AN INVESTIGATION OF THE TECHNOLOGY OF FLAX-CONTAINING YARN PRODUCTION

By

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ABSTRACT

The aim of the work was to improve understanding of structure and properties of cotton-flax yarn and to make recommendations on the yarn quality assessment and acceptable levels of quality criteria.

The main objectives of the study were to make recommendations on the norm of irregularity of ready to use cotton-flax yarn; to investigate the effects of cellulase-based enzymes on the mechanical and surface properties of cotton-flax yarn by application to flax fibre; to investigate fibre migration in yarn; to study yarn hairiness, winding friction coefficient, unevenness in diameter and linear density, tenacity and elongation; to define influence of twist on strength and unevenness of open-end flax blended yarn; to conduct complex assessment of the quality of cotton-flax yarn for knitting.

A review of the development of spinning technology for cotton-flax blends processing and the application of enzymes at different stages of flax fibre processing was carried out. The following subjects were reviewed: morphological structure and chemical composition of flax; primary treatment of flax fibre in the preparation stages for spinning; flax fibre properties in comparison with cotton; methods of flax fibre cottonizing; biochemical methods of flax modification and their application in textile technology; studies related to the processing of fibre blends; influence of flax percentage in blend on yarn quality; production lines of cotton-flax blends processing.

Estimations of hypothetical and actual irregularity, and the index of spinning products irregularity were made. The reasons for the unevenness formation were investigated using spectrogram analysis. The unevenness guidelines for cotton-flax yarn were rated using the recommended unevenness index and the calculated ideal unevenness.

Quantitative assessments of the radial distribution in the cross section of cotton-flax yarns showed that flax fibres are preferentially located in the outer layers of yarn cross-sections. The effect of spinning method on the fibre migration pattern in cotton-flax yarn was investigated. In comparison with open-end yarn the migration pattern in ring-spun yarn showed more significant radial migration of flax component to outer layers of yarn cross-section.
The influence of blend composition on the surface properties of two- and three-component yarns obtained using different spinning methods was determined.

The effect of twist level on yarn tenacity and its variation was investigated. The analysis of regression equations for yarn tenacity and unevenness in strength against twist factor enabled an identification of the presence of an optimal twists zone that makes it possible to produce yarn with decreased variation in strength.

Application of enzyme treatments comprising a cellulase complex for processing of cotton-flax blends enables cotton-flax yarn with reduced hairiness and improved mechanical properties to be produced. The results obtained showed the potential for biochemical removal of fine dust with simultaneous improvement of flax hygroscopic properties.

It was found that diversification of available knitting threads by use of cottonised flax in blends with cotton is possible and expedient. The flax-like appearance of the material is in demand and the properties of the cotton-flax twisted yarn meet the standard requirements for cotton threads for hand knitting.
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CHAPTER 1 INTRODUCTION

This work was carried out as a joint project between the Department of Mechanical Technology of Fibre Materials at the St Petersburg State University of Technology and Design, St Petersburg, Russia, and the Textile Engineering and Materials Research Group at De Montfort University, Leicester, UK.

The application of flax improves sustainability of textile industry due to the environmental problems associated with cotton cultivation. These problems are related to application of toxic and persistent fertilisers and use of irrigated water. Cotton cultivation uses approximately 25% of the world's insecticides and more than 10% of the pesticides (Allan Woodburn, 1995). Because of irrigation related to cotton cultivation the Aral Sea has declined in size by seventy-six percent in comparison with its size in the 1960's.

The use of flax in blends with cotton reduces the production costs and improves appearance and handle characteristics of flax-blended yarns and fabric. Cotton-flax yarn is a relatively new and unusual product because it combines fibres with very different properties.

The difference in yarn properties in comparison with conventional cotton yarn raises the question of assessing the overall quality of cotton-flax yarn and the interpretation of the results of standard tests. It should be defined which levels of cotton-flax yarn properties can be considered as acceptable.

The effect of twist on yarn properties is very well known for cotton yarn. However this effect has not been studied thoroughly for spinning of unconventional blends. The influence of twist on variations in yarn strength and elongation is to be defined for open-end cotton-flax yarns.

The existing technology does not provide the necessary level of uniformity in cotton-flax blends because these fibres possess significantly different properties. This makes it difficult to increase the flax fibre content in blends with cotton and produce high quality yarn or fabric. It is therefore necessary to optimise the process of cotton and flax fibre blending. The research is focused on optimising the cotton-flax blends processing. It is proposed to modify the properties of flax fibre so that it would meet the spinners' requirement relating to the compatibility of flax fibre with cotton. It is
important to develop methods of biochemical treatment that provide optimal properties of flax fibres.

The aim of the work was to improve understanding of structure and properties of cotton-flax yarn and to make recommendations on the yarn quality assessment and acceptable levels of quality criteria. The following parameters were considered: yarn hairiness, twist factor, winding friction coefficient, tenacity and elongation, coefficients of variation in breaking load, diameter and linear density.

The aim can be achieved by investigating the technology of cotton-flax yarn production and properties of cotton-flax yarns with specific interest in yarn unevenness, mechanical properties and hairiness.

Specific objectives of this project were as follows:
- to review the development of spinning technology of cotton-flax blends processing;
- to review the application of enzymes at different stages of flax fibre processing;
- to compare actual and standard parameters of unevenness, to make recommendations on the norm of irregularity of ready to use cotton-flax yarn;
- to investigate the effects of cellulase-based enzymes on the mechanical and surface properties of cotton-flax yarn by application to flax fibre;
- to investigate fibre migration in yarn;
- to study yarn hairiness, winding friction coefficient, unevenness in diameter and linear density, tenacity and elongation;
- to define influence of twist on strength and unevenness of open-end flax blended yarn;
- to consider the possibility to apply airflow method (Micronaire) for short flax fibres;
- to conduct complex assessment of the quality of cotton-flax yarn for knitting.

The objectives can be achieved by investigating the structure and properties of flax-containing materials. It should include a comprehensive literature review, application of statistical methods, methods of mathematical modelling, standard methods and equipment for estimation of geometrical and physico-mechanical properties of textile materials.
CHAPTER 2 LITERATURE REVIEW

2.1 Background

Worldwide fashion trends and consumer demands for natural products with good handle characteristics have forced producers to move towards maximum utilization of natural raw materials (Kessler and Kohler, 1996).

Flax as a traditional European-grown fibre can be used as an alternative source of raw material (Kariakin et al., 1993; Ruta, 1995).

Traditional flax processing, for the extraction of long fibres for linen, generates considerable quantities of "waste" product. One such product is short flax fibre which represents up to 65 % of the whole flax fibre production in Russia. Short flax fibre is used for the production of such low-value materials as fibre-board, paper and in fibre reinforced composites. It can also be blended with other (short) fibres and spun on the cotton system into yarns for use in high-quality textiles.

There is currently a renaissance of interest in flax fibre. The recent animation in the flax fibre market is mainly due to the recent advances in processing flax in blends with other fibres. Therefore, alongside conventional flax spinning techniques other spinning techniques are more and more widely adapted to spin flax fibres. A new technology is emerging in which an essential role is played by cotton and wool spinning machinery. It is preferable to have flax fibre processed on machines that are more productive than conventional ones. For that it is necessary to solve the problem of utilisation of low-grade flax fibres, and to improve the quality of end products by blending flax with other fibres. However, to process flax fibre by a system other than flax spinning, additional operations have to be included in the process to make the fibre compatible with the machinery set-up parameters (Czekalski et al., 2002).

Between World Wars I and II considerable efforts have been made to utilize flax instead of cotton or to use it in blends which could be spun on cotton spinning machines (Cierpucha et al., 1995).

It is quite difficult to ensure normal operation of the process of flax-containing yarn production performed on cotton spinning systems. To achieve this flax fibre should be modified to meet the spinners' requirements for compatibility with cotton. One of the
ways to achieve this is biochemical treatment aimed at fibre modification. Studying the influence of enzyme treatment on properties of fibres, yarn and ready-made materials will help to introduce the suggested methods into the industry (Kruticova et al., 1998).

2.2 Morphological structure and chemical composition of flax

Flax is a common name for members of the Linaceae, a family of annual plants, especially members of the genus Linum, and for the fibre obtained from such plants. Flax (several varieties of L. usitatissimum) has been cultivated since prehistoric times (Mayerson, 2002), possibly at first for food.

Flax fibre has a longer history of application than any other commercial fibre. Some historians claim that flax was cultivated by the ancient Mexicans in the earliest period of our civilization. It is known to have been found in the ruins of the Stone Age lake dwellings of Switzerland, and the ancient Egyptians made linen cloth from flax fibres. It was the major source of fibre until the growth of the cotton industry (c.1800) and the competitive use of other fibres, such as jute. Flax has been transplanted from its native localities in Eurasia to all climate zones of the world that provide a suitable habitat (a cool, damp climate) for its cultivation as a fibre plant. While the plant can be grown in nearly every climate zone of the world, it is produced commercially throughout Europe and in some areas of Africa and Asia, Australia, Northern America. The world's main fibre producers include Russia, Poland, France, Ireland, Belgium, Holland, Finland (Matthews, 1947).

The bast fibre plants are grown each year from seed. Flax is harvested for fibre when the leaves have fallen from the lower two-thirds of the stem. When mature they are pulled out of the ground and allowed to wither and dry. The stalks are then separated from the leaves and seeds by drawing through the prongs of a comb. At this stage the stalks contain about 20-25% of fibrous flax (Baines, 1998).

The microscopic view of the cross-section of a flax stem is shown in Figure 2.1 (Troman, 1987). The outermost layer is the epidermis, 2, which is covered by the skin of the stem, 1, named the cuticle. The epidermis, 2, protects the inner layers from damage. Beneath this there are numerous layers of cells forming a soft tissue which is called cortex. This is the live and growing region of the stem.
Adjacent to the cortex there is a zone of smaller and darker cells, which is known as the phloem, 3. This is the tissue through which the essential minerals extracted from the soil pass up to the leaves and flowers.

Situated in the phloem, 3, bundles of bast fibres, 4, are surrounded in a gummy matrix known as the middle lamella. These bundles of fibres run throughout the whole of length of the stem. They give support to the phloem tissues, 3, and additional strength to the stem.

Adjacent to the phloem is the cambium layer, 5, which is also composed of actively growing tissues. The tissues next to the stem centre, named xylem (wood), 6, consist of very large cells whose walls are a complex of cellulose, hemicelluloses and lignins often known as lignocellulose or wood cellulose. The function of these cells is to give strength to the stem and to transport water up from the roots.

The innermost tissues form the core, 7. In a matured stem it is almost destroyed, so it appears as the void, 8.

Fibre bundles, 4, are located along the stem from root to top. Usually long stems contain bundles consisting of shorter elementary fibres.
Flax fibres vary considerably in length depending on the manner of retting and the method employed in decortication. They may range from 15-100 cm and consist of small fibre cells of relatively pure cellulose cemented together in a matrix of middle lamella hemicelluloses, lignin and protopectin. These individual fibre cells average 10-25 mm in length and 14-25 μm in diameter (Truevtsnev et al., 1995 a).

Flax fibre fibrils have various degrees of orientation and crystallinity (Akin et al., 1996, 1998).

Similar to other bast fibres, flax fibres are divided into concentric layers all of which contain cellulose, hemicelluloses and lignin in varying proportions.

The chemical composition of flax fibres is very complex; it includes cellulose and accompanying substances such as pectin, lignin, pentosans, waxes, proteins and mineral substances (Fridland, 1973). Short and long fibres differ significantly in chemical composition, micro- and macrostructure (Table 2.1). The thinnest fibres are located in upper zones of the stem, the thickest in lower zones. The chemical composition of flax fibres is determined by morphological features and methods of processing (Fridland, 1982).

Table 2.1 The chemical composition of flax fibres produced by dew retting (Boruhson et al., 1974)

<table>
<thead>
<tr>
<th>Fibre type</th>
<th>Content, %</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Cellulose</td>
</tr>
<tr>
<td>Combed flax</td>
<td>76.4</td>
</tr>
<tr>
<td>Tow</td>
<td>71.0</td>
</tr>
<tr>
<td>Short fibres</td>
<td>63.1</td>
</tr>
</tbody>
</table>

The chemical composition influences the spinnability of flax fibres. Partial removal of pectin substances results in a reduction of yarn breakage during spinning and consequently to increased yarn breaking load. After complete
removal of pectin substances however, the index of breakage has been found to increase by 50% (Chigaeva, 2002).

Flax cellulose is a linear co-polymer of β-1,4-linked glucose residues in a chain configuration. Each glucose residue is rotated by 180° with respect to its neighbours along the main chain axis. The cellulose polymer (Figure 2.2) therefore assumes the form of a flat ribbon, with hydroxyl groups located at equal distances from the axis, in which the smallest repeating unit is cellobiose and the number of these units per cellulose molecule is a half of the degree of polymerisation. This structure is stabilized by intra- and inter-chain hydrogen bonding and therefore has relatively high hydrophilic properties. These characteristics of cellulose are responsible for its sub-molecular structure, which in turn determines many of its chemical and physical properties (Fridland, 1973).

Flax cellulose is characterised by highly organised repeating units, linear chains with moderate flexibility, numerous reactive hydroxyl groups and strong inter-chain forces, but because of the relatively high lignin and hemicellulose content of the fibre, it presents a lower crystallinity index than cotton cellulose.

