THE INFLUENCE OF THE CURVATURE RADIUS OF THE GUIDING SURFACE ON THE TENSION OF POLYETHYLENE AND POLYAMIDE COMPLEX YARNS DURING PROCESSING ON WEAVING AND KNITTING MACHINES

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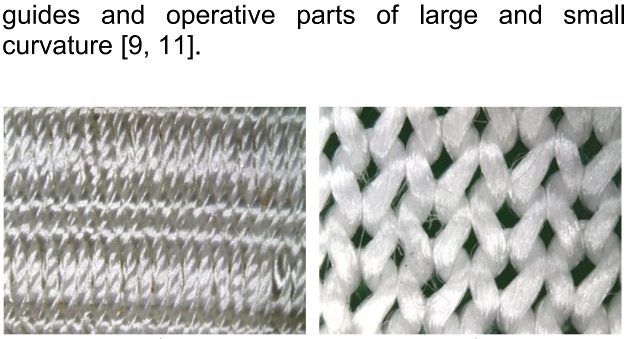
Abstract: *Researches that have been carried out to determine polyethylene and polyamide multifilament yarns tension when interacting with guides and operative parts (of large and small curvature) of looms and knitting machines, helped to establish the mechanism for the process of increase in polyethylene and polyamide multifilament yarns tension after the guide which can be attributed to friction forces in the contact area. It has been proved that increase in tension is explained by varying contact angle between polyethylene and polyamide multifilament yarns and large curved and small curved guides; notably, actual angle for multifilament yarns will be larger comparing to nominal one due to distortion of yarn's cross-section in the contact area. Based on experimental researches for polyethylene and polyamide multifilament yarns, regression dependencies were obtained between the value of tension for polyethylene and polyamide multifilament yarns after the guides and tension before a guide, radius of guide surface curve, a contact angle. Analysis of these regression dependencies allowed to establish extreme values of guide's curve radius at which tension will have the minimum value. As a result, it has been made possible (still at the initial stage of the computer aided manufacturing and usage of recursion) to determine polyethylene and polyamide multifilament yarns tension before fabric and knit formation area depending on geometric and design parameters of equipment and their mechanical and physical properties. Thereby leading to decrease in polyethylene and polyamide multifilament yarns breakages, increase in looms and knitting machines performance due to reduced downtime, and improvement of quality of manufactured fabric and knit. Whereby, we can state that the offered engineering solutions are practically attractive. In particular, the latter deal with determining most suitable geometrical dimensions of guide and operative parts of looms and knitting machines, at which output tension will have minimum necessary value. The procedure has been determined to regulate directionally the process of change in yarns tension at looms and knitting machines by fitting of geometrical dimensions of large curved and small curved guides for polyethylene and polyamide multifilament yarns.*

Keywords: *polyethylene and polyamide multifilament yarn, tension, large curved and small curved guides, contact angle, guide's curve radius.*

1 INTRODUCTION

Industrial fabrics made of polyamide multifilament yarns (Figure 1a) and knits made of polyethylene multifilament yarns (Figure 1b) are the most commonly used in different industry spheres [1-5]. It can be explained by their unique physical and mechanical properties.

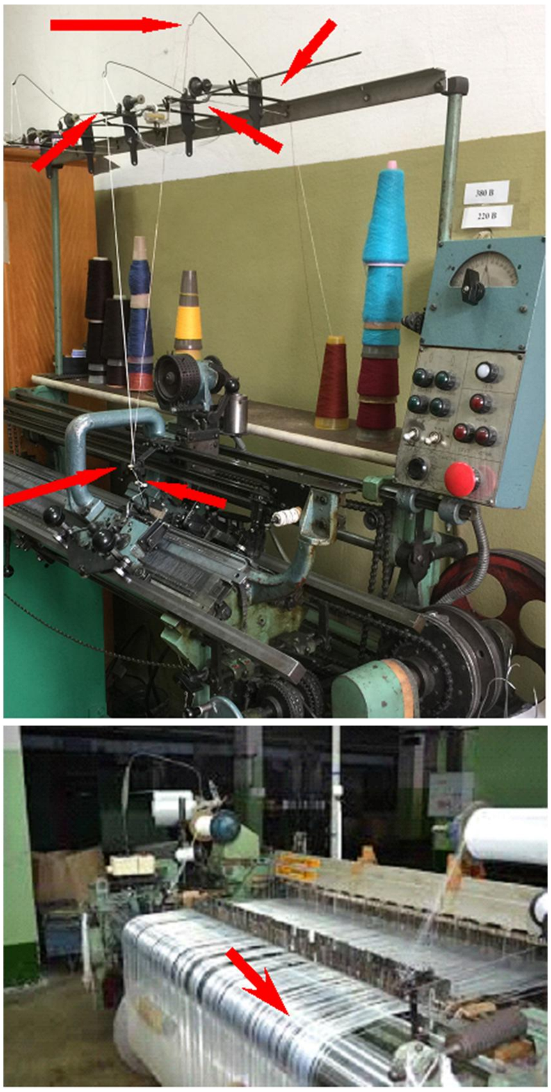
Determination of the value of yarn tension in the working site of technological machine during spun yarn rewinding [6, 7] (loom [8-10], knitting machine [3, 4, 11-14]) makes it possible to evaluate progress density of technological process. The main peculiarity of the most technological processes in textile industry is interaction between yarns and guides and operative parts of large and small curvature [9, 11].



a) b)

Figure 1 Industrial fabrics and knits: (a) multilayer industrial fabric of polyamide multifilament yarns; (b) knit of polyethylene multifilament yarns

Tension of polyamide and polyethylene multifilament yarns before knit manufacturing area (Figure 2a) and multilayer industrial fabric formation area (Figure 2b) includes threading tension and additional tension arising due to friction forces between warp yarns and guides and operative parts of the loom, which are of cylindrical or relatively equal form [13].

