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Numerical Investigations Application for Assessment of the Influence of the Spinning Zone Geometry of a Ring Spinning Machine on the Dynamics of Yarn in the Manufacturing Process

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Abstract

Results of simulation investigations of the influence of changes in the spinning zone geometry of a ring spinning machine on the tension and quality of the yarn manufactured are presented in this study. Changes in the geometry resulted from modification of the conventional drafting system into a compact drafting system. For the investigations, construction parameters of the machine and the technological process of spinning were taken into consideration. Numerical investigations were based on the mathematical model for the dynamics of yarn motion through the twisting-winding unit. Experimental tests were performed on the Polish ring spinning machine type PJ 35, equipped with a conventional drafting system and the author's compact drafting system. It was shown that changes in the spinning zone geometry on the spinning machine caused by modification of the conventional drafting system into a compact system had no effect on the mean tension value of the yarn. Instead it diminished the amplitude of tension during the revolution around the spindle.

Key words: compact spinning, mathematical model, numerical experiment, yarn motion dynamics.

Introduction and aim of the study

Analysis of trends in the development of yarn technologies as well as experts' experience allow to state that progress in the technology of yarns manufactured from staple fibers is aimed at the development of technologies based on the application of compact ring spinning machines [1, 3, 6 - 8, 11, 14, 15], as was confirmed at the exhibition of ring spinning machines during the ITMA 2011 Fair in Barcelona.

There, producers of spinning machines presented a wide range of compact drafting units. They differ from conventional ones in that they are equipped with a compressing, pneumatic or mechanical sub-assembly, situated in place of a traditional pair of delivery rollers on the drafting unit. As a result, the fibre sliver, when leaving the compression zone, is thoroughly narrowed and better prepared for effective fibre compacting into yarn within the spinning zone, enclosed by the delivery rollers and with the guide eye of the twisting-winding unit.

Modification of the conventional drafting system into a compact system by means of a compression sub-assembly - **Figure 1** [6] - causes relocation of the yarn delivery point W from location W_K - characteristic for the conventional system to location W_M . The consequence of this is a change in the spinning zone geometry from the 'conventional K' into

the 'compact M', and a shortening of the yarn segment W_O within this zone.

This raises a very reasonable question to be asked by the spinning engineer:

What is the influence of spinning zone geometry changes, caused by draft system modification from conventional to compact, on yarn tension?

Answering such a question forces to reconsider the above issue from the aspect of the dynamics of the yarn motion through the twisting-winding unit on the spinning machine. Results of experimental tests presented in literature refer mainly to the quality of yarns spun on the compact spinning machine. There are no studies considering the influence of geometric parameters of the spinning zone on yarn tension during bobbin formation. Moreover the numerical investigations dealt mainly with the modelling of yarn

motion within the compression zone on the drafting unit [3, 14, 15].

Examination of the influence of the modifications in the spinning zone on the tension of the yarn is very difficult because tension is an implicit function of technological parameters characteristic for the spinning process, yarn parameters and random deficiencies of the machine. Respectively it is necessary to apply numerical experiments which enables broader qualitative and quantitative estimation of dynamic phenomena for separated yarn and technological process parameters as well as for any combination of the above. Based on knowledge of the field of spinning, theoretical mechanics, dynamics and diagnostic, a research method is proposed aimed at the prediction of yarn dynamics on the ring spinning machine [4, 5]. It is based on the dynamic model for yarn motion through the twisting-winding unit on a spinning machine. PC

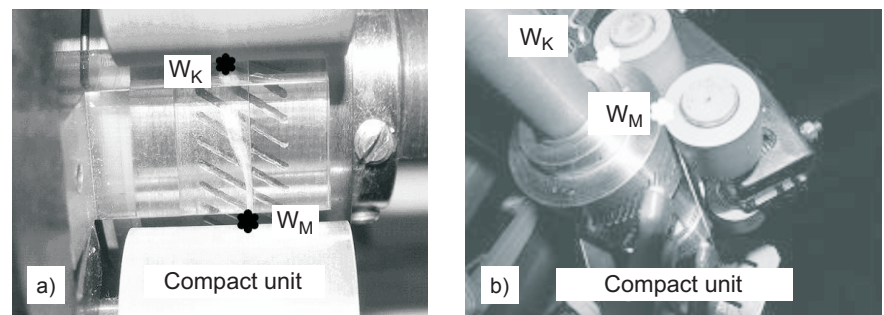


Figure 1. Compression sub-assembly including a sliver of fibres: W_K - point of yarn delivery in the conventional drafting system K (without compression sub-assembly), W_M - point of yarn delivery in the compact drafting system M . Front view - a) [3], Side view - b.

