Correlation between K_F and η for Russian cotton, Classes I and II.*

Table 3. Physical and mechanical properties of the combed rotor-spun yarns.

Yarn parameters			Yarn mark				
			II_1	II_2	II_3	II_4	II_5
Linear density, Tt, tex			17	20	22	23	25
Yarn twist, Tm, m^{-1}			850	850	850	850	850
Breaking force, Fa, cN		$\bar{x}$	244.7	290.9	338.5	377.4	411.5
		SD, cN	23.0	25.9	29.0	32.1	33.5
		CV, %	9.40	8.90	8.57	8.51	8.48
Tenacity, Fr, cN·tex^{-1}		$\bar{x}$	14.39	14.55	15.39	16.41	16.46
		SD, cN	1.35	1.29	1.31	1.39	1.39
		CV, %	9.40	8.90	8.57	8.51	8.48
Elongation at break, ε_p, %		$\bar{x}$	4.79	4.90	5.04	5.16	5.19
		SD, cN	0.36	0.36	0.36	0.37	0.34
		CV, %	7.52	7.26	7.11	7.26	6.63
Breaking work, A, cN·cm		$\bar{x}$	314.0	394.6	460.6	490.5	502.5
		SD, cN	48.5	55.9	61.8	68.2	67.6
		CV, %	15.44	14.16	13.41	13.90	13.46
Irregularity 'Uster'	Um, %	$\bar{x}$	13.00	12.61	11.45	11.40	11.12
		SD, cN	0.210	0.274	0.107	0.215	0.058
		CV, %	1.62	2.17	0.94	1.89	0.52
	CVm, %	$\bar{x}$	16.39	15.91	14.46	14.42	14.02
		SD, cN	0.264	0.350	0.132	0.299	0.074
		CV, %	1.61	2.20	0.91	2.08	0.53
Thin places (-50%), km^{-1}		$\bar{x}$	83	61	20	19	12
		SD, cN	13.53	25.01	6.38	9.29	3.96
		CV, %	16.3	41.0	31.9	48.9	33.0
Thick places (+50%), km^{-1}		$\bar{x}$	141	100	69	52	24
		SD, cN	30.03	26	19.25	10.82	6.74
		CV, %	21.3	26.0	27.9	20.8	28.1
Neps (+280%), km^{-1}		$\bar{x}$	48	37	23	10	6
		SD, cN	16.61	8.92	7.84	4.32	4.04
		CV, %	34.6	24.1	34.1	43.2	67.4
Hairiness, H, -		$\bar{x}$	4.03	4.04	4.12	4.25	4.37
		SD, cN	0.050	0.048	0.070	0.031	0.082
		CV, %	1.25	1.19	1.69	0.72	1.88

parameters defining the mechanical properties of the yarn depend on both the yarn linear density, i.e. the number of fibres in the yarn cross-section, and on the spinning system. Thanks to the combing process, the short staples and the remaining impurities are eliminated, and the fibres are straightened and oriented lengthwise within the band. All this contributes to better spinning-in of the fibre, as well as the better utilisation of its full length in the yarn strength.

The measurements of the yarn irregularity and hairiness of the rotor-spun yarn confirmed the well-known fact that the rotor-spun yarns have very good uniformity and extremely low hairiness. New specially-constructed small-diameter rotors (28, 30 and 32 mm), together with new high wall rotor geometry [14, 19], provides very low hairiness. The hairiness in rotor-spun yarns is about 50% lower than that of the ring-spun yarns [16]. This is especially apparent in combed rotor-spun yarn, due to the combing and the elimination of short staple fibres [20, 21]. As seen in the graphic, yarns made from combed cotton have lower hairiness and better uniformity.

Generally, the hairiness of the rotor-spun yarns increases with the increase of their linear density, i.e. the number of fibres in the yarn cross-section. This is explained by the fact that the higher number of fibres in the yarn cross-section means a higher number of fibres in the length unit (metre) of yarn, so that the number of protruding fibres is higher [22, 23].