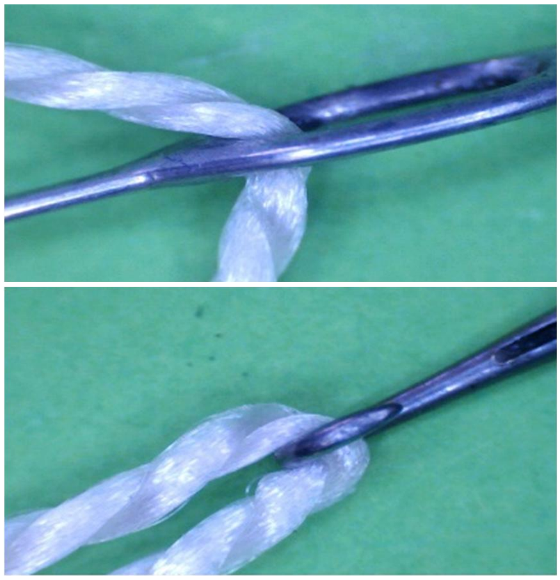


a)

b)

Figure 2 Threading line in the knitting machine (a) and in the loom (b)

Updating of technological processes for manufacturing of multilayer industrial fabrics [2, 3] and knits made of polyethylene and polyamide multifilament yarns involves enhancement of technological efforts based on minimization of yarns tension in the multilayer industrial fabric formation area and knit manufacturing area [4, 11, 14]. Simulation of polyethylene and polyamide multifilament yarns processing process on the loom and knitting machine involves research of interaction between yarns and cylindrical surfaces simulating the following: back-rest surfaces, surfaces of separating rod of yarn break detector, surfaces of heddle eyes of heald frame (Figure 3a) for looms [9]; surfaces of yarns guides, knitting needles surfaces (Figure 3b) for knitting machines [14].



a)

b)

Figure 3 Operative parts of looms and knitting machines: a) heald frame; b) knitting needle

It has been proved that the value of yarns tension before formation area is affected by the number of guides of each specific technological machine, each guide's curve radius, contact angle between yarn(s) and a guide, radial contact angle of yarn(s), mechanical, physical and structural properties of yarns [9, 11, 14]. Values of contact angle between yarn(s) and guides and contact angle between guide's surface and yarn(s) are determined based on geometric parameters and design of both yarn(s) threading system at the production equipment and specific guides [12]. Increase in yarn(s) tension derives from friction forces in the area of contact between the yarns and guides. The value of friction forces is based on yarn(s)' and guides' material [9], curvature of guides' surfaces and operative parts of looms and knitting machines [12], actual contact angle between yarn(s) and large and small curved guides, mechanical, physical and structural properties of polyethylene and polyamide multifilament yarns, as well as tension before a guide. When a yarn passes all guides consecutively from the input area to the fabric and knit formation area, it will result in step-type increase in tension [14]. Output tension parameter after the foregoing guide will be the input parameter for the next guide, thus making it possible to use recursion while calculating tension before the formation area of multilayer industrial fabric [2, 3] and knit. Implementation of this algorithm for determining yarn(s) tension at the production equipment using recursion allows for determining values of yarns tension before fabric and knit formation area at the production equipment [3]. As a result, the possibility appeared (still at the initial stage of the computer aided manufacturing) to determine yarn(s) tension before the multilayer industrial fabric and knit formation area based on geometric and design parameters of equipment, as well as on mechanical, physical and structural properties of polyethylene and polyamide multifilament yarns [14]. Experimental research carried out to determine tension of polyethylene and polyamide multifilament yarns after guide's surface requires to design specific strain-gauge unit. In a proactive planning of the experiment, it is necessary to consider the following: direction of relative shifting of friction surface [16], yarn sliding speed or guide surface movement speed [17, 18], and radius of cylindrical surface curve (guide's curve radius) [19, 20]. The paper [15] emphasizes necessity to consider that spinning of polyamide multifilament yarns affects their bending rigidity. Bending rigidity is significantly affecting the value of actual contact angle between a yarn and guide surface. This has been verified during the research of interaction conditions between polyamide multifilament yarn and guide surface and represented in the paper [4, 14] afterwards.

The papers [9, 11-14] show results of experimental determining of yarns tension with the use of specific units. To increase accuracy of measured polyethylene and polyamide multifilament yarns tension and possibility of ensuring the metrological self-verification, it is better to rely on the method of redundant measurements, which ensures that results of measurements are independent from conversion function parameters, and their deviations are independent from nominal values [21-24]. Design of the experimental unit measures accuracy of the obtained results while determining yarn tension. The papers [17, 18] show the scheme, which helps to determine yarn tension, and includes cylinders with long radius as guides. As its deficiencies, it is important to consider inability to simulate actual conditions of interaction between a yarn and guide and operative parts of looms and knitting machines. Experimental unit with revolving cylinder has the same deficiency [20]. Papers [3, 9, 11, 12] include tension determinations for a variety of cylindrical guide surfaces.

2 EXPERIMENT

As starting materials for experiment the following were chosen: a polyethylene multifilament yarn 44 tex (Figure 4a), which is used to manufacture ultra-strong knits intended to produce items for military serviceman; a polyamide multifilament yarn 58 tex (Figure 4b), which is used to manufacture ultra-strong multilayer industrial fabrics intended for forceful takeovers, laying yard-coated oil and gas pipes.