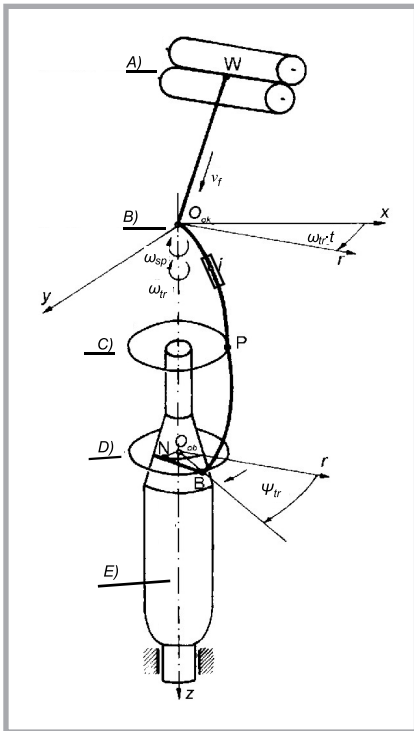


Figure 2. Schematic diagram of the twisting-and-winding unit accepted for consideration [7, 8]: A) plane of the feeding (delivery) roller, B) plane of the guide eye, C) plane of the balloon limiting element, D) plane of the ring, E) axis of the ring spindle.

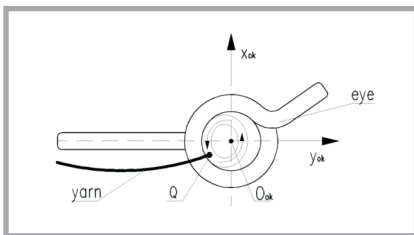


Figure 3. Scheme of yarn trajectory moving through the guiding eye, Q – point of yarn transit within the guiding eye.

software developed on the basis of the above gave the possibility to carry out numerical experiments. They showed, not as yet presented in literature, yarn tension oscillation in the spinning zone, being a response of the object to separate changes in the spinning zone geometry.

Theoretical basis

Physical model of the twisting- and -winding unit including the yarn

For further discussion, a physical model of the unit, presented in **Figure 2** [7, 8], has been applied. The following elements have been distinguished: ponderable and elastic yarn with segment **WO** within the spinning zone, segment **OB** rotating around the spindle and segment

BN within the winding zone, the delivery rollers **W**, the guide eye **O**, the balloon control ring **P**, the traveller collaborating with the ring at point **B**, the spindle with a bobbin, onto which the yarn is being wound at point **N**.

Yarn motion within the spinning zone

Within the spinning zone, a sliver of parallel fibres coming out from the clamps of the delivery rollers of the conventional or compact drafting unit moves with a constant linear delivery speed towards the guide eye. At the same time it is twisted into yarn, thanks to the traveller rotating around the spindle, along the ring. During one revolution of the traveller and yarn segment around the spindle, yarn tension in the spinning zone changes depending on current collaboration conditions between the yarn and guide eye, as well as on yarn tension in the balloon. The scheme of collaboration between the yarn and guide eye is presented in **Figure 3**. Yarn motion in the eye has been mapped with the trajectory of point **Q**, that is the passage of yarn through the eye surface. The trajectory is determined by the spinning zone and balloon geometry, the guide eye geometry, yarn resilient and plastic properties, yarn and eye roughness, as well as by imperfections of the twisting - and - winding sub-assembly.