Hemicelluloses form 70-80% of flax fibre non-cellulose components. Hemicelluloses are low molecular weight, highly branched, generally noncrystalline
heteropolysaccharides having a degree of polymerisation of about 100-200. They are associated in plant cell walls with cellulose, pectins and lignin. The sugar residues found in hemicelluloses include pentoses (D-xylose, L-arabinose), hexoses (D-galactose, L-galactose, D-mannose, L-rhamnose, L-fructose), and uronic acids (D-glucuronic acid). Galactoglucomannans and arabinogalacturonoxylans are the principal hemicelluloses in softwoods. Glucuronylxylan is a major hemicellulose in hardwoods. In flax most of the hemicelluloses are closely related galactoglucomannans and account for about 18% of dry weight of flax fibre.

Removal of hemicellulose, and the destruction of lignocelluloses reduces fibre strength and increases yarn breakage in spinning. It increases the mobility of the fibril structure and increases flexibility of linen fibres (Gurusova and Ivanov, 1989, 1991).

Lignin is found in the cell walls of plants, predominantly in the vascular tissues which are responsible for liquid transport. It is a random copolymer built up of phenylpropane units. Macromolecules of lignin are formed by combination of phenoxy radicals; the degree of polymerisation is about 30.

Lignin is partly responsible for the high rigidity of flax fibres but also gives them mechanical durability and protection of the cellulose against microorganisms. Lignin makes the fibre coarser and dark coloured (Ivanov et al., 1986).

Consequently, to make linen fibre suitable for spinning it should be delignified.

In plant tissues the side chains link the pectin molecules to proteins, hemicelluloses and cellulose to form the insoluble structure known as protopectin, and since the non-methylated galacturonic acid units exist as salts (galacturonates) the pectic substances in plants are pectates (or protopectates) rather than pectins. Pectic substances are the structural constituents of primary cell walls in non-woody tissue, and they are the sole polysaccharides in the middle lamella responsible for cell cohesion.

Young, actively growing tissues contain a high proportion of pectic substances compared with fully mature lignified tissues.

Flax pectin is partially methylated polygalacturonic acid with other sugar units such as galactose, arabinose and rhamnose occurring along with the galacturonic acid, mainly in polysaccharide side chains linked to the polygalacturonic backbone. The pectin contains about 4% by weight of methyl groups with the esterification degree of about
30%. The ability of microorganisms to degrade given pectin depends on its degree of esterification.

The percentage of pectic substances affects fibre moisture retention. Removal of pectic substances leads to decreasing level of yarn breakage (Gurusova et al., 1991).

The results of non-cellulose polysaccharides analysis show that the method of fibre extraction affects chemical composition to a greater extent than the location of the fibre in the stem (Table 2.2) (Derbenev et al., 1968).

Linen fibres contain 1.6 – 2.9 % of waxy substances which may be extracted from the fibre. These substances are situated in the middle lamella and primary cell walls of flax fibres. The melting point of this mixture is 61.5°C, and consists of 81% of non-saponifiable waxy matter.

Table 2.2 Results of non-cellulose polysaccharides breakup analysis

<table>
<thead>
<tr>
<th>Polysaccharides</th>
<th>Percentage, %</th>
<th></th>
<th></th>
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</tr>
<tr>
<td></td>
<td>Untreated</td>
<td>Steam</td>
<td>Explosion</td>
<td>Tank retting</td>
<td>Dew retting</td>
<td>Untreated</td>
<td>Steam</td>
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<tr>
<td>Pectic substances</td>
<td>5.77</td>
<td>5.39</td>
<td>2.30</td>
<td>2.99</td>
<td>6.74</td>
<td>5.22</td>
<td>1.92</td>
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<tr>
<td>including gectosan</td>
<td>1.83</td>
<td>1.67</td>
<td>0.79</td>
<td>1.25</td>
<td>2.23</td>
<td>1.64</td>
<td>0.77</td>
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<td>pentosan</td>
<td>0.93</td>
<td>0.89</td>
<td>0.35</td>
<td>0.32</td>
<td>1.44</td>
<td>0.88</td>
<td>0.38</td>
</tr>
<tr>
<td>polyuron acids</td>
<td>3.02</td>
<td>2.83</td>
<td>1.16</td>
<td>1.42</td>
<td>3.07</td>
<td>2.70</td>
<td>0.77</td>
</tr>
<tr>
<td>Hemicelluloses including</td>
<td>9.19</td>
<td>5.33</td>
<td>7.55</td>
<td>9.00</td>
<td>12.66</td>
<td>6.52</td>
<td>7.17</td>
</tr>
<tr>
<td>gectosan</td>
<td>6.30</td>
<td>3.73</td>
<td>5.16</td>
<td>6.92</td>
<td>6.36</td>
<td>3.80</td>
<td>4.53</td>
</tr>
<tr>
<td>pentosan</td>
<td>1.41</td>
<td>1.03</td>
<td>1.17</td>
<td>1.12</td>
<td>3.95</td>
<td>1.69</td>
<td>1.57</td>
</tr>
<tr>
<td>polyuron acids</td>
<td>1.48</td>
<td>0.57</td>
<td>1.22</td>
<td>0.96</td>
<td>2.35</td>
<td>1.03</td>
<td>1.07</td>
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<tr>
<td>Non-cellulose polysaccharides</td>
<td>14.96</td>
<td>10.73</td>
<td>9.85</td>
<td>11.89</td>
<td>19.40</td>
<td>11.74</td>
<td>9.09</td>
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<td>including gectosan</td>
<td>8.12</td>
<td>5.41</td>
<td>5.95</td>
<td>8.17</td>
<td>8.59</td>
<td>5.44</td>
<td>5.30</td>
</tr>
<tr>
<td>pentosan</td>
<td>2.34</td>
<td>1.92</td>
<td>1.52</td>
<td>1.34</td>
<td>5.39</td>
<td>2.57</td>
<td>1.95</td>
</tr>
<tr>
<td>polyuron acids</td>
<td>4.50</td>
<td>3.40</td>
<td>2.38</td>
<td>2.38</td>
<td>5.42</td>
<td>3.73</td>
<td>1.84</td>
</tr>
</tbody>
</table>

In order to increase capillarity and dye-ability of fibre part of the wax is removed during the scouring and bleaching processes (Fridland, 1982).
Flax fibres also contain mineral substances such as Ca, Mg, K, Cu, Si and many other chemical components. The amount of minerals depends on the maturity of the fibres.

The morphology and chemical composition of flax fibre provide it with unique properties such as high hygroscopicity and low static resistance.

Thus, flax fibre is a multi-component complex containing cellulose and accompanying substances: fats and waxes, lignin, hemicelluloses and pectins, mineral and protein material. The chemical composition depends significantly on the type of flax fibre pretreatment.

It should be noted that at the moment there is no clear classification of flax fibres according to their length.

Physically, the fibres in the stems of flax are actually bundles of tiny fibres called “ultimate fibres”. The bundles of these elementary fibres are called technical flax fibres. (Truevtsev et al., 2001)

Long flax fibres are the best quality fibres extracted from raw flax in order to be processed by conventional flax spinning and then applied for production of high quality linen textiles. Waste from long flax spinning technology and fibres that are not acceptable for the processing by conventional linen system are referred to in this research work as short flax fibres. The term short flax fibre includes technical fibres, ultimate flax fibres and cottonised fibres, i.e. cottonin.

When technical fibres are subjected to breaking into smaller bundles (up to ultimate fibres) this reduces the mean fibre length and diameter thus making them spinnable on cotton equipment. The cotton-like fibre obtained in this way will be referred to as cottonised/modified flax or cottonin.

Fundamental knowledge of the structural and chemical characteristics of flax are important for designing new approaches to produce fibres with specific properties required for industrial applications (Foulk et al., 2002).

2.3 Primary treatment of flax fibre in the preparation stages for spinning

In order to separate flax fibre from other tissues special treatments in the preparation stages for spinning are necessary. To break down tissues of the stem and remove the cementing substances, which hold the different cell structures together,
various processes are employed.

The methods of flax pretreatment are as follows.

Biochemical method. Biological degradation of the flax stem and ultimately the fibre cellulose and accompanying components is attained by the colonisation of the plants by micro-organisms which use these biopolymers as food sources. Different methods of retting are used in practice - water retting, dew retting and chemical retting.

In water retting bundles of the stems are submerged in water in a tank. Putrefactive fermentation caused by bacteria soon sets in. This gradually softens the stems by the destruction of the less resisting tissues and renders the intercellular adhesive substances soluble. When fermentation has reached the appropriate stage, the long fibres can be separated quite easily from the debris of the other tissues. The cost of this pretreatment is negligible, but the operation requires about 3 weeks.

Water retting produces better quality fibres but the stench from fermentation by anaerobic bacteria, the resulting stench-tainted fibres, and high labour costs, prevent water retting from being widely used today. Dew retting, which is the oldest procedure, has wider application because of problems with water retting (Akin et al., 2002).

In dew-retting, flax plants are pulled from the soil and laid out in fields for selective attack by fungi over several weeks. The necessary moisture is supplied either by dew, rain or occasional watering. The process is similar in action to water retting, but slower and weather dependent.

Disadvantages of dew-retting are its dependence on weather conditions and difficulties in providing consistency in moisture and temperature which are necessary for retting; the method produces coarser and lower quality fibre than water retting; there is poor consistency in fibre characteristics; and agricultural fields are occupied for several weeks (Van Sumere, 1992). Further, dew-retting results in a heavily contaminated fibre that is dusty and particularly problematic in textile mills.

The main advantages of the retting methods considered above are effective splitting of fibres and possibilities of waste water recycling. The disadvantages are the long-duration and strict control necessary for the process, and waste of water.

Some biochemical methods of flax pretreatment do not have wide application yet, but they hold much promise. Thus, the use of special species of microorganisms and enzymes to separate flax fibre from the other tissues is ecologically friendly and has such
advantages as the high speed of the process and high quality of the fibre. The disadvantages of the above mentioned processes are the high cost of enzymes and difficulty in controlling the process.

Removing the accompanying substances (pectins and other hemicelluloses) decreases moisture sorption and increases the bio-stability of fibres. A number of existing methods of flax fibre processing are based on the use of acids, alkali, and surfactants (Hazendonk et al., 1995).

**Chemical methods** are based on weakening of bonds between elementary fibres by chemical action, with or without mechanical influence. One of these methods is chemical retting (Van Sumere, 1992) when the tissues are softened by boiling with dilute oxalic acid or alkali at atmospheric or high pressure. After treatment, the soluble products formed by degradation of the less resistant tissues are washed away. The process is considerably quicker than those relying upon natural fermentation. It should be noticed that fibre treatment with solutions of acid or alkali is always accompanied by some degradation of macro-molecules of polymers (cellulose), and thus reduces the mechanical characteristics of the fibre. It is therefore necessary to find such methods of fibre treatment that would remove most of the fats, lignin and hemicelluloses, but would preserve good mechanical properties and moisture sorption (Shamolina et al., 2003).

Chemical pre-treatment enables flax fibre with reduced rigidity, heightened softness and plasticity to be obtained; this, however, is accompanied by the reduction of fibre strength. Contaminated waste water and the need for reagent recycling are the disadvantages of the chemical methods, as well as high cost.

Fibre splitting can also be achieved by using surfactants. In this case green flax could be treated regardless of the weather. Unfortunately this method is not perfect and is accompanied by plenty of technological problems and waste water.

Splitting the fibres by mechanical action and the boiling of straw with chemicals, termed as flashing, belongs to physicochemical methods of flax pretreatment. Disadvantages of the method are high power consumption and the large quantity of waste water produced. Nevertheless the technology is applied because of the high quality of flax fibre obtained.

Explosion, hydroheat and ultra-sound pre-treatment of flax are among the group of **physical methods**.
The explosion method consists of fibre separation using steam under pressure and high temperature followed by a sudden release of pressure. The disadvantages of the process are high cost, waste water, high power consumption and relatively small batches of fibre being processed (Kessler and Kohler, 1996).

The hydroheat method constitutes splitting of the fibres under high pressure and temperature. As in the case of flashing it is possible to treat green flax, but the method is quite power-consuming.

The ultra-sound method is characterized by high speed treatment and an acceptable quality of fibre being obtained. This method is based on splitting the fibre by the influence of ultra sound. The disadvantage of the method is the need for the special equipment.

Extraction of flax fibre from the other tissues can be accomplished by means of mechanical methods. In this case fibre is separated from stem after retting using mechanical procedures - breaking, scutching and hackling. It makes it possible to reduce the duration of dew-retting and water wastage. This method is acceptable for green flax treatment, but is accompanied by significant loss of raw material and a high percentage of short fibres.

The majority of “negative properties” (high content of impurities, stiffness, unevenness in length and fineness, etc.) arise due to ineffective methods of flax fibre pre-treatment.

The quality of the final technical flax fibre (either complex or elementary) will be affected by all the processes used in its extraction, in addition of course to the specific features of the raw material resulting from the plant’s variety and the conditions of it’s cultivation. The quality of the final technical fibre also depends on the structure of the elementary fibres, and their arrangement and combination in the bundle of technical fibre (Mankowski, 1999).

2.4 Flax fibre properties in comparison with cotton

It is known that among various cellulose-based materials produced from vegetable fibres flax-containing textiles are highly valued for their end-use properties. This is attributed to the fine features of flax fibre structure, morphology and the
presence of additional substances. Among the advantages of flax-containing textiles are their high resistance in wear, high comfort, air permeability, good moisture sorption, and low electrical charge (V.I. Popa and I.G. Breaban, 1995).