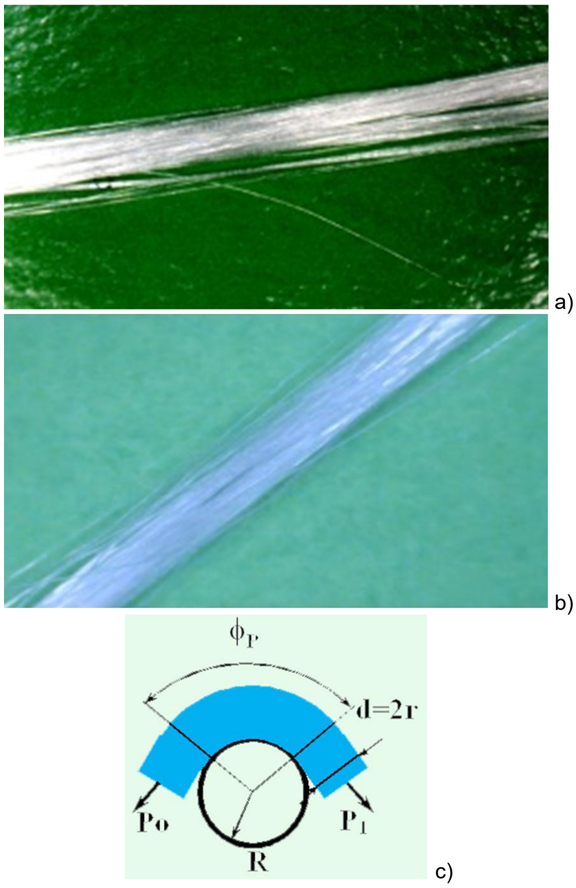


Figure 4 Multifilament yarns: a) polyethylene multifilament yarn 44 tex; b) polyamide multifilament yarn 58 tex; c) diagram of interaction between a yarn and guide

The paper includes three series of implemented experiments: A; B; C for a polyethylene multifilament yarn 44 tex and a polyamide multifilament yarn 58 tex. Series A has been conducted for small curved guides, where guide's radius significantly longer comparing to nominal radius of the yarn cross-sectional view. In addition, tension before a guide has been equal to initial tension while unwinding the yarn from a bobbin of the knitting machine or while unwinding the yarn from the beam of the loom. The value of the input tension (for Series A) varies within the following range: 10-30 cN. The value of the guide's curve radius (for Series A) varies within the following range: from 30-50 mm. The value of the contact angle between the yarn and the guide surface (for Series A) varies within the following range: from 70° to 110°. The above parameters variation ranges conform with yarns entering production area.

Series B has been performed for guides with mean curvature, when guide's radius is commensurate with the various guides' radii of looms and knitting machines. In addition, tension before the guide has conformed with tension in the centre of yarns threading line of looms and knitting machines. The value of input tension (for Series B) varies within the following range: 40-60 cN. The value of the guide's surface curve radius (for Series B) varies within the following range: from 4-8 mm. The value of the contact angle between the yarn and the guide surface (for Series B) varies within the following range: from 60° to 110°.

Series C has been performed for guides with large curvature, when guide's radius is comparable to radii of polyethylene and polyamide multifilament yarns' cross-sections. In addition, tension before the guide has conformed with yarn tension in the multilayer industrial fabric formation area of the looms and yarn tension before knitting area of the knitting machines. The value of input tension (for Series C) varies within the following range: 50-80 cN. The value of the guide's curve radius (for Series C) varies within the following range: from 0.5-2 mm. The value of the contact angle between the yarn and the guide surface (for Series C) varies within the following range: from 90° to 180°.

For series A, series B and series C the paper provides a plan and implementation of the second-order orthogonal design for three factors to determine combined influence of input tension of a yarn P_0, cylindrical guide radius R, and nominal value of contact angle φ_P to output tension of a yarn P. The diagram of interaction between a yarn and guide is shown in Figure 4c). Overall form of regression equation is as follows:

$$P = b_0 + b_1x_1 + b_2x_2 + b_3x_3 + b_{12}x_1x_2 + \\ +b_{13}x_1x_3 + b_{23}x_2x_3 + +b_{11}x_1^2 + b_{22}x_2^2 + b_{33}x_3^2 \quad (1)$$

where: x_1 - the value of polyethylene and polyamide multifilament yarns input tension before guide surface; x_2 - guide's curve radius; x_3 - nominal value of contact angle between polyethylene and polyamide multifilament yarns and guide's surface.

Table 1 shows matrix of orthogonal design for determining polyethylene and polyamide multifilament yarns tension after guide's surface for series A.

Table 1 Matrix of orthogonal design for determining polyethylene and polyamide multifilament yarns tension after guide's surface for series A

№	Factors					
	Input tension		Curvature radius		Contact angle	
	x_1	P_{0A} [cN]	x_2	R_A [mm]	x_3	φ_{PA} [°]
1	+1	30	+1	50	+1	110
2	-1	10	+1	50	+1	110
3	+1	30	-1	30	+1	110
4	-1	10	-1	30	+1	110
5	+1	30	+1	50	-1	70
6	-1	10	+1	50	-1	70
7	+1	30	-1	30	-1	70
8	-1	10	-1	30	-1	70
9	-1.215	8	0	40	0	90
10	+1.215	32	0	40	0	90
11	0	20	-1.215	28	0	90
12	0	20	+1.215	52	0	90
13	0	20	0	40	-1.215	66
14	0	20	0	40	+1.215	114
15	0	20	0	40	0	90

Connection between open-label and coded values for series A is as follows:

$$x_1 = \frac{P_{0A} - 20}{10}, x_2 = \frac{R_A - 40}{10}, x_3 = \frac{\varphi_{PA} - 90}{20} \quad (2)$$

At the second stage the tension is determined, when guide's radius is comparable to radii of different guides of looms and knitting machines. Table 2 shows matrix of orthogonal design for determining polyethylene and polyamide multifilament yarns tension after guide's surface for series B.