The behaviour of yarn in the eye is connected with the phenomenon of the “free” passage of yarn twist from the whirling zone to the spinning zone, which depends on the wrapping angle of the eye with the yarn during the yarn revolution around the spindle and on the friction coefficient between the yarn and eye. This can be described by Euler’s **Equation 1**:

$$T_P = T_0 \cdot e^{m_y \cdot \theta_{ok}} \quad (1)$$

where: T_P – tension of yarn within the spinning zone, T_0 – tension in the upper yarn of the balloon, θ_{ok} – wrapping angle of the eye with yarn, m_y – friction coefficient between the yarn and eye.

The easiest way to describe behaviour of the yarn in the eye is to analyse two cases: case I – the yarn remains in direct contact with the eye; in this case the tension within the spinning zone is lowered due to the friction force of the yarn and guide eye, in accordance with (1). Case II – the yarn is not in contact with the eye; tension within the spinning zone is equal to that within the balloon: $T_P = T_0$.

Fluctuations of tension within the spinning zone result in shortening or lengthening the yarn segment above the eye. Considerable deviations in tension on both sides of the eye may result in ‘hampering’ of the twist propagation as well as an increase in hairiness and even yarn breakage.

Yarn tension modelling

The author’s mathematical model for the dynamics of yarn motion through the twisting-and-winding unit (**Figure 2** [4, 5]) was the basis for the research methodology applied. It was developed in accordance with d’Alembert’s rule [2, 7, 8].

The assumptions for the model are that the yarn is an elastic body, the traveller – a stiff body, and changes in the yarn segment length are described in accordance with Hooke’s law.

The model developed considers:

- the dynamic equilibrium of yarn discrete elements: within the free part of the balloon, close to the traveller, close to the control ring and close to the guide eye,
- the dynamic equilibrium of the traveller collaborating with the ring,
- yarn segment length changes as a result of the irregularity of the winding speed.

Stochastic yarn and traveller vibrations have also been taken into consideration.

General equations of yarn and traveller motion and changes in the length of the yarn element ‘i’ are (2), (3) & (4). The coordinate system $Oxyz$ is linked with the traveller moving around the spindle.

The scheme of forces acting on the elementary segment of yarn is presented in **Figure 4** [5], where – T_y and $(T_y + dT_y)$ are the tension of the yarn, dF_a – the air resistance force, dF_{cen} – the centrifugal force, dF_{CS} – the Coriolis force, $dF_{y,in}$ – the inertia force of the yarn element ‘i’, v_y – the speed of the elementary ‘i’ segment of yarn within the balloon [8]. Equations of the dynamic equilibrium for an ‘i’ discrete element of the yarn with mass dm_y have the form below:

$$\begin{aligned} \sum F_r = 0: & \quad -dm_y \cdot r + \sum dF_{y,r} = 0, \\ \sum F_\psi = 0: & \quad -dm_y \cdot \psi + \sum dF_{\psi,r} = 0, \quad (2) \\ \sum F_z = 0: & \quad -dm_y \cdot z + \sum dF_{z,r} = 0, \end{aligned}$$

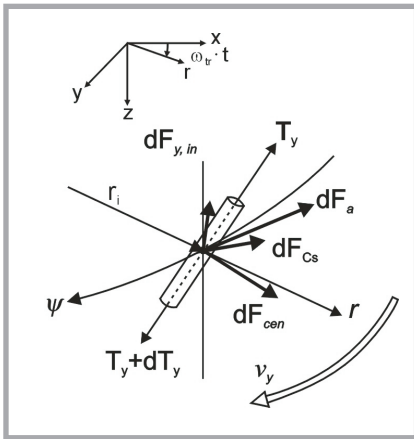


Figure 4. Forces acting on the element 'i' of the yarn segment within the balloon; T_y and $(T_y + dT_y)$ tension of yarn, dF_a – air resistance force, dF_{cen} – centrifugal force, dF_{Cs} – Coriolis' force, $dF_{y,in}$ – inertia force of yarn element 'i', v_y – speed of elementary 'i' segment of yarn within the balloon [5].

where ΣF_y - sum of forces acting on the yarn segment.