One of the problems with flax fibre processing in the textile industry is associated with the utilisation of wastes and short fibres remaining after separation of long fibres. Pure flax yarn could not be successfully manufactured from short fibres due to their great stiffness and low cohesiveness with each other. Therefore, it has been suggested that blended yarns, composed of chopped short flax fibres with other natural fibres like cotton and wool, can be produced. However, in this case the problems of manufacturing good quality blended yarns are caused by significant differences between the properties of flax and other fibres. The short flax fibres are generally too long for blending and further processing with wool and cotton and they have greater stiffness and less cohesiveness. This difference results in instability of technological processes, increased yarn unevenness and decreased quality of the final product. Therefore the flax fibres require to be chopped to an appropriate length and processed to decrease their stiffness.

The diameter and length of ultimate fibres are approximately equal to those of cotton fibres. Flax fibres absorb about 50% more moisture than cotton fibres. Hence, garments made from flax fibres will feel cooler and drier than cotton garments, especially on hot and humid days. The major part of the world’s spinning and weaving equipment is designed to use fibres with the approximate length and diameter of cotton fibres and most synthetic fibres are extruded so they can be used in the cotton system of textile manufacturing (Flax Council of Canada, 2002).

Thus, the preferable method of utilising short flax fibres is the manufacture of cotton-flax blended yarn. However, short flax fibres are different from cotton fibres in their chemical composition because they contain more fats and waxes, lignin, hemicelluloses and pectins. This affects the mechanical and end-use properties of flax fibres. Fats, lignin, hemicelluloses and pectins reduce the contact angle in comparison with that of cotton fibres (Hazendonk, 1995).

The cellulose molecules in flax are almost parallel to the fibre axis, in contrast to the spiral arrangement in cotton. This higher degree of orientation leads to greater tensile strength, higher modulus of elasticity, lower breaking extension and smaller
work of rupture in comparison with cotton (Morton and Hearle, 1962; Perepelkin, 1985).

Also the characteristic macro-structure of flax fibres leads to lower inter fibre cohesiveness in comparison with cotton.

Comparative characteristics of flax and cotton fibres are presented in Table 2.3.

Pectic substances are highly hygroscopic, they promote fibre conglutination to bundles and heightened normal moisture retention. The anisotropic crystal structure of cellulose imparts a typical property of crease retention to flax. Flax is characterized by high thermal conductivity and endurance (up to 300 °C), and weather-resistance.

Table 2.3 Comparative characteristics of flax and cotton fibres

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Cotton</th>
<th>Flax fibre</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length, mm</td>
<td>20-40</td>
<td>60-140 (T)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>10-20 (U)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>40-60 (M)</td>
</tr>
<tr>
<td>Diameter, µm</td>
<td>12-14</td>
<td>15-18 (U)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>20-28 (M)</td>
</tr>
<tr>
<td>Linear density, tex</td>
<td>0.16-0.20</td>
<td>0.3-0.4 (U)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.8-1.0 (M)</td>
</tr>
<tr>
<td>Tenacity, cN/tex</td>
<td>15-36</td>
<td>20-60</td>
</tr>
<tr>
<td>Elongation at break, %</td>
<td>6.0-9.0</td>
<td>1.5-3.0</td>
</tr>
<tr>
<td>Constant of tensile stress relaxation</td>
<td>1.5-1.6</td>
<td>1.4</td>
</tr>
<tr>
<td>Friction coefficient</td>
<td>0.28-0.29</td>
<td>0.27-0.28</td>
</tr>
</tbody>
</table>

Note: T – technical fibre; U – Ultimate fibre; M- modified fibre

Flax fibres are nonuniform in length and diameter. This together with low elongation, lack of crimp and low cohesiveness determines the reduced spinning ability of flax fibre in comparison with cotton.

These two fibres are considerably different in rigidity. The twisting rigidity and bending rigidity of flax fibre are much higher then those of cotton. All these factors lead to the following conclusions:

- short-fibre flax can be processed on cotton carding spinning system only after special preparation;

- short-fibre flax is desirable to process in blends with cotton or other short staple fibres;

- before mixing with other blend components short-fibre flax should be
subjected to additional splitting and purification.

2.5 Methods of flax fibre cottonising

Over the years, the unique properties of flax fibres and the fact that short-fibre flax and waste from long flax spinning technology were not used to their full potential, have led to the development of processes which attempt to break down flax fibre bundles into ultimate fibres to produce a flax based fibre that could be spun on cotton equipment. Such flax is generally referred to as cottonised flax (cottonin).

In recent years, various processing lines designed for the production of cottonised flax have been developed and maintained in Europe. The majority of these are based on mechanical methods of cottonising. Chemical and biochemical methods are applied rarely, because of the significant increase in the processing cost.

There are many mechanical, physical, chemical and biochemical methods of cottonised flax manufacturing (Figure 2.3); however, all of them are characterized by some advantages and disadvantages. Cottonised fibres produced by various methods differ in properties that determine the specific area of subsequent fibre application: blend composition, yarn linear density, range and function of end-products.

The mechanical method of flax cottonising is the most commonly used because it is non-polluting and the simplest from the technological point of view. Mechanical treatment consists of breaking technical fibres into smaller bundles (up to ultimate fibres) and reducing the mean fibre length and diameter. A number of techniques to transform short-fibre flax into cotton-like fibre are used in mechanical processing lines.

A cutting method is used for the production of oriented fibres. Initially a sliver is formed and thinned on drafting machines, and after this the sliver is chopped on special cutting machines to lengths that are required for blending with cotton or other fibres and subsequent processing. This method is described in a number of patents (for example: RU 2003135479 A2005.05.20; GB 1434330 A, 05.05.1976; DE 10208969 A1, 11.09.2003).
To eliminate long fibres the cutting method is the simplest, it allows the mean fibre length to be predetermined and matched to the length of the other blend fibres. An additional advantage of this technique is that conventional equipment can be used. During the cutting process, however, there is no fibre splitting and the percentage of very short fibres increases. To avoid the appearance of a large quantity of lint-length fibres the cutting length should be the maximum possible, or even greater than required if chopping is followed by additional fibre splitting (as at La Roche line) (Zhivetin et al., 2000).

In the case of the rupture method, a partly oriented mass of fibres is processed. This method consists of cleaning, splitting, orientation and rupture of fibres fed between the nips of two pairs of rollers rotating at different speeds. Rupture of the fibrous sliver shortens and splits those fibres that are longer than the roller setting. (Patents: RU 2048000 C1, 10.11.95; FR 2089037 A, 01.09.72; DE 1601524 A, 02.10.70).

Mechanical cottonisation does not produce flax containing a high percentage of ultimate fibres. Fibre obtained by mechanical methods is quite coarse and contains a
considerable amount of dust, shive and fibres which are shorter than 15 mm. However, this technique is non-polluting and more resource-saving than, for example, chemical methods.

The research work conducted by Krylova (2004) included an analysis of a number of cottonising processing lines: La Roche (France), Temafa (Germany), Lott (Germany), CSRIALI (Russia) and IChS RAS (Russia) et al.

The spinnability of fibres obtained using different equipment was estimated by processing them in a blend with cotton (length: 31/32 mm, tenacity: 28.2 cN/tex) in ratio 30 to 70% using open-end and ring spinning machines. According to the experimental results flax fibre cottonised on the Lott line proved to be the best for blending with cotton. The increased spinnability of the fibres processed on this line made the spinning process more stable – yarn breakage decreased, the spinning products obtained were more even in linear density in comparison with other variants.

The cottonised flax produced using the technique developed in SPSUTD (Patent RU No-2074578 C1) was considered in this research work. The technology is based on a new method of short flax fibre rupture which provides the desirable distribution of fibre length and decreased fibre stiffness. It includes an intensive mechanical pretreatment of bast fibre. This procedure enables additional cleaning of low count flax, and splits technical fibres into shorter and thinner complexes and ultimate fibres suitable for blending with other fibres and yarn manufacture on cotton-spinning systems. The production line for the production of cottonised flax includes a tow scutching equipped with a needle bar.

This method does not use any chemicals which is its main advantage. The rupture technique makes it possible to produce yarn characterized by a higher breaking load than that of the cutting method (Truevtsev et al, 1995 b). The chemical method of cottonising consists of the procedures as follows: preliminary cleaned fibres are subjected to scalding or bleaching, then after rinsing and centrifugal drying the wet fibre mass passes through an opening system, which is followed by the second drying and carding. This is described in patents RU-2175361-C1, 2001.10.27 and RU 97120483 A 1999.01.27.

Because of high costs and the high volume of effluent produced the chemical method is not widely used, however the fibre produced meets the requirements for
blending and processing on cotton-spinning equipment. An important feature of this technique is that the natural colour of the flax disappears, and the amount of waste and dust decreases.

The mechano-chemical method of flax cottonising is a complex combination of mechanical and chemical treatments applied to bast fibre bundles. The combined action of mechanical and chemical treatments has a greater effect than the two techniques carried out separately.

Initially flax is subjected to a preliminary mechanical splitting, after which a chemical treatment follows. The first procedure promotes the appearance of numerous cracks among fibres in the bundle, this produces favourable conditions enabling the lamella to be completely dissolved at a higher rate by chemical reagents.

In recent years techniques of combined dyeing and cottonising have been developed for the production of melange textiles; see, for example, patents: RU-2190052-C1, 2002.09.27; GB 2186002 A, 05.02.1987. This technology is more economically advantageous in comparison with conventional dyeing of cotton-flax fabrics.

Technologies of cottonising based on steam explosion and ultra-sound have not yet found wide application. Steam explosion is a physicochemical method, which disaggregates technical fibres by means of electro-hydraulic action applied to a material placed in liquid (Patent - RU 2003114717; A2005.01.10). Flax cottonising by means of ultra-sound provides a controllable method of mechanical-chemical fibre splitting. The process is accompanied by a high level of dust-removal.

One of the most promising methods of flax cottonising and refining is the application of enzyme preparations at different stages of manufacturing.

Division of technical bast fibres can be improved by introducing a biological agent (enzyme) to the cottonising process (Sedelnic, 1999). Biological methods of cottonising are based on the application of micro flora existing in specific conditions (as in the case of retting). The essence of biological cottonising is the use of specific species of micro organisms and enzymes, which use these biopolymers as substrates, to split technical flax fibres (bundles of ultimate fibres) and to separate them from accompanying components.
The cottonising effect is due to the action of enzyme at low temperature on the cuticle, shive and peptic substances which cement the ultimate fibres into bundles. However, the fibre strength and the average length (no less then 30 mm) should be preserved.

Enzyme treatments of fibres are free from the majority of disadvantages that are typical for chemical methods used in the textile industry. For example, biopreparation of textiles may involve one or several processes such as scouring (removing noncellulosic impurities) and bleaching. Scouring and bleaching require the use of harsh chemicals such as NaOH and hydrogen peroxide at high concentrations to aid the removal of impurities and render the fabric suitable for dyeing. The bleaching bath may contain surfactants, stabilisers, soda ash and sequestering agents to achieve a high level of whiteness necessary for dyeing to light shades. These environmentally "unfriendly" systems provide a good rationale for enzyme-based alternatives.

2.6 Biochemical methods of flax modification and their application in textile technology

Recent advances in the development of new textile technology aim to make manufacturing processes friendlier to the environment. Therefore, technologists and researchers are paying more and more attention to the possible use of enzymes in technological processes, as these natural agents undergo complete degradation in effluents (Lipp-Symonowicz, 2004).

Flax fibre is a complex mixture of various biopolymers. Wood fibre, a similar ligno-cellulosic complex, is already successfully treated by a mixture of chemical and enzymatic methods in the paper industry (Farell, 1987). The modification of flax fibres by enzymes therefore presents an opportunity to change their structure, and hence to improve their properties, especially their compatibility with other fibres.

The application of enzymes in flax processing accelerates retting, improves product quality, and simplifies purification of effluents from scouring, desizing and bleaching processes. Much research work has been conducted on the enzyme activities relevant to retting flax (Akin et al., 1997, 2002; Akin and Henriksson, 1998; Derbenev et al., 1968; Van Sumere, 1992).
By using enzymatic agents in finishing processes, it is possible to obtain textile products with an improved comfort in use (a soft handle or feel, decreased fabric weight, reduced tendency to pilling) and increased lustre, as well as reduced shrinkage in the case of wool fabrics (Kumar et al., 1997; Ledakowicz et al., 2000).

Enzymes are biocatalysts with selective and specific activity. They accelerate specific reactions and remain unchanged after the reaction. From an environmental and economical point of view, the moderate reaction conditions of enzyme-catalysed processes, and the possibility of enzyme recycling, make enzymes particularly attractive catalysts. Today enzymes are produced by biotechnological processes in commercial quantities with constant quality, and are therefore applicable to large scale processes (Hemmel, 1991).

Chemically, enzymes are colloidal macromolecular compounds consisting exclusively of a homogeneous protein substance (monocomponent enzymes) or two or three components – protein and non-protein substances known as the prosthetic group (bi- or multi-component enzymes).

Enzymes are mostly classified on the basis of the reaction they catalyse. Similarly, the names of enzyme groups or particular enzymes are derived from the name of the reaction or the compound which undergoes enzymatic effects. Therefore, the group of enzymes which catalyse the hydrolysis of substrates into simpler compounds with water is called hydrolases, while the enzymes which decompose ester bonds are called esterases, the enzymes catalysing pectin hydrolysis are pectinases, cellulose hydrolysis - cellulases, etc. (Guzicska et al., 2002; Lipp-Symonowicz, 2004).