Table 2 Matrix of orthogonal design for determining polyethylene and polyamide multifilament yarns tension after guide's surface for series B

№	Factors					
	Input tension		Curvature radius		Contact angle	
	x_1	P_{0B} [cN]	x_2	R_B [mm]	x_3	φ_{PB} [°]
1	+1	60	+1	8	+1	100
2	-1	40	+1	8	+1	100
3	+1	60	-1	4	+1	100
4	-1	40	-1	4	+1	100
5	+1	60	+1	8	-1	60
6	-1	40	+1	8	-1	60
7	+1	60	-1	4	-1	60
8	-1	40	-1	4	-1	60
9	-1.215	38	0	6	0	80
10	+1.215	62	0	6	0	80
11	0	50	-1.215	3.6	0	80
12	0	50	+1.215	8.4	0	80
13	0	50	0	6	-1.215	56
14	0	50	0	6	+1.215	104
15	0	50	0	6	0	80

Connection between open-label and coded values for series B is as follows:

$$x_1 = \frac{P_{0B} - 50}{10}, x_2 = \frac{R_B - 6}{2}, x_3 = \frac{\varphi_{PB} - 80}{20} \quad (3)$$

At the third stage the tension is determined when guide's radius is comparable to radii of polyethylene and polyamide multifilament yarns cross-sectional view. Table 3 shows matrix of orthogonal design for determining polyethylene and polyamide multifilament yarns tension after guide's surface for series C.

Connection between open-label and coded values for series C is as follows:

$$x_1 = \frac{P_{0c} - 60}{20},$$

$$x_2 = \frac{R_C - 0.75}{0.25},$$

$$x_3 = \frac{\varphi_{PC} - 135}{145} x_1 = \frac{P_{0B} - 50}{10}, \quad (4)$$

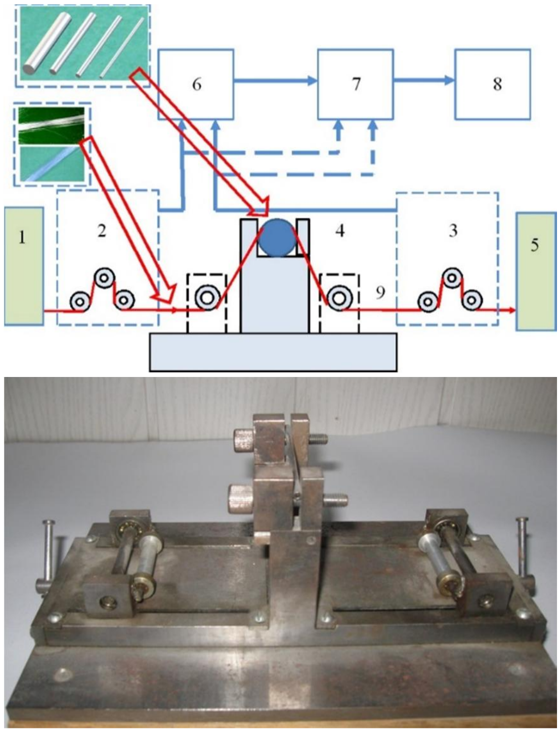
$$x_2 = \frac{R_B - 6}{2}, x_3 = \frac{\varphi_{PB} - 80}{20}$$

Table 3 Matrix of orthogonal design for determining polyethylene and polyamide multifilament yarns tension after guide's surface for series C

№	Factors					
	Input tension		Curvature radius		Contact angle	
	x_1	P_{0C} [cN]	x_2	R_C [mm]	x_3	φ_{PC} [°]
1	+1	80	+1	1	+1	180
2	-1	40	+1	1	+1	180
3	+1	80	-1	0.5	+1	180
4	-1	40	-1	0.5	+1	180
5	+1	80	+1	1	-1	90
6	-1	40	+1	1	-1	90
7	+1	80	-1	0.5	-1	90
8	-1	40	-1	0.5	-1	90
9	-1.215	36	0	0.75	0	135
10	+1.215	84	0	0.75	0	135
11	0	60	-1.215	0.4	0	135
12	0	60	+1.215	1.1	0	135
13	0	60	0	0.75	-1.215	80
14	0	60	0	0.75	+1.215	190
15	0	60	0	0.75	0	135

Figure 5a) shows principal scheme of experimental unit. Unit 1 represents yarns threader and tensioner. Input tension has been generated with a help of cymbal yarn tensioner.

Units 2 and 3 are intended to measure slack side and tight side tension of the yarn 9. They include two rollers, which are installed in bearings of the stationary axle. The third roller is installed on the cantilever fitted beam in a way that inner ring of bearing fitted on it, and roller interacting with the yarn is rigidly fixed with outer ring of the bearing. Friction forces in bearings can be neglected. The warp yarn has been loomed up to the pulley in a way that slack side and tight side have been placed at both sides of right triangle. Affected by warp yarn tension, central bar has been bending which has resulted in variations in resistance of strain-gauge indicator. These variations have been registered at the corresponding channel of the amplifier 8ANCH-7M. Lateral and longitudinal dimensions of the beam have been chosen such that free-running frequency of the beam has been 1400 Hz. This frequency goes beyond frequency of the highest tension component way more. Figure 5b) represents central metering unit 4 of the experimental unit. This metering unit is intended for simulation of interaction conditions between the yarn 9 and cylindrical guides. Two slider pairs, on which aluminium rollers are fixed in rotation bearings, are installed on the foundation in the horizontal grooves. The position of the slider pairs with respect to the central fixed bracket is changed with the help of two screw pairs by turning the two levers on the left and on the right. The central, fixed vertical bracket serves to secure the cylinder guides of different diameters, needles of knitting machine, heddles. The fastening is carried out by two screw pairs and clamping bars.



a)

b)

Figure 5 Scheme of the experimental unit: a) principal scheme: 1 - the yarn threading unit; 2 - metering unit for slack side tension of the yarn; 3 - metering unit for tight side tension of the yarn; 4 - unit for simulation of interaction conditions between the yarn and guides and operative parts of the textile machinery; 5 - yarn receiving unit; 6 - amplifier; 7 - analogue-to-digital converter ADC; 8 - PC; 9 - the yarn; b) central metering unit

The warp yarn 9 speed was varied due to a fixed ratio round belt transmission (the 5th unit at Figure 5a). Driving pulley of the transmission is rotated by AC motor that was firmly fixed to the foundation of the main measurement system. Analogue signals from the 3rd and 4th units measuring yarn tension are being received by the amplifier 6 or by analogue-to-digital converter 7, enabled as a multifunction board L-780M with signalling processor ADC 14 bit/400 kHz having 16 differential input analogue and output digital channels, which is connected to the PCI-connector 8.