The scheme of forces acting on the traveller is presented in **Figure 5** [8], where T_{NB} – tension of winding, T_{BM} – tension of the bottom yarn of the balloon, $F_{tr,cen}$ – centrifugal force acting on the traveller, $F_{tr,f}$ – friction force between the traveller and ring, $F_{tr,n}$ – the normal force of the traveller is affected by the ring, $F_{tr,in}$ – inertia force of the traveller, and ω_{tr} – rotational speed of traveller [8]. The equation of the dynamic equilibrium of the traveller with mass m_{tr} moving along the ring of radius R has the form:

$$\Sigma F_{\psi} = 0: -m_{tr} \cdot R \cdot \psi_{tr} + \Sigma dF_{tr} = 0, (3)$$

where: ΣF_{tr} - sum of forces acting on the traveller.

The equation determining changes in the length δl_y of elementary yarn segment 'i' of linear density Tt and stiffness $(E_y^{Tt} \cdot Tt)$, as a result of changes in yarn tension δT_y , has the form:

$$\delta l_y - \delta T_y \cdot dl_y / (E_y^{Tt} \cdot Tt) (4)$$

where: E_y^{Tt} – linear elasticity modulus of yarn in cN/tex.

Equations 2, 3 and 4 form the mathematical model of the dynamics of yarn motion through the twisting-and-winding sub-assembly on a ring spinning machine. Geometric parameters of the spinning zone, the guide eye, the yarn, and the coefficient of friction between the yarn and eye have been introduced into this model.

Aim of the studies and scope of work

The object of the studies is the twisting-and-winding unit, for which changes in the spinning zone geometry from the conventional K to the compact M have been taken into account.

Based on a comparative analysis of the tension of the yarn determined for values of parameters describing the 'conventional' spinning zone, and then by relating them to the 'compact' values, the effects of changes in the spinning zone geometry on the tension of the yarn have been traced.

The technological efficiency of real objects with the conventional and compact spinning zones has been estimated on the grounds of the parameters of the yarns manufactured.

A PC software application [8] based on the mathematical model of the dynamics of yarn motion through the twisting-and-winding unit enables simulation of yarn tension within the spinning zones K and M.

Results of the numerical experiments are as follows:

- tension of the yarn within the spinning zone $TP = TP(t)$,
- mean tension Tsr and tension variance $\sigma_2 T$ of the yarn.

The technological efficiency of real objects has been assessed on the grounds of:

- longitudinal views of yarns, received by means of an electron microscope,
- hairiness, measured (on Shirley's apparatus) with the number of fibres which have not been compacted into the yarn, at distances of 1 mm, 3 mm and 5 mm from the yarn surface,
- hairiness ratio according to Uster Tester 3 apparatus,

Table 1. Values of parameters changed in the numerical experiment [9].

No	Parameter	Symbol	Unit	Values of parameters
1.	Parameters of delivery point for sliver fibre within conventional K spinning zone	$W_K(W_{K,y}, W_{K,z})$	mm	$W_K(-27,5; 235)$
2.	Parameters of delivery point for sliver fibre within compact M spinning zone [9, 13]	$W_M(W_{M,y}, W_{M,z})$	mm	$W_M(-10,5; 215)$
3.	Rotational speed of spindle	N	r.p.s.	167 – 250
4.	Mass of traveller	m_{tr}	g	0,046; 0,052; 0,072
5.	Ring radius	R	mm	25
6.	Balloon height	H	Formed package base	
7.	Minimum radius of winding	$r_{nw,min}$	Bobbin radius	
8.	Maximum radius of winding	$r_{nw,max}$	Full package radius	

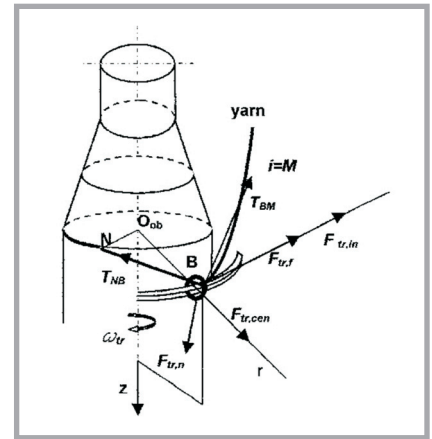


Figure 5. Forces acting on traveller B moving on the ring: T_{NB} – tension of winding, T_{BM} – tension of bottom yarn of the balloon, $F_{tr,cen}$ – centrifugal force acting on the traveller, $F_{tr,f}$ – friction force between the traveller and ring, $F_{tr,n}$ – normal force with which the traveller is affected by the ring, $F_{tr,in}$ – inertia force of the traveller, ω_{tr} – rotational speed of traveller [5].