The large dimensions of enzyme molecules and their spatial arrangement reduce their abilities to penetrate the complex fibre structure. However, according to the view of some researchers the action of enzymes on fibres results in the disturbance of fibre structure which, depending on the treatment intensity, assumes the form of partial fibrillation or superficial defibrillation, due to the enzymatic hydrolysis of the fibre material (Sedelnik, 1999; Shamolina et al., 2003).

Considering the effects of enzymatic treatments of cellulose fibres, it can be assumed that major changes will result from the removal of non-cellulose substances present in the fibres in various amounts as well as those resulting from cellulose decomposition and its partial removal from fibres. These changes will be followed by
the modification of the fibre's morphological structure and properties (especially surface properties) which in turn affect properties of the final products.

The major problem in using enzymatic agents is selecting the appropriate enzyme in order to achieve the desired effects during treatment (Cavaco Paulo, 2002).

Mechanisms of the action of various kinds of enzymes on components of flax fibre are the subject of a considerable number of publications. Examples include the enzymatic degradation of flax fibre pectins (by pectinesterase, pectinases and protopectinase) (Bernfeld, 1955; Evans et al., 1992); flax cellulose (by cellulase enzymes) (Glazer and Nikaido, 1994; Heikinheime et al., 1998; Medve et al., 1994); hemicellulose (by hemicellulases) (Gurusova and Ivanov, 1989, 1991; Ivanov et al, 1986); and flax fibre lignin (using enzymes secreted by wood-decaying fungi) (Higuchi, 1986; Kirk, 1983; Kirk and Schultz, 1978; Glazer and Nikaido, 1994).

According to the European Organization for Economic Co-operation and Development (OECD) biotechnological technologies have the widest application in USA and Germany (Krichevsky, 1998).

Enzyme treatment in the linen industry used to be applied at the stage of primary treatment of flax straw or in fabric finishing processes.

The works of Li and Hardin (1998), Akin et al. (1997), Hartzell and Hsieh (1998), Sawada et al. (1998), Whitaker (1990) and Henke (1999) describe successful techniques in flax treatment using pectinases (Aspergillus niger, Aspergillus japonicus, Aspergillus aculeatus, Aspergillus foetidus-26, Rhizopus species). As a consequence of the destruction of pectic substances, which glue bundles of bast fibres together, by enzyme preparations, a higher degree of flax fibre splitting has been obtained. The fibres have been characterized by reduced content of pectins and non-cellulose admixtures and heightened hygroscopicity.

Primary treatment of flax fibre with xylanases (Aspergillus niger) in the research works of Akin et al. (1997), Hartzell and Hsieh (1998) Sawada et al. (1998), Akin and Henriksson (1998), Kundu et al. (1993), Akin et al. (1999 a, b), Buchert and Miettinen-Oinonen (1999) and Hardin et al. (1998) has enabled production of fibres with a high level of split and increased water absorbency.

The method of flax fibre finishing includes application of lignases (Pleurotus ostreatus, Pleurotus florida, Phanerochaete chrysosporium) and oxidoreductases

The treatments lead to increased whiteness of flax fibre. The same effect has been achieved by lignin destruction and removal of the decomposition products using peroxidases, oxygenases and polyphenoloxidases (Kirk et al., 1978; Dordick et al., 1986; Farell, 1986; Kantelinen, 1988; Jurasek and Paice, 1988; Klahorst et al., 1994; Reiko et al., 1993).

The work of Buchert and Miettinen-Oinonen (1999) has shown that elasticity and softness can be increased by means of treatment with lipases (Mucor-pusillus).

Removal of wax substances and admixtures of starch sizing compound from cellulose containing fabrics using amylase (Aspergillus orizae) is accompanied by increase of capillarity and whiteness of treated material (Cavaco-Paulo, 1998; Jurasek and Paice, 1988).

Cellulases (Trichoderma reesi, Trichoderma veride, Aspergillus niger, Hamicola insolens) have been applied in finishing of fabrics containing bast, cotton and viscose fibres (Klahorst et al., 1994; Buschle-Diller and Zeronian, 1994 a; Chaulam and Chingyee, 1995; Hemmel, 1991; Sarkar and Etters, 1999; Scheer et al., 1999; Wong and Yuen, 1998). Properties such as pilling, lustre, plasticity, softness and dyeability have been improved due to the treatments.

Fabric finishing has also been carried out using hemicellulases (Ceraceomyces sublaevis), which are able to decompose non-cellulose polysaccharides of flax fibre (Cavaco-Paulo, 1998; Evans et al., 2003; Lipp-et al., 2004; Bailey, 1989; Buschle-Diller and Zeronian, 1994 b; Bhattacharyaand and Shah, 2004).

Different variants of treatment with these enzyme preparations reduced the linear density of linen yarn and increased fabric hydrophilicity.

Thus the application of microbe enzymes, especially cellulase complexes, opens up new possibilities to change the structure and, correspondingly, the properties of flax substrates in conditions that meet up-to-date environmental requirements for the textile industry.
2.7 Studies related to the processing of fibre blends. The main principles of the heterogeneous fibres blend formulation.

Fibre properties such as fineness, length, strength, elongation, bending, torsion rigidity, tensile rigidity and friction affect fibre spinnability. It is universally accepted that the spinnability would be higher if the fibre is finer and more uniform in length. It is known that the qualitative and quantitative composition of a blend is determined by such factors as properties of end product, its prime cost and spinnability of the blend.

In this respect, there are still many problems related to flax fibre spinning: the possibility of joint processing of the mixture of heterogeneous fibres, the acceptable degree of difference in their properties, the nature of this difference and its influence on the quality of yarn and semi-products, and the stability of the spinning processes.

These problems are widely covered in the research works of A. Barella (Barella, 1979), J.E. Ford (1970), J.W.S Hearl, P. Grossberg and S. Backer (1969), A. Kemp (1955), V.I. Martindale (1945), H. Breny (1953), W. Wegener (1968), Gusev V.E. (1970), Vanchikov A.N. (1970), Sevostyanov A.G. (1962). As a result requirements have been formulated for blend components (regardless of fibre type), the geometrical properties of which have to satisfy the following conditions.

When choosing the length of fibres that are to be processed in a blend it is recommended to use fibres that increase the spinnability by means of increased length and reduced length unevenness.

The main technological process that is the most sensitive to the difference in length of heterogeneous blend components is drafting. Increasing the variation of length of fibres being processed leads to discontinuity during the drafting process, this adversely affects the quality of spinning products and productivity of manufacturing equipment. The length of all fibres in the blend must be compatible with the roller setting.

Consequently, to determine the possibility of using cottonised flax in blends with cotton it is necessary to compare staple diagrams of cottonin with standard cotton diagrams.

Another important criterion for the estimation of fibre spinnability in a blend is the difference in the mean linear density of the components. From the point of view of spinning processes a smaller difference is better.
The permissible difference in linear density of heterogeneous fibres forming the blend has not been established. It can be assumed that this difference depends on yarn linear density, blend composition, spinning method employed and end-use of the material produced. Fibre breakage and web cleanliness in carding define the allowable minimum in fibre linear density.

It has been ascertained that joint processing of fibres that significantly differ in thickness results in changes of fibre structure and properties. However, the influence of this difference and the blend composition, as well as correlation of these parameters with yarn linear density and spinning methods employed have not been adequately explored.

The higher the linear density of the flax component in a blend, the greater the quantity of these fibres wasted (Truevtsiev et al., 1995 b). Consequently, it is advisable to use flax fibre with a permissible minimum linear density that is as close as possible to that of the base component (cotton).

The quality and percentage of short flax fibre in a blend have the most significant influence on the spinnability of flax containing blends.

Experimental investigations into processing of different blends show that introducing more than 50 % of flax into the blend leads to a decrease in the quality of the end product; spinnability of the blend is reduced; wear and tear of equipment is increased; and optimisation of technological parameters becomes difficult.

The spinnability of a fibre blend also depends on the impurities content. Because natural fibres possess natural impurities it is preferable to process blends of flax with such fibres as viscose, which are free from natural impurities. However, taking into account such factors as customer demand for natural products, industrial ecology and simplicity of waste recycling, it is preferable to produce textiles (especially intended for garments) from natural fibres.

Usually a preliminary preparation of short flax fibre is necessary for joint processing with cotton. Pre-processing equipment intended for the refinement of contaminated blends or blends of various fibre wastes and secondary raw materials is used. However, the content of impurities after such treatment averages 10-13 %, this requires the use of an opener-scutching plant with increased cleaning capability for processing cotton-flax blends.
Another criterion that determines the spinnability of a blend is the uniformity of component mixing. The physical essence of this process lies not only in the blending of the fibres of each component, but also in the uniform distribution of the component fibres throughout the blend mass. It is well known that components can be mixed at the opener-scutching stage or at draw frames. Drawing on existing experience of flax containing blend processing it is preferable to carry out this procedure at the stage of opening, because in this case a more even distribution of the components throughout the spinning product can be achieved than in the case of sliver mixing (Truevtsev et al., 1994, Lavrenteva, 2001 b).

2.8 The influence of flax percentage contained in yarn blend on yarn quality

It is known that the quality of a multi-component yarn depends to a certain extent on the percentage of each component in the yarn and on the magnitude of deviation from the actual blend composition.

Results of investigations conducted by scientists at SPSUTD have shown that the actual percentage of components in flax containing yarn considerably differs from those in the blend before processing. There are evidences of significant loss of flax fibre, which is coarser than cotton, at all stages of the technological process (Truevtsev et al., 1994).

Pilot production of two- and three-component ring and open-end spun yarn has shown that yarn performance characteristics deteriorate when the percentage of flax in the blend increases. This tendency is especially noticeable when the flax percentage is higher than 50 % (Gladyshev and Truevtsev, 1995).

Gladyshev and Truevtsev (1995) established that an increase in percentage of cottonised flax leads to a less uniform fibre distribution in the sliver; every 10 % increase of flax fibre results in a twofold decrease in sliver breaking energy.

Analysis of mixing irregularity of fibre components in yarn cross-sections has shown that it increases simultaneously with flax percentage. When cottonin forms half of a blend the unevenness exceeds 20 %.
Data from the Russian Central Research Institute of Staple fibres (Krylova and Tarasov, 1999) characterise the influence of cottonin percentage in a blend on the composition of yarn (Figure 2.4).

The data confirm that it is ineffective to include more than 30% of flax fibre in the blend with cotton for processing on standard cotton equipment. Figure 2.4 represents only the tendency of flax loss during processing flax cotton blends. The values of wastes are typical for the processing line employed in the experiment. Other technological lines are characterized by different values, for example the La Roche line enables production of cotton-flax yarn containing 17 – 18% of flax fibre, while its primary percentage in the blend before processing is 30% (Gubina et al., 2004, Zhivetin et al., 2000).

![Graph showing the influence of percentage of cottonized flax in blend on composition of cotton-flax yarn]

Figure 2.4 Influence of percentage of cottonized flax in blend on composition of cotton-flax yarn

The low cohesion of short flax fibres with other blend components and a significant content of impurities hinder the increase in the percentage of flax beyond 30-40% in a blend for processing on a carding spinning system.

In addition, the majority of researchers who have investigated cotton-flax blends conclude that inclusion of more than 30-35% of the flax component leads to an increase in the unevenness in yarn cross-section distribution. In turn it causes undesirable increasing unevenness in all performance characteristics, resulting in instability of technological processes, and increases in yarn breakage.
There is a correlation between the flax percentage in a blend and the yarn breaking load and elongation, the coefficient of variation of these characteristics and the linear density.

2.9 Production lines for processing cotton-flax blends

The quality of a yarn substantially depends on the equipment used for its production and the process parameters employed. The sequence of processes transforming a fibre mass into semi-products and yarn is carried out using a spinning system that involves all manufacturing operations and equipment along the processing line.

Over recent years the research work aimed at the development of technology and equipment for the production of cottonised flax and yarn from its blends with cotton, wool and chemical fibres has been conducted actively in Europe and in a number of different countries and companies.

At present cotton, wool, flax and silk spinning technologies are scrutinized closely. These spinning systems consist of a number of manufacturing operations, which are similar in aims but could be considerably different in the way they are implemented. Design and development of a new technology is a prolonged process, which is generally directed to unification of known methods of raw materials treatment. The processing technology for production of cottonised flax containing blends is one of such techniques.

It is known that in conventional flax spinning technical fibres are gradually broken up into smaller complexes and ultimate fibres during all stages of treatment (Sharma and Van Sumere, 1990). The new processing technology for cottonised flax in blends with natural and chemical fibres results in a change of the geometrical characteristics of the source technical fibres at the first stages of treatment. This enables the required degree of mixing of cotton in with other blend components.

One more problem is the fact that mechanical treatment of fibre blends in the course of cotton-flax yarn production does not cause significant changes in cotton properties, while flax is subjected to further splitting (right up to ultimate fibres). The fibre splitting is a random process; this makes it difficult to choose industrial equipment
for the processing of flax containing blends and to optimize technological process parameters.

Another difficulty in processing flax in blends is its high content of shive and impurities, which results in an increased quantity of dust and yarn breakage.

It is necessary to take into consideration the fact that flax fibre is more rigid, coarser and longer (before processing in spinning) and less uniform in comparison with cotton.

All the features mentioned above make it necessary to optimize the new technology for cottonised flax processing in blends with natural and chemical fibres on cotton spinning equipment.

A number of Russian research institutions have wide experience in developing the technology of flax containing yarn production on cotton and wool spinning systems.

The work of Krylova (2004) describes an industrial experiment aimed at the production of low linear density flax containing yarn on silk and cotton spinning systems.