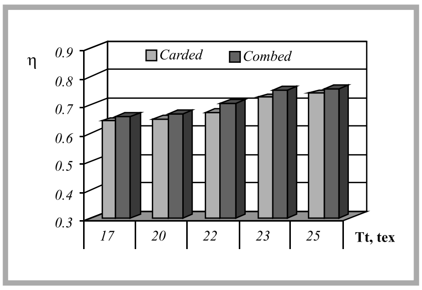


***Figure 5.** The ratio of fibre strength's utilisation coefficient in the yarn (η) for carded and combed yarns.*

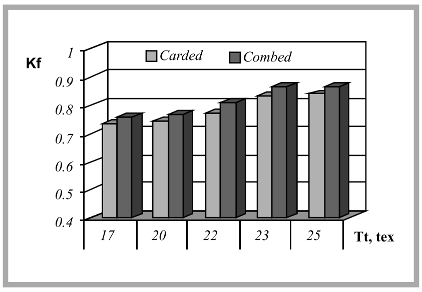


***Figure 6.** The ratio of fibre spinning-in coefficient in the yarn (K_F), for carded and combed yarns.*

Conclusions

- The use of up-to-date technical and technological developments has established rotor spinning as one of the most significant processes for yarn production from short staple cotton-type fibres, which has resulted in a higher share of rotor-spun yarns in worldwide cotton yarn production. Apart from a regular increase in the production capacities of rotor-spun yarns, new end uses have been found for these yarn types. They are now widely used for products that until recently were almost exclusively made from ring-spun yarns. Earlier, they used to produce only the coarse rotor-spun yarns of up to 30 tex, which were characterised by poor physical and mechanical properties. Such yarns could only be used to produce garments for work and recreation.
- The new generation of rotors with altered geometry for improving the inner structure of rotor-spun yarns has made it possible to increase the rotor-spun yarns fineness, that is, a decrease in yarn linear density. By increasing the rotor wall height (to 10 and 16 mm) and extending the doffing-tube-to-peel-off distance, the number of so-called 'wild fibres' in the yarn wrapper ?has fallen, whereby the mechanical properties of the yarn are improved. This allows the production of finer rotor-spun yarns with quality parameters similar to those of ring-spun yarns.
- The inner structure of rotor-spun yarns is significantly improved by fibre combing, i.e. by production of the so-called 'Ricofil' yarns. The

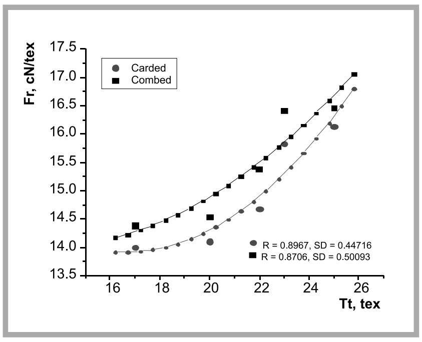


Figure 7. The yarn tenacity in dependence on the yarn liner density and the spinning system.

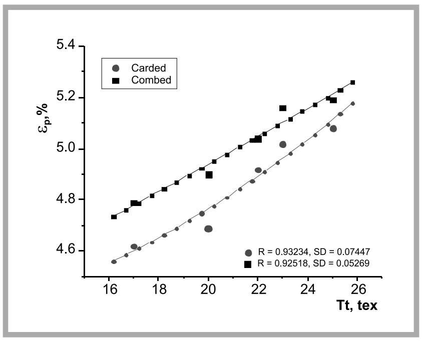


Figure 8. The yarn breaking elongation in dependence on the yarn linear density and the spinning system.

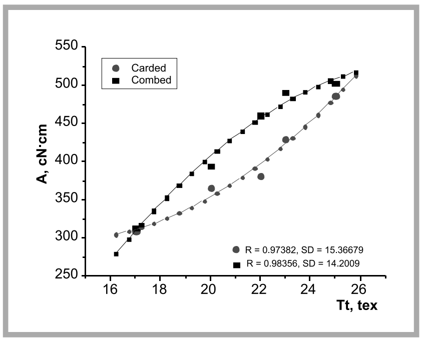


Figure 9. The dependence of the breaking work on the yarn linear density and the spinning system.

measurements have shown that the inner structure of the rotor-spun yarns, expressed by the spinning-in coefficient (K_F), changes when the spinning system is changed.

- The distribution of K_F values for the combed yarns shows that the greater part of the fibres have been incorporated into the yarn, which brings about better physical and mechanical properties. In carded yarns, this coefficient is slightly lower, indicating the presence of a larger number of entangled fibres and fibres incorporated into the yarn with less than half their length.
- The combing process is used to eliminate the short staple fibres and to straighten most of the entangled fibres, whereby the rotor-spun yarns obtain better quality, comparable to that of the ring-spun yarns. This is especially true of yarn strength, since early experiences showed that the rotor-spun yarns were weaker by 15-30% than the ring-spun yarns.

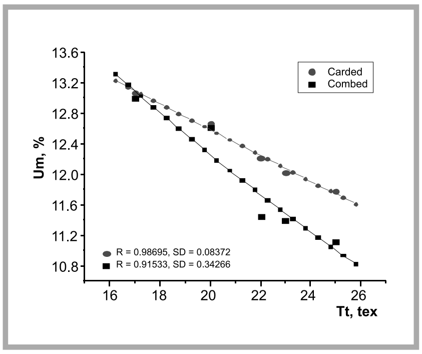


Figure 10. Yarn irregularity in dependence on the yarn linear density and the spinning system.

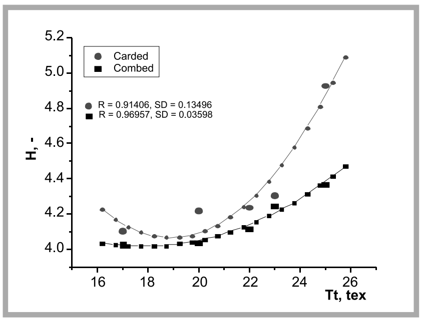


Figure 11. Yarn hairiness in dependence on the yarn linear density and the spinning system.

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