- yarn tenacity in cN/tex and its elongation in w %,
- metric twist factor of the yarn,
- coefficient of friction between the yarn and steel.

Conditions of simulation tests

Numerical experiments were conducted for parameters reflecting a real technological process, with conditions assuring:

- stability of the ring spinning balloon [2, 7, 9]
- maximal productivity [2, 7, 9].

In detailed calculations, values of construction parameters of the Polish cotton ring spinning machine PJ 35 were applied [9] to the authors' compact zone [13]. Coordinates of the delivery point for the conventional K and compact M spinning zones are in the uniform Cartesian coordinate system Oyz , with the beginning at the point of guide eye surface perforation by the spindle axis - **Figure 2** [7, 8].

Simulation was carried out with the reference to the twisting-and-winding unit, in which the forced function was noticed:

- basic deterministic – connected with the construction of the twisting-and-winding unit on the machine,
- stochastic – reflecting irregularity of yarn linear density and coefficient of friction between the yarn and steel.

Experiments were conducted for cotton yarn of linear density $T_t = 25$ tex, characterised by a coefficient of mass variation $CV = 14\%$ for segments with a length of $l = 10$ mm. The following essential values of technological parameters were changed:

- package radius,
- rotational speed of the spindle,
- mass of the traveller.

Values of delivery points $WK(WK,y, WK,z)$ and $WM(WM,y, WM,z)$ coordinates in the Cartesian coordinate system Oyz and parameters changed in the experiment are in **Table 1** [9].

Results of numerical experiments

From a technical point of view it is very difficult to carry out tests reflecting the effects of changes in the spinning zone geometry on a ring spinning machine with the respect to the real object on the tension because it is an implicit function of construction and technological parameters as well as of the variability of yarn inertial and resilient properties during package formation [2, 7, 8].

Presentation of the separated influence of the spinning zone geometry on yarn tension is possible to determine by carrying out a numerical experiment. For this purpose calculations were made in three numerical experiments, in which the response of objects K and M to changes in the three basic technological parameters was examined: package radius, rotational speed of the spindle and mass of the traveller. Values of parameters subjected to changes in the numerical experiment are presented in **Table 1** [9].

Effect of changes in the bobbin radius on the tension of yarn within the conventional and compact spinning zones

Figure 6 present the variation in yarn tension $T_P = T_P(t)$ and calculated values of yarn tension variance within the conventional K and compact M spinning zones, during its winding on an empty bobbin $r_{nw} = \min$ (curve b) and on a bobbin of maximum diameter $r_{nw} = \max$ (curve a), with a rotational speed of the spindle $n = 167$ r.p.s.

It is easy to notice that the tension variation is a harmonic curve with a random noise [7, 8]. The main frequency is equal to the rotation of yarn and traveller around the spindle [7, 8]. The random noise is caused by the irregularity of the yarn linear density and coefficient of friction between the yarn and elements of the twisting-and-winding unit.

Analysis of yarn tension variation in spinning zones K and M allows to make the statement that both units operate stably and generate comparable mean

tensions in the yarn. On the other hand, tension fluctuations, characterised by the tension variance, show differences. The numerical experiment confirms that in comparison with the conventional spinning zone K, fluctuations of yarn tension within the compact spinning zone M are nearly twice lower.

Thus it can be concluded that changes in the spinning zone geometry, consequent to supplementary installation of the author's compression unit on the conventional tensioning unit, did not cause any change in the dynamics of yarn mean tension during package formation. Only values of tension fluctuation in the yarn during its revolution around the spindle were diminished.