Staff of the Central Research Institute of Bast Fibres have developed technological processes for the manufacture of a yarn with linear density 50 – 200 tex containing cottonised flax (Zhivetin et al., 2002).

In Kostroma (Russia) the technique of cottonin production has been developed. It is based on the cutting method of flax cottonising and enables yarn containing up to 30 per cent of flax to be produced (Ilyin and Repina, 1995). A three-component flax containing yarn was produced in Ivanovo (Russia). The blend used for yarn production consisted of cotton, flax and polyester fibres in different proportions. The linear density of the yarn produced was in the range 33.3 – 50.0 tex (Fridman, 1995).

In the Central Research Chemicobiological Institute and Institute of Chemical Solutions of Russian Academy of Sciences investigations aimed at the production of yarn containing cottonised flax on cotton spinning equipment have been conducted. Industrial production of a three-component yarn (33.3 – 100 tex) was proposed. The blends used consist of short flax fibre cottonised by the cutting method (22 %), cotton (43 %) and synthetic fibres (35 %). The yarns produced are used in the knitting industry for production of outer clothing knits and hosiery (Moryganov, 2001; Razumov et al., 2000).
There are also examples of viscose-flax yarn production (Lavrenteva, 2001a). Two variants of yarn have been produced on the processing lines of different producers. The linear densities of the yarns are 50 tex and 29 tex, and the compositions 70% flax: 30% viscose fibre and 30% flax: 70% viscose. Results of the research work included recommendations to apply the Rieter equipment (Switzerland), that was used in the investigation, for the processing of cottonised flax in blends with viscose fibre in proportion 30 to 70 to produce 29.4 tex yarn.

Techniques of yarn production from blends of flax and chemical fibres have been also developed in the Russian Central Research Institute of Staple Fibres by Krylova and Tarasov (1999).

It should be noted that an important contribution to the evolution of investigations in this field has been made by St. Petersburg State University of Technology and Design due to research conducted under the supervision of Prof. N. Truevtsev. A number of methods of production of flax containing yarn have been developed by the members of staff at the MTFM (Mechanical Technology of Fibre Materials) department. One method addresses the manufacture of cotton-flax, flax-viscose, flax-polyester-viscose 29 tex yarns by a ring spinning method on a cotton spinning carding system (Gladysh and Truevtsev, 1995). Another technology proposed has been adopted at wool spinning mills for the production of flax-wool yarn with linear density 29-140 tex (Truevtsev et al., 1995a).

These suggested technologies are characterized by a high loss of cottonin in spinning processes (up to 65%).

A number of research centres in Poland have experience in flax containing yarn production from blends of cotton and chemical fibres with flax cottonised by cutting, rupture and biochemical methods. Linear density of the yarns produced on cotton and wool spinning systems has been in the range of 32 - 64 tex. For instance spinning mill "Wloknolen" (Lembork, Poland) has produced a 50 tex flax-polyester yarn using a worsted spinning system. The yarn produced is intended for upholstery manufacturing. An imperfection of this technology is significant losses of flax component during the opening-beating manufacturing step (30 – 35 %) (Kozlovski, 2000; Sedelnik, 2000).

The same company has been using low grade flax tow for the production of cotton-flax yarn on cotton spinning equipment. The manufacturing process has been
characterized by a high level of yarn breakage (300 breaks on 1000 spindle per hour). The yarn produced is intended for apparel textiles, but its drawback is a high level of breaking load irregularity (Chastmova, 1988).

The Zintops Company (Belgium) has developed mechanical techniques of flax fibre splitting suitable for spinning a bi-component yarn of 29 – 50 tex. Cotton-flax yarn did not have the required performance characteristics, for this reason the methods suggested have been mainly applied in the processing of flax-viscose blends (Prunier, 1988).

Flax containing open-end spun yarn of 40 – 100 tex was produced in Germany on Temafa and Schlafhorst machines (Temafa prospect, 1995). The yarn was obtained from flax-viscose mixtures. The characteristics of the yarn produced are as follows: average tenacity: 7.7 – 11.0 cN/tex; elongation at break: 4 – 6 %; tenacity variation coefficient: 10%; variation coefficient of linear density (Uster) up to 10 %.

A number of research studies have been carried out to apply the methods of cottonised fibre production to jute and ramie and to process them in blends with cotton and chemical fibres (Wedemann and Tschmarke, 1991; Syubao, 1990).

The research work of Ivanov (1992) includes investigation of the processing of blends of jute with cotton and chemical fibres on cotton spinning systems. The tenacity of jute-cotton yarn was 7.7 cN/tex, variation coefficient of breaking load – 12.5 %.

Patent investigations have been conducted by the author into the production of industrial cotton-flax yarn designs. The patent search has shown that much work has been done in the area of cotton-flax yarn manufacturing. The variants of yarn described in the references differ in technical characteristics and properties from those obtained within the scope of this research work.

2.10 Conclusions

Flax as a traditional European-grown fibre can be used as an alternative source of raw material. The application of flax improves sustainability of the textile industry due to the environmental problems associated with cotton cultivation. These problems are related to application of toxic insecticides and pesticides and use of irrigated water.
Traditional flax processing, for the extraction of long fibres for linen, generates considerable quantities of "waste" product. One such product is short flax fibre which represents up to 65 % of the whole flax fibre production. Short flax fibre can be blended with other short fibres and spun on the cotton system into yarns for use in high-quality textiles.

The literature review has shown that cotton-flax yarn is an unconventional and relatively new product that combines fibres with significantly different properties. The difference in yarn properties in comparison with conventional cotton yarn raises the question of assessing the overall quality of cotton-flax yarn and the interpretation of the results of standard tests. It should be defined which levels of properties can be considered as acceptable.

The aim and specific objectives of this project can be achieved by investigating the technology of cotton-flax yarn production and properties of cotton-flax yarns with specific interest in yarn unevenness, mechanical properties and hairiness. Subjects and methods of the investigation are indicated in the Chapter 3.
CHAPTER 3 METHODOLOGY

In order to improve understanding of structure and properties of cotton-flax yarn and to achieve objectives listed in Section 2.10 the following fibres, yarns and methods of investigation were used.

3.1 Fibres and yarns used in the investigation

Experimental production of cotton-flax yarn was required for the investigation. The yarn was produced on standard cotton spinning equipment using a carding spinning system. The blend processed contained 70% of cotton and 30% of cottonised flax pre-processed using the technique described on page 19 (Patent RU No-2074578 C1). Two variants of open-end yarn of 35.5 tex yarn and 71.4 tex were obtained from the “Sovetskaya Zvezda” spinning mill (St-Petersburg, Russia). Samples of 72 tex ring spun yarn were obtained using the laboratory-scale spinning plant Shirley Platt.

Parameters of fibres and yarn samples are presented in Tables 3.1 and 3.2.

Table 3.1 Fibre characteristics

<table>
<thead>
<tr>
<th></th>
<th>Cottonised flax</th>
<th>Cotton</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 – 15mm length</td>
<td>4.2% *</td>
<td>Length, mm 32/33</td>
</tr>
<tr>
<td>15 – 50mm length</td>
<td>44.5% *</td>
<td>Modal length, mm 30.3</td>
</tr>
<tr>
<td>50 – 100mm length</td>
<td>47.6% *</td>
<td>Staple length, mm 32.8</td>
</tr>
<tr>
<td>Over 100mm length</td>
<td>3.7% *</td>
<td>CV, % 25</td>
</tr>
<tr>
<td>Average length</td>
<td>51.1mm</td>
<td>R16, % 10</td>
</tr>
<tr>
<td>Linear density</td>
<td>1.4 tex</td>
<td>Linear density 0.149 tex</td>
</tr>
<tr>
<td>Breaking load, cN</td>
<td>53.5</td>
<td>Breaking load, cN 4.2</td>
</tr>
<tr>
<td>Tenacity, cN/tex</td>
<td>38.2</td>
<td>Tenacity, cN/tex 28.2</td>
</tr>
<tr>
<td>Moisture retention, %</td>
<td>11.7</td>
<td>Moisture retention, % 8.4</td>
</tr>
</tbody>
</table>

* Note: percentage was measured by weight
Table 3.2 Yarn characteristics

<table>
<thead>
<tr>
<th>Linear density, tex</th>
<th>Blend composition</th>
<th>Spinning method employed</th>
</tr>
</thead>
<tbody>
<tr>
<td>72.0</td>
<td>70% cotton, 30% flax</td>
<td>Ring spun</td>
</tr>
<tr>
<td>35.5</td>
<td>70% cotton, 30% flax</td>
<td>Open-end</td>
</tr>
<tr>
<td>71.4</td>
<td>70% cotton, 30% flax</td>
<td>Open-end</td>
</tr>
</tbody>
</table>

3.2 Methods

3.2.1 Determination of flax fibre length distribution

For the purposes of the investigation it was necessary to estimate flax fibre length distribution. Sample preparation and classification of fibre length into 2 mm intervals were carried out using a Zhukov’s mechanical device with a special system of cylinders.

The variation in flax fibre length was characterized by the mean fibre length, modal length, standard deviation of fibre length and the variation coefficient of fibre length.

Mean length of flax fibre samples, $L$ (mm), was obtained using the formula (3.1):

$$L = \frac{\sum (L_i, n_i)}{\sum n_i},$$

(3.1)

where $L_i$ is the mean length of each group, mm;

$n_i$ is the number of fibres in the group.

Modal length $L_m$ corresponds to the average length of the most numerous group of fibres.

Standard deviation, $S$ (mm), and variation coefficient, $C$ (%), characterise the non-uniformity of the fibre length. These were calculated from the formula:

$$S = \sqrt{\frac{\sum n_i (L_i - L)^2}{n}},$$

(3.2)

$$C = \frac{100S}{L},$$

(3.3)
where \( L \) is the mean length of groups of fibres, mm;

\( L \) is the mean fibre length, mm.

Fibre length distribution and staple diagram were then constructed in a standard way.

**3.2.2 Fibre diameter measurement**

The cross-sectional shape of a single flax fibre is an irregular polygon but can be considered as approximately circular and thus it is reasonable to characterise the fineness of single fibre by its 'diameter'. However, the term diameter is misleading when making practical measurements as it implies that fibres are circular in cross-section (Grishanov et al., 2006).

Work by Grishanov et al. (2006) has established a new method for estimating the single flax fibre diameter using the LaserScan instrument. The method is based on the mathematical modelling of the experimental fibre and fibre bundle width distribution and enables the flax fibre sample composition to be analysed in terms of proportions of single fibre and fibre bundles.

For fibre diameter measurement a Sirolan-Laserscan instrument was used. The principle of operation is based on the application of Helium-Neon laser (Charlton, 1995).

The diagrammatic representation of the operation of Laserscan is given in Figure 3.1.

Sample measurement commences when a prepared 0.03g test specimen of 2mm long fibre snippets is dropped into the dispersion bowl at the top of the Laserscan cabinet. The snippets are mixed in the isopropanol/water mixture in the bowl to form a dilute slurry.

A Helium Neon laser on the optical bench illuminates a round pinhole. Light emerging from the pinhole passes through the measurement flow cell. Some of the light is split off from the laser beam before the cell and monitored at the reference detector to correct for changes in laser power.

Fibre in the cell, on passing through the beam, scatters and diffracts the laser light. The main detector catches some of the diffracted light from the fibre and the drop
in power at the detector gives a direct measure of fibre diameter. Some of the light emerging from the cell is split off and diverted onto the face of an optical fibre discriminator (or fibre bundle). The discriminator is used to pick up invalid measurements such as dirt, fragments and ends, all of which are excluded from the diameter distribution results.

The cell is designed to preferentially align the snippets perpendicular to the flow direction and has had careful attention to detail during manufacturing and assembly in order to avoid fibre blockages. The Silastic inlet tube to the cell is clamped in position at the factory and set to achieve a typical acceptance rate of 55% - 65% when measuring snippets guillotined from wool top.

Figure 3.1 Laserscan schematic diagram

In the case of highly non-uniform fibres such as flax some 5,000 accepted snippet measurements are required for a reliable characterisation of fibre fineness (Grishanov et al., 2006). The method provides information that includes the mean diameter, standard deviation and coefficient of variation, percentage of fibres thicker than 30 micrometres, the number of snippets counted as valid measurements and the acceptance percentage these measurements represent of the total number of measurements recorded. The diameter distribution histogram is provided with both the actual number of counts in each histogram bar and the cumulative total (AWTA, 1999).
Additionally an airflow (Keisokki Micronair device) method has been employed for measuring the diameter of a fibre. This method is based on the measurement of the pressure drop of airflow through a standard mass of fibres.

This method of measuring the mean fibre diameter uses a standard mass of the scoured, dried and carded sample or a standard mass of sliver pre-conditioned at standard temperature and humidity. A test specimen is compressed to a fixed volume and a current of air is passed through it. The rate of flow is then adjusted so that the pressure drop across the sample equals a predetermined value; alternatively, the pressure drop across the sample is adjusted until the airflow equals a predetermined value. The rate of flow in the first case, or the pressure difference in the second case, is used as an indicator of the mean fibre diameter of the fibre in the sample.

The method does not provide information about fibre diameter distribution nor does it give an absolute figure for the fibre diameter. It only provides an indication of fibre fineness, which can then be related to mean fibre diameter by comparison with known standard calibration samples (IWTO-6-98; IWTO-28-00, 2001; ISO 2370, 1980) (Grishanov et al., 2006).