3 RESULTS AND DISCUSSION

Resulting from implemented plan of the experiment (Table 2) for variant 1 (A), variant 2 (B), variant 3 (C) and variant 4 (D), I area, there were 10 parallel measurements for each variant.

Applying popular method for determining coefficients in the regression equation (1) for the second order orthogonal design the values if the coefficients have been determined and represented in Table 4 for series A, series B and series C.

Table 4 Coefficients values in regression equations (1) for series A, series B and series C

Series	Polyethylene multifilament yarn 44 tex	Polyamide multifilament yarn 58 tex
A	b_0 = 25.7908 b_1 = 11.9401 b_2 = 0.339144 b_3 = 1.37034 b_{11} = -0.138088 b_{12} = 0.14375 b_{13} = 0.52875 b_{22} = -0.0354837 b_{23} = 0.08875 b_{33} = 0.0248715	b_0 = 27.1641 b_1 = 12.8646 b_2 = 0.210052 b_3 = 1.76228 b_{11} = -0.100905 b_{12} = 0.0925 b_{13} = 0.775 b_{22} = -0.0194259 b_{23} = 0.065 b_{33} = 0.0499825
B	b_0 = 56.9215 b_1 = 10.8305 b_2 = 0.298468 b_3 = 1.64657 b_{11} = -0.0227247 b_{12} = 0.04625 b_{13} = 0.24875 b_{22} = -0.00160041 b_{23} = 0.12875 b_{33} = 0.0195239	b_0 = 62.0331 b_1 = 11.8738 b_2 = -0.0135212 b_3 = 2.978 b_{11} = -0.019865 b_{12} = -0.00375 b_{13} = 0.52125 b_{22} = 0.0857566 b_{23} = 0.09875 b_{33} = 0.06765
C	b_0 = 72.9452 b_1 = 22.9467 b_2 = -1.39519 b_3 = 3.17507 b_{11} = -0.186325 b_{12} = -0.39 b_{13} = 0.7225 b_{22} = 0.725039 b_{23} = 0.135 b_{33} = -0.0112949	b_0 = 92.5662 b_1 = 29.1817 b_2 = -6.02246 b_3 = 8.88939 b_{11} = -0.61332 b_{12} = -1.5575 b_{13} = 2.545 b_{22} = 2.82994 b_{23} = -0.58 b_{33} = -0.0731409

Resulting from the implemented second order orthogonal design for three factors (Table 1) for series A, there were 10 parallel measurements and their average values represented in Table 5.

Table 5 Results of the experimental researches aimed at determining combined influence of yarn tension before the guide, guide's radius and nominal value of the contact angle on the yarn tension after the guide, when guide's radius is far longer comparing to nominal radius of yarn's cross-sectional view (series A)

№	Factor			P_{AE} [cN]	P_{AA} [cN]
	Input tension	Curvature radius	Contact angle		
	x_1	x_2	x_3		
1	+1	+1	+1	40.35	43.18
2	-1	+1	+1	14.55	15.14
3	+1	-1	+1	39.11	42.38
4	-1	-1	+1	14.07	14.82
5	+1	+1	-1	36.26	37.87
6	-1	+1	-1	12.76	13.04
7	+1	-1	-1	35.56	37.44
8	-1	-1	-1	12.45	12.87
9	-1.215	0	0	10.95	11.25
10	+1.215	0	0	40.19	42.75
11	0	-1.215	0	25.31	26.88
12	0	+1.215	0	26.17	27.39
13	0	0	-1.215	24.11	25.06
14	0	0	+1.215	27.57	29.44
15	0	0	0	25.78	27.16

Applying known method for determining coefficients in the regression equation (1) for the second order orthogonal design, and taking into account dependencies (2) and data from Table 5, regression dependencies have been obtained for series A, where:

$8\ cN \leq P_{0A} \leq 32\ cN,\ 28\ mm \leq R_A \leq 52\ mm,$

$66° \leq \varphi_{PA} \leq 114°$

For the polyethylene multifilament yarn 44 tex:

$$\begin{gathered} P_{AE} = 1.29 + 0.95P_{0A} - 0.007R_A - \\ -0.013\varphi_{PA} + 0.0014P_{0A}R_A + \\ +0.0026P_{0A}\varphi_{PA} + 0.00045R_A\varphi_{PA} - \\ -0.0014P_{0A}^2 - 0.00035R_A^2 + 0.0000\varphi_{PA}^2 \end{gathered} \quad (5)$$

For the polyamide multifilament yarn 58 tex:

$$\begin{gathered} P_{AA} = 1.88 + 0.94P_{0A} - 0.012R_A - \\ -0.025\varphi_{PA} + 0.0009P_{0A}R_A + \\ +0.0039P_{0A}\varphi_{PA} + 0.0001R_A\varphi_{PA} - \\ -0.001P_{0A}^2 - 0.00019R_A^2 + 0.00012\varphi_{PA}^2 \end{gathered} \quad (6)$$

Table 6 represents average values of 10 parallel measurements for series B received resulting from implemented second order orthogonal design for three factors.