Within the process of spinning, a mean value of yarn tension is the result of construction and technological parameters of the twisting-and-winding unit. On the other hand, fluctuations of tension within the spinning zone are a result of collaboration conditions between the yarn and eye, and the yarn and unit imperfections. In the numerical experiment discussed, modification of spinning zone K into an M design did not cause any change in the tension of yarn within the balloon TO, because conditions of collaboration between the traveller, ring and yarn remain unchanged. Change in the spinning zone geometry caused only a diminishing of the wrapping angle: $\theta_{ok,M} < \theta_{ok,K}$, and, respectively - in accordance with **Equation 1** – a decrease in the fluctuation amplitude of yarn tension.

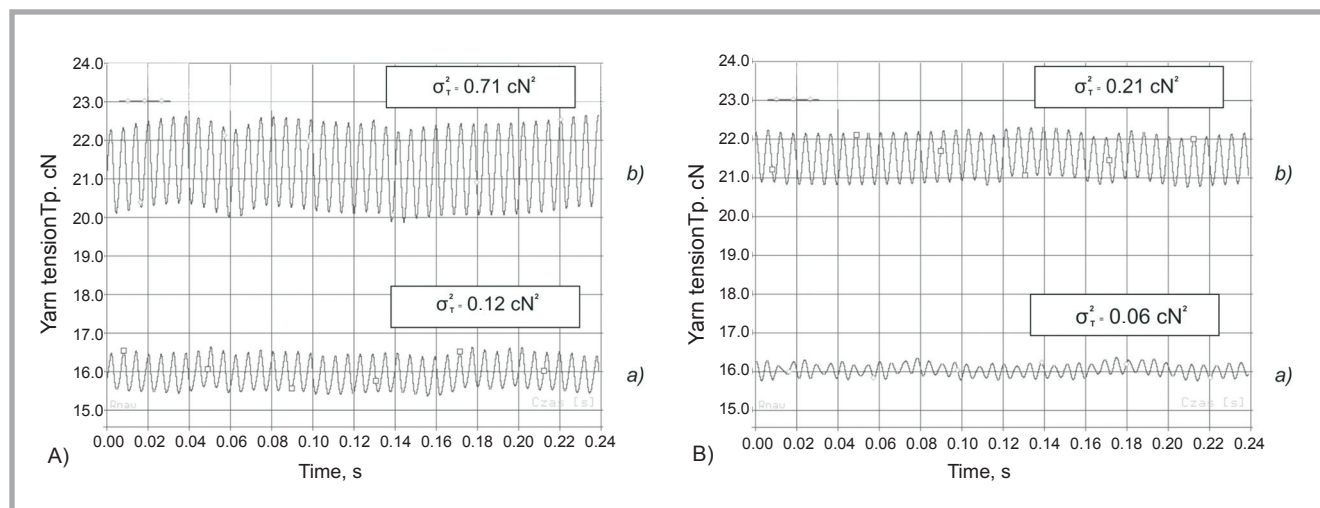


Figure 6. Yarn tension $T_P = T_P(t)$ curve within the conventional spinning zone: A) K and B) M resulting from changes in the bobbin radius; a) – maximum package radius, b) – bobbin radius, σ_T^2 – tension variance.