This method has been applied by Akin et al. (1999 a) for the analysis of quality of enzyme-retted flax fibres by comparing fibre fineness with calibrated flax standards. It was pointed out that although the method was sufficiently sensitive to differentiate the fibre fineness resulting from different treatments, the values at present do not indicate performance properties as they do for cotton.

3.2.3 Determination of flax fibre content in the yarn

At present there is no standard method of determination of flax component percentage in cotton-flax yarn obtained on a carding spinning system using standard cotton spinning equipment. In the course of this research work the following method has been applied. In a random way at least ten 10-mm long specimens of yarn were selected and cut from each of 3 yarn samples. These small samples were manually divided into components and the number of flax, cotton and other fibres in every length of yarn were counted using a low magnification optical microscope.
If the variation coefficient of the total number of fibres in a yarn specimen (coefficient of variation of the total number of fibres) exceeded 10 % or the variation coefficient of the number of flax fibres in 10 mm yarn length exceeded 35 %, the measurement for such a sample was repeated.

It should be noted that counting the flax fibres in a yarn specimen is complicated, because flax fibre is represented both by ultimate and technical fibres. The latter constitute complexes containing several ultimate fibres, the quantity of which is quite difficult to determine, because it fluctuates from two to seven. The mean linear density of flax fibres in the yarn depends on fibre pre-treatment and the technological parameters of blend processing.

Average linear density of flax fibres in the yarn was calculated as:

\[ d_\delta = 0.0357 \sqrt{\frac{T}{\delta}}, \]  

(3.4)

where \( \delta \) is fibre volume weight, accepted as 0.95 mg / mm\(^3\)

\( T \) is flax fibre average linear density, tex;

\( d_\delta \) is flax fibre diameter mean, determined using optical microscope, mm.

Flax fibre content in bi-component yarn has been estimated using the formula

\[ m_{\text{flux}} = \frac{100 n_{\text{flux}} T_{\text{flux}}}{n_{\text{flux}} T_{\text{flux}} + n_{\text{cotton}} T_{\text{cotton}}}, \]  

(3.5)

where \( n_{\text{flux}} \) and \( n_{\text{cotton}} \) is a number of flax and cotton fibres respectively in 10 mm specimen of yarn;

\( T_{\text{flux}} \) and \( T_{\text{cotton}} \) are respectively flax and cotton fibres average linear density in the yarn, tex.

The applicability of the described method could be proved by comparison with the existing standard method for bi-component yarn. The content of cotton in flax-polyester yarn has been determined using the aforementioned technique and method based on selective dilution of one of the components (ISO 1833-99). The results obtained confirmed that these methods were close to each other with an insignificant difference of 2%.
3.2.4 Breaking load and elongation of yarn

Samples of yarn were subjected to tensile tests on Statigraph L (ISO 2062). The Statigraph L is designed as a desktop device and is equipped with a draw-off clamp driven by a single spindle. The input of the test parameters and output of the test results is via the operating panel with LC-display or the Textechno Testcontrol PC system.

Gauge length is adjustable in 1-mm steps, its minimum is 10 mm. Maximum travel of the draw-off clamp is 850 mm depending on the clamp used. Speed of draw-off clamp is 0.1 - 800 mm/min.

The force measuring device includes two load cells with maximum load of 100 N and 2500 N. The elongation measuring device is equipped with an incremental transducer, with a resolution of 2 μm.

Gauge length applied in this research work was 500±1 mm. Speed of draw-off clamp was 150 mm/min.

The mechanical properties of yarn can be described by several parameters as follows.

Breaking load \((P)\) is the load at which specimens break, it is expressed in Newtons \((N)\).

\(L\) is the elongation for a given load applied to a specimen, mm;

\[
L = L_f - L_0, \tag{3.6}
\]

where \(L_f\) is the length of specimen after applied load, mm;

\(L_0\) is the initial length of the specimen (gauge length), mm.

Breaking elongation \((E)\) is the elongation of specimen at the breaking point, expressed as a percentage:

\[
E = \frac{100L}{L_0}, \tag{3.7}
\]

where \(L\) is the elongation (at break), mm.

Breaking load and elongation were chosen to characterize the strength of the samples for the following reasons. Breaking load (as well as tenacity) and elongation are specified in standards for yarn quality and published literature considerably more
often than moduli. Therefore in order to compare the results obtained during this research work with the results of other researchers breaking load and elongation were used. Moduli of cotton-flax yarn are planned to be investigated in further research work.

3.2.5 Preparation of yarn cross-sections

Yarn produced from blends of short flax with cotton, wool and chemical fibres has properties which differ from those of conventional yarn. Fibre properties alone cannot explain the characteristics of a yarn without some knowledge of its structure. The efficiency of mixing of heterogeneous fibres in a blended yarn is estimated by the uniformity of fibre distribution in yarn cross-section and along its length. Radial distribution of fibre components in a yarn cross-section is of great interest, because it determines the appearance and the properties of the end-product. Therefore it is recommended that the yarn cross-section be analysed (Hearle J.W.S. et al., 1972).

A method of producing yarn cross-sections was described by Espinoza (1985) and is designed to maintain the twist in a yarn. A variation in the twist of the yarn can change fibre cohesion, stiffness, elasticity, and roughness of the yarn.

The yarn is introduced into a hard gelatin capsule (Figure 3.2) via holes at both ends of the capsule; the diameter of the hole should be appropriate for the yarn thickness. The capacity of the gelatin capsule is 0.95 ml; the capsule is 23 mm long and is 7 mm in diameter; the diameter of the lid is 8 mm. The method guarantees that the structure of the yarn within the capsule will not change.
When the yarn is fastened between two horizontal bars, a small amount of candle wax is placed on the yarn, close to the bottom capsule, then the capsule is moved down, so that the wax is both outside and inside the bottom of the capsule. When the wax is dry, the resin is introduced into the bottom part of the capsule and then the capsule lid is moved down until the whole capsule is enclosed. Resin is prepared from a mixture of Technovit 7100, and two types of hardener. Polymerization takes about 100-120 minutes.

A cross-section of 12 μm thick slices of the yarn is produced using a microtome. It is an instrument used to obtain very thin sections and cuts which are suitable for examination under a microscope.

Images were retrieved from a CCD colour camera mounted on a microscope using a DT 2781 colour frame grabber board running under Global Colour Lab software. Two magnification levels are recommended: 10× for yarns with linear density less than 100 tex and 4× for yarns with linear density more than 100 tex.

### 3.2.6 Determination of yarn friction

Friction, emulsification, and waxing of yarn are of great importance in production processes and further processing in the textile industry. Processes that are under the influence of friction include yarn tension during rewinding, gliding of fibre product on cylinders or yarn guides, behaviour of fibres in drafting, fibre cohesion in yarn subjected to various external forces, etc.

The well known principle of friction (Bowden and Tabor, 1956) asserts that frictional force is proportional to normal pressure and does not depend on the contact
area of two rubbing surfaces. Thus, if $F$ is the force of friction, $N$ is normal pressure, the following equation is obtained:

$$F = \mu N,$$

(3.8)

where $\mu$ is the friction coefficient.

However, in the case of fibres and other polymer materials some amendments are introduced into the principle. Thus in the case of a given pair of surfaces frictional force is related to normal pressure by the equation:

$$F = aN^n,$$

(3.9)

where $a$ and $n$ are constants.

The magnitude of exponent $n$ varies in the range $\frac{2}{3}$ to 1. But if the pressure is constant and the nominal contact area changes, the friction force will be

$$F = bA^{(1-n)},$$

(3.10)

where $A$ is nominal contact area;

$b$ is a constant.

It is evident that in this case the friction coefficient is not constant. Nevertheless, the proportion $F = \mu N$ is often used in experiments, since it serves as measure of friction magnitude at certain conditions.

To determine friction as kinetic characteristics of moving threads the WIRA YFM:001 device was applied. It is a compact instrument for the determination of yarn friction. A tension device and associated tension measuring head eliminate the effect of any changes in thread tension due to differences between yarn packages. This system operates in the following manner: one head measures the yarn input tension (T1) while the other head measures the yarn output tension (T2) which is the sum of the input tension and the tension due to friction. The difference between these two values (T2-T1), representing the frictional component, is obtained electronically.
Figure 3.3 WIRA yarn friction meter

The digital L.E.D. display indicates the yarn tension in cN during the test and holds the last reading when the motor stops. The friction unit comprises two elements, the lower fixed plate and the upper movable plate, that can be dismounted easily and replaced by other devices for more specific tests, if required.

WIRA YFM:001 device was calibrated on cotton yarn prior to testing cotton-flax samples.

The friction coefficient of a moving thread $\mu$ is determined as a ratio of yarn tension to the pressure of the upper plate on it:

$$\mu = \frac{f}{P}, \quad (3.11)$$

where $\mu$ - friction coefficient (WIRA);

$f$ - horizontal yarn tension, cN;

$P$ - weight of upper plate (64g).
3.2.7 Determination of the unevenness of yarn and other spinning products

The properties of the fibres located in cross-sections of a spinning product change along the length of the material. These properties include length, durability, extensibility, fineness, and elasticity. The relative position of different fibre components changes between cross-sections. Accordingly, there are many types of product unevenness in properties and structure. However, in many cases unevenness in linear density is the most important factor that determines the quality of spinning products.

At the present time various types of devices are used for continuous measurement of the thickness of a product with the purpose of estimation of its unevenness. The main difference between these devices is in the construction of the sensor.

When choosing the measuring element it is necessary to take account of its sensitivity and response time. An element’s sensitivity \( K \) is a ratio of change in the element’s output signal \( \Delta Y \) to the change in input signal \( \Delta X \):

\[
K = \frac{\Delta Y}{\Delta X}, \quad (3.12)
\]

at the limit:

\[
K = \frac{dY}{dX}. \quad (3.13)
\]

Consequently the derivative of the function expressing the dependence of output quantity against input is equal to sensitivity of the measuring element. The response time of a sensor is the time lag between the change in measured parameter and change in the output signal.

At present many evenness testers, such as USTER Tester 3 and USTER Tester 4-SX (Switzerland), Kiesokki (Japan), KLA (Russia) (Uster, 1988, 1998), use a capacitive sensor.

The advantages of using capacitive sensors within evenness testers are as follows: (i) the method of measurement is contactless which obviates deformation of tested material; (ii) the accuracy of the measurement is not affected by the geometry and
volume density of the examined product; (iii) the ability to test materials with large irregularity in thickness at high speed.

Among the disadvantages of capacitive sensors are the dependence of measurement results on material impurities and changes in humidity, and relative complexity of the measuring devices.

Some evenness testers are equipped with photoelectric (optical) sensors. The main advantage of optical sensors is that measurements do not depend on yarn blend composition and its regain. Application of infrared sensors enables absolute measurements of yarn diameter to be obtained. In the latter case even if yarn is stationary, the sensor will produce a signal corresponding to the yarn diameter, while conventional optical sensors reproduce diameter changes only.

Ultrasonic sensors also find some application. The principle of operation is based on the power change of ultrasonic waves depending on the thickness of tested product. A comparison of evenness results for sliver tested using a gravimetric method and an ultrasonic sensor has shown a significant correlation coefficient \( r = 0.83 \).

The complexity of the measuring scheme and the dependence of measurements on product moisture content are among the disadvantages of the ultrasonic method.

The principle of a pneumatic sensor device operation is based on measurement of the air permeability of the material.

However, pneumatic sensors require the need to compensate readings changes according to product traverse speed and there are difficulties in low-level output signal registration and conversion.

During this research work the Keisokki KET-80/III B evenness tester was used. The device is designed for the measurement of yarn, thread, roving and sliver unevenness in linear density. It measures the variation of mass of moving product by means of a capacitive sensor.

Tests were carried out at a feeding speed of sliver of 8 m/min, and for yarn a feeding speed of 50 and 100 m/min.

The tester is equipped with a personal computer and software which enables the operator to set up test conditions and to control the testing process. The main merits are the possibility of initial setup in accordance with linear density, independence of
measurement result on hairiness and product colour. Disadvantages of the tester are
dependence on air moisture and blend composition of the spinning product.

The evenness tester with capacitive sensors provides signals in proportion to the
mass per unit length of the yarn, while the tester with the optical sensor measures the
diameter of the sample in the measuring field.

The quality of the spinning process is generally controlled on the basis of the
weight per unit length of material. Measuring the irregularity of spinning semi-products
and yarn is necessary to detect and control the yarn faults generated in the spinning
process.

Once the yarn is spun, various tests such as yarn evenness, count, twist, strength,
elongation, hairiness and their variations are carried out to determine the characteristics
of yarns. The results of these tests are important for predicting the efficiency of the
subsequent processes and appearance of the end products.

3.2.8 Yarn hairiness

A Laserspot LST II was used for the estimation of yarn unevenness and
hairiness in the course of the research work. Laserspot measures evenness and hairiness
simultaneously by means of Fresnel diffraction of a Laser beam. The yarn hairiness is
considered as one of the key parameters for quality control.

Investigation of hairiness in the second half of the 20th century led to the
development of a number of methods and devices for its estimation (Barella, 1957, 1979,

The hairiness has an influence on yarn processing in weaving and knitting
processes. The decrease in hairiness is one of the reasons for the reduction in yarn
breakage in technological operations which use yarn guides. The difficulties
encountered in weaving of a high hairiness yarn and additional costs related to
decreasing of hairiness in a ready-made material must be taken into account. This
parameter influences the properties of yarn products.