Table 6 Results of the experimental researches aimed at determining combined influence of yarn tension before the guide, guide's radius and nominal value of the contact angle on the yarn tension after the guide, when guide's radius is far longer comparing to nominal radius of yarn's cross-sectional view (series B)

№	Factor			P_{BE} [cN]	P_{BA} [cN]
	Input tension	Curvature radius	Contact angle		
	x_1	x_2	x_3		
1	+1	+1	+1	70.39	77.95
2	-1	+1	+1	47.66	52.64
3	+1	-1	+1	69.39	77.74
4	-1	-1	+1	46.92	52.48
5	+1	+1	-1	66.25	70.61
6	-1	+1	-1	44.59	47.45
7	+1	-1	-1	65.84	70.86
8	-1	-1	-1	44.29	47.62
9	-1.215	0	0	43.63	47.48
10	+1.215	0	0	70.14	76.51
11	0	-1.215	0	56.56	62.21
12	0	+1.215	0	57.28	62.13
13	0	0	-1.215	54.92	58.48
14	0	0	+1.215	58.99	65.80
15	0	0	0	56.92	62.04

Applying known method for determining coefficients in the regression equation (1) for the second order orthogonal design, and taking into account dependencies (3) and data from Table 6, regression dependencies have been obtained for series B, where:

$38\ cN \leq P_{0B} \leq 62\ cN,\ 3.6\ mm \leq R_B \leq 8.4\ mm,$

$56° \leq \varphi_{PB} \leq 104°$

For the polyethylene multifilament yarn 44 tex:

$$P_{BE} = 2.22 + 0.993P_{0B} - \\ -0.219R_B - 0.0068\varphi_{PB} + \\ +0.0023P_{0B}R_B + 0.0012P_{0B}\varphi_{PB} + \\ +0.0032R_B\varphi_{PB} - 0.00023P_{0B}^2 - \\ -0.0004R_B^2 + 0.000049\varphi_{PB}^2 \quad (7)$$

For the polyamide multifilament yarn 58 tex:

$$P_{BA} = 3.71 + 0.99P_{0B} - 0.45R_B - \\ -0.023\varphi_{PB} + 0.00019P_{0B}R_B + \\ +0.0026P_{0B}\varphi_{PB} + 0.0025R_B\varphi_{PB} - \\ -0.0001P_{0B}^2 + 0.021R_B^2 + 0.00017\varphi_{PB}^2 \quad (8)$$

Table 7 represents average values of 10 parallel measurements for series C received resulting from implemented second order orthogonal design for three factors.

Table 7 Results of the experimental researches aimed at determining combined influence of yarn tension before the guide, guide's radius and nominal value of the contact angle on the yarn tension after the guide, when guide's radius is far longer comparing to nominal radius of yarn's cross-sectional view (series C)

№	Factor			P_{CE} [cN]	P_{CA} [cN]
	Input tension	Curvature radius	Contact angle		
	x_1	x_2	x_3		
1	+1	+1	+1	99.40	128.42
2	-1	+1	+1	51.58	66.79
3	+1	-1	+1	102.29	143.95
4	-1	-1	+1	53.32	75.51
5	+1	+1	-1	91.09	106.62
6	-1	+1	-1	46.57	54.59
7	+1	-1	-1	94.93	119.25
8	-1	-1	-1	48.44	61.57
9	-1.215	0	0	44.79	56.74
10	+1.215	0	0	100.58	126.95
11	0	-1.215	0	76.31	106.98
12	0	+1.215	0	72.08	88.12
13	0	0	-1.215	68.95	81.89
14	0	0	+1.215	77.00	103.59
15	0	0	0	72.88	92.17

Applying known method for determining coefficients in the regression equation (1) for the second order orthogonal design, and taking into account dependencies (4) and data from Table 7, regression dependencies have been obtained for series C, where

$36\ cN \leq P_{0C} \leq 84\ cN,\ 0.4\ mm \leq R_C \leq 1.1\ mm,$
$80° \leq \varphi_{PC} \leq 190°$

For the polyethylene multifilament yarn 44 tex:

$$P_{CE} = -1657.39 + 56.78P_{0C} - \\ -29.26R_C + 0.012\varphi_{PC} + \\ +0.078P_{0C}R_C + 0.0008P_{0C}\varphi_{PC} + \\ +0.012R_C\varphi_{PC} - 0.465P_{0C}^2 + \\ +11.6R_C^2 + 0.00005\varphi_{PC}^2 \quad (9)$$

For the polyamide multifilament yarn 58 tex:

$$P_{CA} = 20.75 + 1.49P_{0C} - 66.32R_C + \\ +0.056\varphi_{PC} - 0.31P_{0C}R_C + \\ +0.0028P_{0C}\varphi_{PC} - 0.052R_C\varphi_{PC} - \\ -0.0015P_{0C}^2 + 45.28R_C^2 + 0.0001\varphi_{PC}^2 \quad (10)$$

For nominal value of the contact angle $\varphi_{PA} = 90°$ in the centre of experiment, equations (5), (6) rearrange as follows:

$$P_{AE} = 0.59 + 1.19P_{0A} + 0.03R_A + \\ +0.0014P_{0A}R_A - 0.0014P_{0A}^2 - 0.00035R_A^2 \quad (11)$$

$$P_{AA} = 0.64 + 1.29P_{0A} + 0.018R_A + \\ +0.00093P_{0A}R_A - 0.001P_{0A}^2 - 0.00019R_A^2 \quad (12)$$

For nominal value of the contact angle $\varphi_{PB} = 80°$ in the centre of experiment, equations (7), (8) rearrange as follows:

$$P_{BE} = 1.98 + 1.09P_{0B} + 0.039R_B + \\ +0.0023P_{0B}R_B + 0.00023P_{0B}^2 - 0.0004R_B^2 \quad (13)$$

$$P_{BA} = 2.94 + 1.21P_{0B} - 0.23R_B - \\ -0.00019P_{0B}R_B - 0.0002P_{0B}^2 + 0.021R_B^2 \quad (14)$$

For nominal value of the contact angle $\varphi_{PC} = 135°$ in the centre of experiment, equations (9), (10) rearrange as follows:

$$P_{CE} = -1655.70 + 56.89P_{0C} - 27.64R_C + \\ +0.078P_{0C}R_C - 0.465P_{0C}^2 + 11.6R_C^2 \quad (15)$$

$$P_{CA} = 29.03 + 1.88P_{0C} - 73.27R_C - \\ -0.31P_{0C}R_C - 0.0015P_{0C}^2 + 45.28R_C^2 \quad (16)$$

Figure 6 represents response surfaces for series A, series B, and series C. Adequacy of obtained regression dependencies has been verified with SPSS program for statistical processing of experimental data [9, 10].