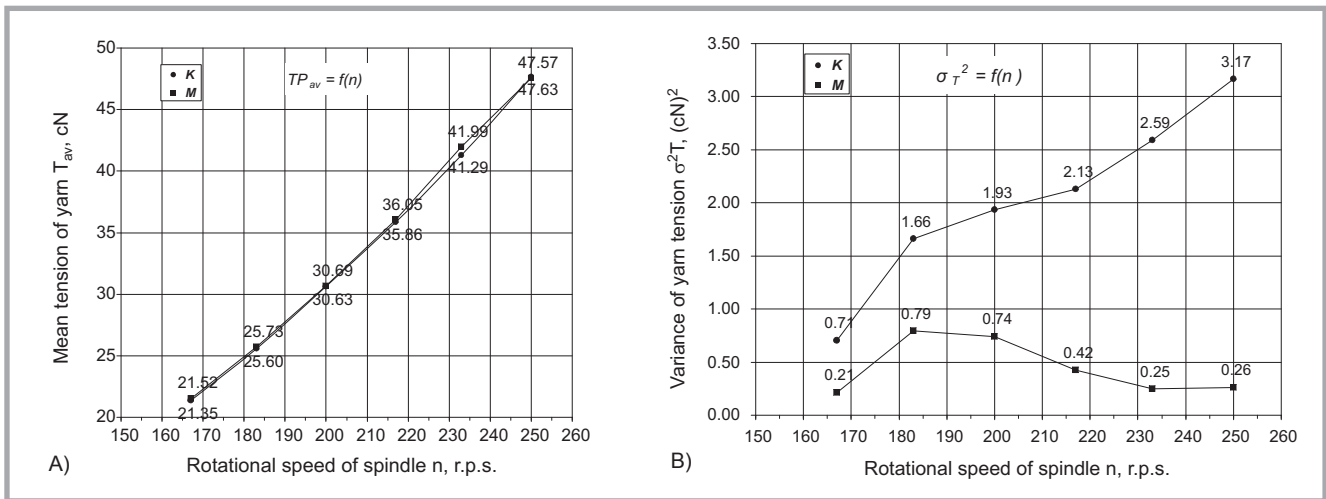


Figure 7. Mean tension of yarn (a) and yarn tension variance = $f(n)$ (b) on objects K and M analysed caused by changes in the rotational speed of the spindle.

Effect of changes in the rotational speed of the spindle on the tension of yarn within the conventional and compact spinning zones

The influence of the spindle speed on the tension of yarn in the objects compared is presented in **Figure 7**. Changes in the mean tension as a function of the rotational speed of the spindle - is presented in **Figure 7.A**. Changes in the tension variance as a function of the rotational speed of the spindle - is presented in **Figure 7.B**.

Taking into consideration mean values of yarn tension within the spinning zone resulting from changes in the rotational speed of the spindle, it becomes evident that both objects K and M are equally sensitive to changes in the spindle speed. Similar to the first experiment, differences are noticed only with respect to values of the tension variance - (**Figure 7.B**). As is visible during the formation of yarn within the conventional object K, along with an increase in the rotational speed of the traveller, a very rapid increase in tension fluctuation is observed. In the case of the author's compact object M, generally lower values of tension fluctuations are observed. A visible increase in the amplitude of tension fluctuations within the range $n \in < 183, 200 >$ r.p.s. is probably caused by a change in balloon geometry [2, 7, 8].

Effect of changes in the mass of the traveller on the tension of yarn within the conventional and compact spinning zones

Also in this experiment, differences in the sensitiveness of the objects exam-

ined, K and M, to changes in the mass of the traveller are reflected only in the values of tension variance within the spinning zone, as presented in **Figure 8**, where $\sigma_T^2 = f(m_{tr})$. It appears from the above that in object K, along with an increase in the mass of the traveller, a very rapid increase in tension variance of the yarn is observed. In object M tension fluctuations are considerably lower.

Technological efficiency of the ring spinning machine with a conventional drafting unit and modified drafting unit

The technological efficiency of the real objects examined were evaluated on the grounds of the measured parameters of yarns manufactured on a ring spinning machine with conventional and modified spinning zone geometry [6]. Examples of longitudinal views of yarns and values of basic yarn parameters are presented in **Table 2**.

It can be stated that the quality of yarn manufactured on the spinning machine equipped with the author's compact spinning zone is higher in comparison with that manufactured in the conventional spinning zone, which is particularly reflected in the value of hairiness ratio measured with the Uster Tester 3 apparatus. Its value for compact yarn is ca. 15% lower in comparison with conventional yarn. The above was confirmed by tests of hairiness and hairiness variation performed on the Shirley's apparatus. This refers mainly to the hairiness measured from the number of fibres at a distance of 3 mm and 5 mm from the yarn surface. The hairiness of compact yarn in comparison with conventional yarn is

lower, respectively: for 3 mm – by about 20%, and for 5 mm – 30%. Besides this, the yarn is more uniform. The reported reduction in the hairiness of yarns manufactured on a ring spinning machine type PJ, equipped with the original compact unit, corresponds with results published in [3, 10, 12]. Moreover the compact yarn manufactured shows lower 'roughness', characterised by a friction coefficient variation between the yarn and steel, and has a higher tenacity and coefficient of twist.