Barella (1957) classified yarn hairiness into three types: protruding fibre ends,
fibre loops, and wild fibres. For ring-spun yarns, Wang (1997) pointed out that yarn
hairiness may consist of 82-87% protruding fibre ends (including both leading and
trailing ends), 9-12% fibre loops, and 4-6% wild fibres. Several researchers (Datye, 1981; Lridag, 1999; Ozipek, 1999; Pillay, 1964; Wang, 1999 a,b) focused mainly on the influence of fibre properties (such as length, diameter, rigidity) and spinning conditions on yarn hairiness, as well as the measurements and measuring equipment for hairiness.

Rust (1992) ascertained that fibres migrate even during the winding process, increasing yarn hairiness afterwards, and a higher winding tension and/or higher yarn velocity leads to more fibre migration and hence more severe yarn hairiness. Tarafder (1992) studied the influence of the winding process on yarn hairiness; he observed that the hairiness at the bottom of the bobbin was greater than that at the top after winding. Chellamani (2000) and Krishnaswamy (1990) found that the number of short fibre trailing ends decreased due to winding if the bobbin yarn was excessively hairy.

During the winding process, when a yarn passes the tension disk, the yarn guide, and the grooved drum, the loose fibre ends on the surface of the yarn are rubbed acutely, which inevitably causes changes in yarn hairiness. The problem of change in yarn hairiness due to contact with the tension disk and grooved drum during the winding process was explored by Lang et al. (2004).

The yarn consists of the core part (characterized by diameter) and hairiness (Figure 3.4). Hairiness is generated because a section of those fibres in the yarn protrude from the core part. Hairiness can be classified into two types, where type I includes long hairiness and type II covers diffusion range where both ends of fibres are in the core but their central parts jump out of the core in the shape of a loop.

![Figure 3.4 Yarn structure](image)

Irregularity in visual thickness causes an irregular appearance of the yarn. Grading the yarn by comparing the yarns wound on a blackboard to a standard
photograph is the conventional method. Recently, an optical tester to evaluate the visual thickness has been developed. Such a tester is available for yarns with small hairiness, however, the yarn diameter (size of the core) influences the appearance. To measure the diameter correctly, the areas of hairiness and diffusion range should be separated from the core part. The Laserspot enables this separation to be made automatically.

When irradiating a linear sample material such as yarn with the coherent parallel rays (laser beam) with a wavelength (\( \lambda \)) , the interference fringes that are proportional to the yarn thickness (\( d \)) appear at the right angle to the yarn due to Fresnel Diffraction. Let the angle \( \alpha \) be the expansion (generation) of interference fringes (Figure 3.5).

\[
\sin \alpha = \frac{\lambda}{d}
\]  

(3.14)

Consequently, by measuring the expansion of interference at the right angle to the yarn, the thickness (\( d \)) can be obtained. At this time, the hairiness exists at the right angle to the yarn and does not affect the interference fringes of the yarn.

Hairiness also causes interference fringes but the light spreads in the direction of yarn. The amount of the diffused light is proportional to the level of hairiness (estimated as number of hairiness \( \times \) length). Since the refraction of light caused by the thickness of the yarn, as mentioned above, appears at the right angle to the yarn, it does not affect the diffraction of light due to hairiness.

Laserspot separates these two kinds of light by means of spatial frequency filtering and measures two individual signals of yarn thickness and hairiness from the corresponding sensors.

The conventional optical hairiness tester is influenced by the variations of yarn thickness due to the utilization of the diffused reflection of the light. Laserspot is free from the influence of yarn thickness because of the spatial filter which enables Laserspot to measure the hairiness alone. Figure 3.5 shows the above mentioned principle schematically (Keisokki, 1997).
When determining the hairiness using Laserspot LST II, all the hairs are classified into six classes, according to the thickness of the places from which hairs stick out and 3 classes by the length of the hairs (limits are set to 5.0 mm, 3.0 mm and 1.0 mm from the top of the hairs). The speed of test can be varied from 8 to 400 m/min.

The characteristic that is measured \((Ha)\), represents the hairiness equal to the total length of hairs (in mm) on 1 cm lengths of yarn.

The main advantages of the measurement using laser sensors are the capability to identify any yarn defect regardless of its length and to make absolute measurements of yarn diameter; high measurement accuracy; and the fact that measurements do not depend on the yarn blend composition, air moisture, product colour and changes in exterior lighting.

The main disadvantage of the device is that dust deposited on the light source influences the measurement accuracy.

### 3.2.9 Microscopy

Information about structural changes in flax fibre surfaces is of particular interest, since the structure of complex flax fibre in many respects determines its technical characteristics such as capillarity, strength, colour, fineness, flexibility etc.
Scanning Electron Microscopy (SEM) was used to observe changes in the surface of flax fibre after various treatments. Digital images were obtained using a S-430 LEIKKA scanning electron microscope at magnifications ranging from \( \times 100 \) to \( \times 2000 \).

The research work also included application of the microscope computer system Mesdan Microcolor 2000 250-LAB for the investigation of transparent, translucent and opaque objects with optical magnification from \( \times 0.63 \) to \( \times 60.00 \), and digital up to \( \times 32 \).

3.2.10 Measurement of the twist level of open-end spun yarn

The research included the study of yarn twist and its influence on the mechanical properties of the yarn. At present there is no standard methodology for measuring the twist level of open-end spun yarn. The distinctive features of yarn structure can explain this. It is difficult to measure the open-end yarn twist using the so-called "method of untwisting", because fibres at external layers are wound on the yarn core, so it is practically impossible to lay them parallel (Kukin et al., 1989).

The application of the method of double twisting usually leads to underestimation of the magnitude of open-end yarn twist level. More accurate results of measuring the open-end yarn twist can be obtained by using the "balanced twist" method. By using the method of double twisting it is possible to obtain the difference between the number of turns during twisting and untwisting, because of the increase of the yarn length. To reduce this difference to a minimum, a three-stage procedure of "untwisting-twisting" (with a change of direction) of the same yarn (Figure 3.7) should be applied (Kueny and Schutz, 1975).
Figure 3.6 Twist estimation scheme

\( n_1, n_2, n_3 \) are readings of the twist tester obtained after each "untwisting-twisting" operation. With reference to Figure 3.6

\[
\begin{align*}
n_1 &= 2n + x_1; \\
n_2 &= 2n + x_1 + x_1 + x_2 = 2(n + x_1) + x_2; \\
n_3 &= 2(n + x_1) + x_2 + x_2 + x_2 = 2(n + x_1 + x_2) + x_3.
\end{align*}
\]

Yarn twist can be determined as

\[
K = \frac{(n_1 - 2n_2 + n_3)}{4} \cdot \frac{1000}{L},
\]

where \( n_1, n_2, n_3 \) are readings of the twist tester obtained after each "untwisting-twisting" operation;

\( L \) is the length of yarn between clamps, mm.

The methods described in Chapter 3 were chosen to improve understanding of structure and properties of cotton-flax yarn. The spinning methods applied to produce cotton-flax yarn are specified in Chapter 4.
CHAPTER 4 PRODUCTION OF COTTON-FLAX YARN

The objectives of this part of the research were as follows:
- to produce the cotton-flax yarns specified in the Chapter 3 (section 3.1);
- to carry out experimental analysis of unevenness at the stages of spinning processes;
- to compare actual and standard parameters of unevenness, to make recommendations on the norm of irregularity of ready to use cotton-flax yarn;
- to recommend biochemical methods to produce cotton-flax yarn with reduced hairiness and improved mechanical properties;
- to evaluate the potential of fine dust removal with simultaneous improvement of hygroscopic properties of cottonised flax by means of enzyme treatment.

4.1 Production of cotton-flax ring spun yarn

In the course of the research work an experiment on cotton-flax ring spun yarn production on a carding spinning system was conducted. Samples of 72 tex yarn were obtained from a blend containing cotton (70 %) and cottonised flax (30 %) using the technique based on a rupture method (Patent RU No-2074578 C1).

Fibres were spun into a yarn using the laboratory-scale spinning plant Shirley Platt, which enables production of low and medium linear density yarn from 42 grams of raw stock. This plant simulates a cotton carding spinning system, the performance characteristics of yarn obtained are similar to those obtained on the same system in industrial conditions.

The "Shirley Platt " miniature spinning plant, comprising card, draw frame and ring spinning frame, was designed to provide a ready means for obtaining a quick and reliable assessment of the spinnability of very small samples of cotton and staple fibres, either alone or in blends, of staple lengths up to 63.5 mm.

The carding machine is a small version of the standard cotton card, the main difference being that the flats are stationary and their number is reduced to eight. It comprises a feed apron, feed roller and feed plate, along with a taker-in, cylinder and

52
doffer fitted with metallic wire and spring loaded flats, covered with clothing wire. The web from the doffer comb is wound onto a drum and consolidated into a fleece by a self weighted calender roller. The intensity of carding on a laboratory-scale card is higher than on a conventional card.

The draw frame is a single delivery machine with a creel accommodating a drum from either the card or a sliver. A four roller, two zone drafting arrangement with "Shirley" fluting of the bottom rollers is fitted. For the experimental processing of cotton-flax blends the machine was equipped with bottom rollers of 28.5 mm, 25.4 mm, 28.5 mm and 28.5 mm in diameter. The top rollers were spring weighted and a weight relieving motion was fitted. Flat, reciprocating clearers were applied to both top and bottom lines of rollers.

The spinning frame used was an eight spindle single sided machine with a creel accommodating two drums of sliver from the draw frame. A two zone, Casablanca long apron drafting system enables staple fibre up to 63.5 mm long to be processed with drafts up to 400. The top rollers are covered with synthetic coats and the saddles are spring loaded with quick release arrangement on the front rollers.

Production of yarn samples was achieved in the following way.

A random sample of 42 g of material was taken, opened and cleaned by hand, pre-treated at a Labormixer device, and spread evenly over 51 cm of the feed apron of the card. The sample was known to have high trash content, therefore the initial weight of the sample was increased by 3 g making it 45g.

A second passage through the card is considered to be desirable for blending experiments when processing material with high trash content (Shirley-Platt, 1961). The flats, cylinder and doffer were cleaned with the stripping brush before the second passage. After carding, the drum with fleece was transferred to the creel of the draw frame. After two passages through the draw frame, a drum containing 20 coils of sliver was obtained. The sliver produced was approximately 2050 tex, although the sliver count is not normally tested at this stage. Each drum of sliver feeds four spindles of the ring frame. The draft at the ring frame was adjusted to produce yarn of 72 tex.

Yarn production was accompanied by considerable levels of breakage; this could be explained by significant difference in properties of the blend components.

Characteristics of the yarn obtained are presented in Chapter 3, 4 and 5.
Yarns spun on the miniature plant usually contain more neps than those spun on conventional machinery using the same cotton. However, it was found that the visually assessed level of unevenness is generally the same as that obtained for yarns processed on conventional systems even when combed.

The ring spun cotton-flax yarn produced on the laboratory carding system and miniature spining plant was of a satisfactory quality. This confirmed that the fibre blend used is acceptable to be processed on the industrial spining system. The industrial experiment conducted consisted of production of open-end yarn on the carding/spinning system in the working environment of the “Sovetskaya Zvezda” spinning mill.

4.2 Production of cotton-flax open-end spun yarn

Experimental production of flax-containing yarn on standard cotton spinning equipment was conducted at the “Sovetskaya Zvezda” spinning mill. 35.5 tex and 71.4 tex open-end yarns were obtained from the blend consisting of cotton (70 %) and cottonised flax (30 %).

Yarns have been produced according to the spinning plan represented in appendix A. In the course of the experiment adjustment of equipment setup parameters such as settings, loadings, drafts distribution in draft zones and speeds of discharging elements were undertaken.

The process flowsheet applied for the processing of the cotton-flax blend in the industrial experiment was as follows.

The equipment used to mix the components for yarn production was in the following sequence:

- automatic opener ARK-2;
- mixer SN-3;
- ultra cleaner ON-6-P;
- porcupine opener RG-7;
- scutchter T-16.

During the experiment it was found that the opening-scutching plant had insufficient mixing and cleaning capability. In order to intensify the opening and
scutching processes the plant incorporated an additional mixer MSP-8 and a second ultra cleaner ON-6-P, which are standard for Russian cotton spinning mills.

The carding process was carried out on a Wirkbau carding machine equipped with a Holengswart card. It should be noted that the carding machine used for processing flax containing blend not only removes trash, but also splits flax technical fibres into individual fibres. From this point of view the condition of the working parts of cards and their settings should be appropriate for the blend composition.

To reduce fibre losses in carding the settings of the "card cylinder – flats" zone were increased in comparison with those applied for processing of conventional blends. Stability of the carding process was achieved by the application of local air humidification. No blockage of the coiler canal and reels to the cylinders card was observed.

Processing of card sliver was carried out in two passages of draw frames L2-50-1 and L2-50-220. The yarn samples were spun on BD-200-RC rotor spinning machines.

Open-end yarn production was accompanied by increased breakage on the spinning frames (within 200-350 breakages per hour per 1000 rotors). The yarn breakage that took place was considerably higher than is normal for cotton open-end spinning. However, cotton-flax blends processing is known to be accompanied by such a yarn breakage of about 300 breakages per hour on 1000 rotors/spindles (Chastmova, 1988; Krylova, 2004).

The technology of flax blended yarn production is a sequence of mechanical actions applied to the blend of fibres which results in a certain quantity of waste. The waste yield depends on fibre properties and the intensity of mechanical action, which is determined by the spinning system.