For nominal value of the contact angle $\varphi_{PA} = 90°$, yarn tension before the guide $P_{0A} = 20\ cN$, in the centre of experiment, equations (11), (12) rearrange as follows:

$$P_{AE} = 23.87 + 0.062R_A - 0.0004R_A^2 \quad (17)$$

$$P_{AA} = 26.01 + 0.036R_A - 0.00019R_A^2 \quad (18)$$

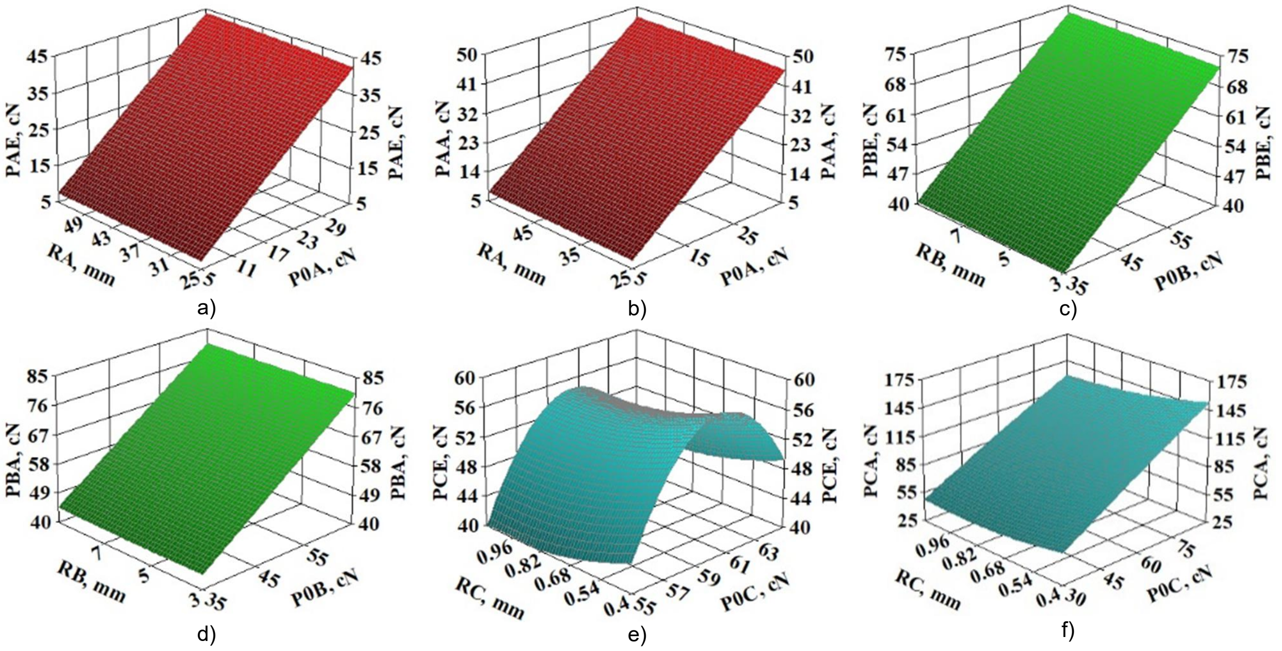


Figure 6 Response surfaces for series A, B and C created to determine combined influence of the yarn tension before the guide and guide’s radius on the yarn tension after the guide: for the polyethylene multifilament yarn 44 tex: a) series A, c) series B, e) series C; for the polyamide multifilament yarn 58 tex: b) series A, d) series B, f) series C

Figure 7 represents graphical dependencies (curves) reflecting influence of guide’s radius on yarn tension after the guide for series A, that have been obtained with the use of dependencies (17), (18).

in the centre of experiment, equations (13), (14) rearrange as follows:

$$P_{BE} = 56.01 + 0.154R_B - 0.0004R_B^2 \quad (19)$$

$$P_{BA} = 62.84 - 0.24R_B + 0.021R_B^2 \quad (20)$$

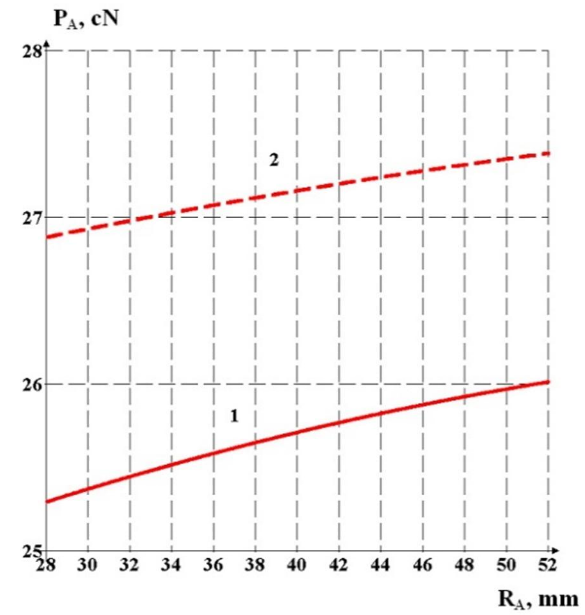


Figure 7 Graphical dependencies (curves) reflecting influence of guide’s radius on yarn tension after the guide for series A: 1 - for the polyethylene multifilament yarn 44 tex; 2 - for the polyamide multifilament yarn 58 tex