It is probable that the higher quality of compact yarns is a combined effect of more accurate preparation of sliver fibre within the compression zone [3, 10 - 15], as well as of diminishing yarn tension fluctuations and reduction in twist propagation 'hampering' within the spinning zone. The hypothesis formulated requires further tests to be carried out.

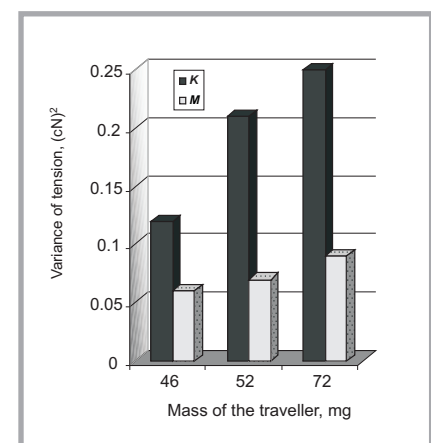


Figure 8. Yarn tension variance = $f(m_{tr})$ on objects K and M caused by changes in mass of the traveller.

Table 2. Parameters of yarns manufactured on a ring spinning machine equipped with a conventional drafting unit and modified drafting unit.

No.	Parameter of yarn	Unit	Value of parameter	
			Conventional yarn K	Compact yarn M
1.	Linear density of yarn	tex	24.8	24.5
2.	Coefficient of linear density variation CV_{1cm}	%	13.1	13.0
3.	Hairiness according to Shirley ■ 1 mm ■ 3 mm ■ 5 mm	1/m	180.1	178.4
			54.7	43.5
			8.3	5.7
4.	Coefficient of hairiness variation according to Shirley ■ 1 mm ■ 3 mm ■ 5 mm	%	1.7	1.2
			6.6	5.4
			4.7	3.6
5.	Hairiness ratio according to Uster Tester 3	-	6.7	5.8
6.	Tenacity	cN/tex	13.2	14.8
7.	Elongation	%	5.6	5.8
8.	Metric twist factor of yarn	-	104	105
9.	Coefficient of friction between yarn and steel	-	0.16	0.16
	Coefficient of variation for coefficient of friction	%	6.41	6.18

Conclusions

Results of numerical analyses of yarn tension based on the dynamic model of yarn passing through the spinning zone of a ring spinning machine lead to the conclusion that changes in the spinning zone geometry of the Polish ring spinning machine PJ 35 caused by the supplementary installation of the compression unit M designed by the authors on the conventional tensioning unit K:

- have no influence on the time-depending shape of yarn tension. Comparison of curves 6 and 7 shows that both present harmonic changes and random noise. The harmonic frequency is equal to the rotation speed of yarn and traveller rotating around the spindle axis. The random noise is caused by the random non-uniformity of the linear density of yarn and by the friction coefficient of yarn against the elements of the twisting and winding unit.
- have no influence on the yarn mean tension. Both units K and M generate a nearly equal mean yarn tension,
- diminish yarn tension variance. Fluctuations of yarn tension in compact zone M are nearly twice lower than in the conventional zone K.

Answering the question asked in the introduction, it can be stated that changes in the spinning zone geometry of the

Polish ring spinning machine PJ 35 caused by the supplementary installation of the author's compression unit M on the conventional tensioning unit K, do not disturb the stability of the ring spinning balloon.

The conclusions presented refer to the results of numerical experiments carried out.

Tests conducted in semi-technical conditions on a conventional K and modified M ring spinning machine also proved our conclusions, as can be seen in the quality parameters presented in **Table 2**.

Therefore it can be stated that the quality of yarn manufactured on the spinning machine equipped with the author's compact spinning zone is higher in comparison with that manufactured in the conventional spinning zone.

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