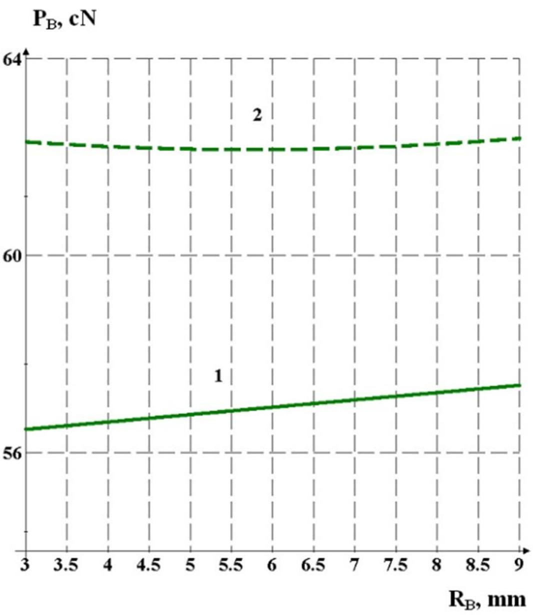


Figure 8 Graphical dependencies (curves) reflecting influence of guide’s radius on yarn tension after the guide for series B: 1 - for the polyethylene multifilament yarn 44 tex; 2 - for the polyamide multifilament yarn 58 tex

For nominal value of the contact angle $\varphi_{PB} = 80°$, yarn tension before the guide $P_{0B} = 50\ cN$,

For nominal value of the contact angle $\varphi_{PC} = 135°$, yarn tension before the guide $P_{0C} = 60\ cN$, in the centre of experiment, equations (15), (16) rearrange as follows:

$$P_{CE} = 83.86 - 22.96R_C + 11.6R_C^2 \qquad (21)$$

$$P_{CA} = 136.07 - 91.99R_C + 45.28R_C^2 \qquad (22)$$

Figure 9 represents graphical dependencies (curves) reflecting influence of guide's radius on yarn tension after the guide for series C, that have been obtained with the use of dependencies (21), (22).

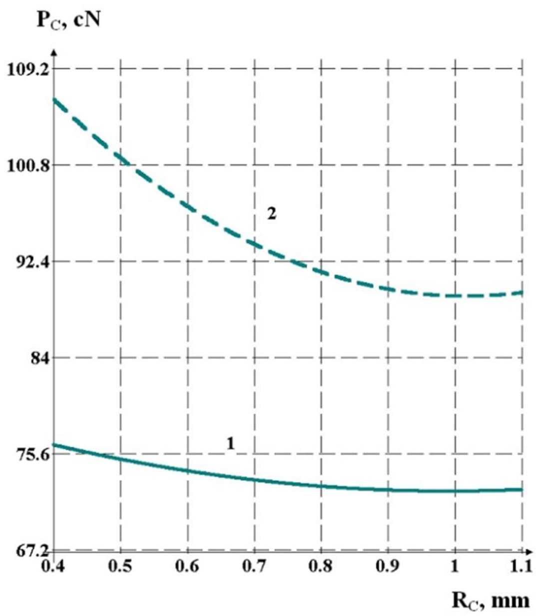


Figure 9 Graphical dependencies (curves) reflecting influence of guide's radius on yarn tension after the guide for series C: 1 - for the polyethylene multifilament yarn 44 tex; 2 - for the polyamide multifilament yarn 58 tex

4 CONCLUSIONS

Resulting from carried out complex experimental researches for polyethylene and polyamide multifilament yarns, there have been obtained regression dependencies between value of yarn tension after the guide and yarn tension before the guide, guide's surface curve radius, and contact angle. Researches that have been carried out to determine polyethylene and polyamide multifilament yarns tension when interacting with guides and operative parts (of large and small curvature) of looms and knitting machines, helped to establish the mechanism for the process of increase in polyethylene and polyamide multifilament yarns tension after the guide which can be attributed to friction forces in the contact area. It has been proved that increase in tension can be explained by varying contact angle between polyethylene and polyamide multifilament yarns and large and small curvature guides. In addition, the actual contact angle for multifilament yarns will be larger than nominal one due to distortion of the yarn's cross-section in the contact area.

The paper includes three series of experiments (A; B; C) implemented for the polyethylene multifilament yarn 44 tex and the polyamide multifilament yarn 58 tex. Series A has been carried out for small curved guides, where guide's radius significantly longer comparing to nominal radius of the yarn cross-section. In addition, tension before the guide varies within the following range $8\,cN \le P_{0A} \le 32\,cN$, the value of the guide's surface curve varies within the following range $28\,mm \le R_A \le 52\,mm$, the value of the contact angle between the yarn and guide's surface, for series A, varies within the following range $66° \le \varphi_{PA} \le 114°$.

Series B has been performed for guides with mean curvature, when guide's radius is commensurate with the various guides' radii of looms and knitting machines. In addition, tension before the guide varies within the following range $38\,cN \le P_{0B} \le 62\,cN$, the value of the guide's surface curve radius varies within the following range $3.6\,mm \le R_B \le 8.4\,mm$, and the value of the contact angle between the yarn and the guide surface, for series B, varies within the following range $56° \le \varphi_{PB} \le 104°$.

Series C has been performed for guides with large curvature, when guide's radius is comparable to radii of polyethylene and polyamide multifilament yarns' cross-section. In addition, tension before the guide varies within the following range $36\,cN \le P_{0C} \le 84\,cN$, the value of the guide's surface curve radius varies within the following range $0.4\,mm \le R_C \le 1.1\,mm$, the value of the contact angle between the yarn and the guide surface, for series C, varies within the following range $80° \le \varphi_{PC} \le 190°$.

As a result, it has been made possible (still at the initial stage of the computer aided manufacturing with usage of recursion) to determine polyethylene and polyamide multifilament yarns tension before fabric and knit formation area depending on geometric and design parameters of equipment and their mechanical and physical properties. Obtained results may be used when improving technological processes in textile and knitting industries.

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