Mechanical actions on flax fibre in spinning cause technical fibres to split into ultimate fibres; this increases the quantity of fibres in wastes. When blends with short flax fibres are processed, it is flax fibres that are mainly lost due to their greater linear density and higher rigidity.

Thus, processing of short flax in blends is accompanied by increased loss of this fibre in wastes. This adversely affects the flax content in the yarn, the yarn output from the blend and consequently the production cost. However, production of waste is
technologically inevitable since one of the main aims of high quality yarn manufacture is to remove all impurities initially present in the blend.

The greatest quantity of trash in cotton-flax yarn manufacture is obtained during opening and carding. The quantitative characteristics of wastes in blended flax yarn production were studied.

The quantity of wastes produced have been measured during the processing of cotton-flax blends by the opening-scutching plant and carding. This enabled the actual proportion of waste yield, relative to the mass of blend processed, to be determined. Trash yield in these stages is shown in Table 4.1.

The analysis of waste yield produced during the opening, scutching and carding processes shows that during the processing of cotton-flax blends, the quantity of waste on the same plant is 35 % higher than those of 100 % cotton processing. To aid comparison, the trash yield rate for 100 % cotton in opening and scutching is 3.7 %, and in carding is 3.9 %.

Table 4.1 Trash yield for cotton-flax blends during processing

<table>
<thead>
<tr>
<th>Machinery</th>
<th>Trash Yield, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ultra cleaner ON-6-P</td>
<td>1.74</td>
</tr>
<tr>
<td>Porcupine opener GR-7</td>
<td>0.44</td>
</tr>
<tr>
<td>Scutcher T-16</td>
<td>0.47</td>
</tr>
<tr>
<td>Distributor PRC</td>
<td>0.55</td>
</tr>
<tr>
<td>Distributor’s filter</td>
<td>0.79</td>
</tr>
<tr>
<td>Wirkbau cards:</td>
<td></td>
</tr>
<tr>
<td>- short fibres from carding flats</td>
<td>2.45</td>
</tr>
<tr>
<td>- short fibres from swift</td>
<td>2.34</td>
</tr>
<tr>
<td>Filter fly</td>
<td>2.84</td>
</tr>
<tr>
<td>Total</td>
<td>11.62</td>
</tr>
</tbody>
</table>

For comparison existing data about processing blends of 30 % flax with 70 % of cotton have been considered. The research work by Krylova (2004) included experimental determination of waste yield quantity produced during processing of short flax in blends with cotton (in ratio 30 % to 70 % accordingly) on the technological line (Patent RU 2158790, C1, 2000.11.10). After processing 100 kg of cotton-flax blend on an opening-scutching plant and carding machine, the waste obtained was weighed and the actual percentage of waste determined. Results showed that trash yield in the opening and scutching processes was 6.85 %, and 9.64% in carding, 16.49 % in total
(whereas the trash yield for 100 % cotton was 7.6 %). Also it has been established that processing of cotton-flax blends was accompanied by a higher trash yield in comparison with the processing of flax-polyester blends on the same plant.

The investigations by Krylova (2004) included the processing of modified flax obtained on different cottonising lines in blends with cotton. The blend composition consisted of 30 % cottonised flax and 70 % cotton. It was established that the trash quantity at the opening-spinning stage ranged from 17.9 % (in the case of application of flax cottonised on “Lott” line) to 27.4 % (La Roche line cottonising).

Thus, the waste yield during the opening, scutching and carding sections of this work, at the rate of 11.62 % in processing of the blend investigated, can be considered as acceptable.

A 71.4 tex open-end yarn produced from cotton-flax blend was used for the manufacture of knitting threads “Lenok” in accordance with the following process.

Yarn doubling was carried out using an electronic Savio AES 12 winder with independent heads. Twisting of folded yarn was carried out using a two for one frame Savio TDS 17 N, and yarn winding using a MNK balling machine.

Investigation of the structural features of twisted thread produced from open-end yarn showed that the presence of a loose external layer of wound fibres in the yarn plays an important part in twist composition. It has been established that twisting of open-end yarns, produced at low twist in spinning, leads to a decreased untwisting of strands in cases of low and medium levels of second twist. This could be explained by the presence of the loose external layer and wound fibres in open-end yarns, which by entangling during the twisting process creates greater surface contact and prevents strands untwisting.

It is now generally recognized that unevenness in fibre properties, instability of spinning processes, imperfections in the machine working parts and incorrect setup parameters can all contribute to unevenness in yarn properties. It is important to minimise this tendency, because it results in instability of later technological processes, increases yarn breakage, and leads to decreasing productivity and quality of the final product.

Such properties of the fibres located in cross-sections of the spinning product leads to variations in yarn durability, extensibility, fineness, and elasticity along the
length of the yarn. The relative position of different fibre components changes along
the yarn. Accordingly, there are many types of product unevenness in properties and
structure, but in many cases unevenness in linear density is the most important factor
that determines the quality of spinning products.

4.3 Unevenness theory, experimental analysis of unevenness at the stages of
the spinning process

The research work included experimental analysis of unevenness during
different stages of the spinning process. The intermediate products and yarn obtained
(71.4 tex; 70% cotton, 30% flax) were examined using the Keisokki evenness tester
KET-80/III B. Estimations of hypothetical and actual irregularity, and the index of
spinning products irregularity were made. The reasons for the irregularity formation
were investigated using spectrogram analysis.

It is generally recognized that opening, mixing and carding processes do not
provide a uniform arrangement of fibres. The machine components responsible for
these processes determine the random arrangement of fibres in fibre flow or sliver.
However, the actual arrangement of fibres differs significantly from the ideal
(randomized) structure.

The unevenness of actual products is higher than those of ideal products, i.e.
products with a randomized arrangement of fibres. This difference is due to
imperfections and instabilities in machine components, including drawing mechanisms.
Thus, the magnitude of the difference between actual and ideal product characteristics
makes it possible to assess the efficiency and performance of production processes and
the evenness of the product obtained.

At the present time almost all existing models of fibre product unevenness
assume Poisson’s pattern of fibre arrangement along the product.

The first model of fibre product was developed by Spencer-Smith and Todd
(1941). According to this model the probability that a fibre is located at a particular
portion of the product tends to zero.

In addition to the work of Spencer-Smith and Todd, comprehensive
investigations of the Poisson model have been carried out by Martindale (1945), Breny
(1953), Monfort (1960), Sulser (1953 ), and Grichin (1964, 1966) et al.
A large number of research investigations have been devoted to the theory of an ideal (random) sliver. Significant contributions to development of the theory are attributed to J. Martindale (1945), H. Breny (1953), H. Picard (1951), K. Fujino (1965), S. Kawabata (1965), H. Olerup (1952), Q.A.R. Foster (1946), A. Sevostyanov (1962) et al. These works are based on two main models of ideal sliver formation – Poisson and Bernoulli, for each of them random function characteristics are determined such as correlation function, spectral density and unevenness gradient.

In order to study the fibre arrangement in a product and to estimate its unevenness, an ideal product model is used since research on the actual arrangement of fibres is extremely complicated. According to the Poisson model and the specification of the number of fibre ends along the product, the probability of the intersection of the product cross section by \( n \) fibres is:

\[
P(n) = \frac{(kl)^n}{n!}e^{-kl},
\]  

(4.1)

where \( n \) – is number of fibres traversing the product cross;

\( l \) – is average fibre length;

\( e \) – is natural logarithm base;

\( k \) – is average linear density of fibre ends:

\[
k = \frac{m}{2L},
\]  

(4.2)

where \( m \) – is number of fibres at \( 2L \) length;

\( kl = n_{av} \) — is average number of fibres in products cross-section.

The hypothetical unevenness, \( C_{hyp} \), of the product linear density, in which the cross-section distribution of the fibres is defined by Poisson’s pattern, is determined by the formula:

\[
C_{hyp} = \frac{100}{\sqrt{n}}, (\%)
\]  

(4.3)

where \( n \) is number of fibres in the cross-section that is defined by the formula:
\[ n = \frac{T_{\text{yarn}}}{T_{\text{fibre}}} \]  

(4.4)

This formula is correct only for a product consisting of separated fibres that are identical in properties and located in a random way along the product. In the case of a real product the value of ideal coefficient of variation is slightly higher, it is defined by Martindale’s formula:

\[ C_{\text{hyp}} = \frac{100}{n} \sqrt{1 + 0.0004 C_{S}^{2}} \]  

(4.5)

where \( C_{S} \) - is the coefficient of variation of fibre cross-section area.

Some researchers amended the formula 4.5 with correction indexes. For example, Dyson (1974) suggested that the straightness of fibres in the yarn should be taken into account when estimating the hypothetical unevenness. The modified Martindale formula is as follows:

\[ C'_{\text{hyp}} = \frac{100}{nK} \sqrt{1 + C_{T}^{2} + C_{K}^{2}} \]  

(4.6)

where \( K \) – is the coefficient of straightness of the fibre in the product (yarn).

\( C_{K} \) – is the variation coefficient of straightness of the fibre in the product;

\( C_{T} \) – is the variation coefficient of fibre linear density;

In the case of a uniform distribution of fibre straightness \( C_{K} = \frac{1 - K}{K \sqrt{3}} \).

Substituting this into (4.6) and taking into account that for cotton fibres \( C_{T} \approx 0.35 \) and \( K \approx 0.8 \) this yields:

\[ C'_{\text{hyp}} = \frac{100}{\sqrt{nK}} \sqrt{1.225 + \frac{(1 - K)^{2}}{3K^{2}}} \]  

(4.7)
4.4 Unevenness of intermediate spinning products

The number of tests on the evenness tester «Keisokki» KET 80/III B was determined according to Professor Solov'ev method (1966). It was found that five tests for each sample were sufficient. The experimental confidence error did not exceed 3%. The calculations were performed using the following formula:

\[ n = \left( \frac{100t \sigma_n}{mCV_{av}} \right)^2 + 1, \]  \hspace{1cm} (4.8)

where \( t \) is Student’s coefficient for the appropriate number of degrees of freedom \( f \) and confidence probability \( P = 0.95 \) (at \( n \geq 20 \ t = 2.09 \));

\( \sigma_n \) is an estimated standard deviation;

\( CV_{av} \) - average coefficient of variation on Keisokki KET 80/III B device;

\( m \) is experimental confidence error (accepted as 3%).

An example for calculating the number of tests for card sliver is presented below. Sampling was carried out at two carding machines. Each sample of sliver was tested three times on the Keisokki evenness tester with capacitive sensor elements. The average coefficient of variation for the six trials was 6.56%. Average range of deviation at three tests was \( R_{av} = 1.31 \). Using the average range of deviation the standard deviation \( \sigma_n \) has been estimated using the formula:

\[ \sigma_n = \frac{R_{av}}{d}, \]  \hspace{1cm} (4.9)

where \( d \) – is constant equal to 2.326.

At \( n = 3 \) formula (4.9) yields \( \sigma_n = 0.536 \).

Using formula (4.8) the requisite number of tests for sliver from the first set of draw frames was determined as \( n_t = 4 \).

In the same way, the number of tests was defined for the products obtained at other manufacturing stages. The calculated and accepted number of trials on the evenness tester for intermediate spinning products are given in Table 4.2.
Table 4.2 Calculated and accepted number of tests of spinning semi products at Keisokki evenness tester

<table>
<thead>
<tr>
<th>Machines at manufacturing steps</th>
<th>Number of tests</th>
</tr>
</thead>
<tbody>
<tr>
<td>WIRKBAU carding machine (card sliver)</td>
<td>4.15</td>
</tr>
<tr>
<td>L2-50-1 draw frame (sliver 1)</td>
<td>4.50</td>
</tr>
<tr>
<td>L2-50-220 draw frame (sliver 2)</td>
<td>3.85</td>
</tr>
<tr>
<td>BD -200-RC rotor spinning machine (yarn)</td>
<td>4.80</td>
</tr>
</tbody>
</table>

To express the unevenness in linear density the following parameters are usually applied:

- linear unevenness (irregularity);
- the coefficient of variation;
- unevenness index.

Linear unevenness, $U$ (%), is the average of the absolute values of the linear densities of the integrated lengths between which unevenness is measured and expressed as a percentage of the average linear density for the total length within which unevenness is measured. It is caused by uneven fibre distribution along the length of the strand. The $U$ value was the only value calculated by the older Uster equipment. Nowadays, the coefficient of variation, $CV$ (%), is commonly used to define the variability of yarn properties. Currently, it is one of the most widely accepted methods of quantifying irregularity.

It is known that in the case of a normal distribution of the product linear density the variation coefficient and the linear unevenness are linked by a formula as follows (Kazama K., 1965, 1966):

$$CV = 1.25U.$$  \(4.10\)

The unevenness index is a very important parameter because it characterizes the technological process at each manufacturing step. The unevenness index is calculated as
a ratio of measured unevenness to the hypothetical unevenness which is the irregularity of an ideal spinning product:

\[ I = \frac{C_{\text{act}}}{C_{\text{hyp}}} \]  \hspace{1cm} (4.11)

where \( C_{\text{act}} \) – is measured coefficient of variation in linear density;

\( C_{\text{hyp}} \) – is hypothetical (ideal) coefficient of variation in linear density.

In this research work the hypothetical unevenness was calculated by Dyson’s version of the Martindale formula, which takes into consideration the straightness of the fibres in the product.

The values of hypothetical unevenness of intermediate spinning products and cotton-flax yarn are shown in Table 4.3.

Normally the product unevenness increases from stage to stage, because the number of fibres in the cross section steadily decreases and their uniform arrangement becomes more disrupted. Each drafting operation increases the unevenness of the output product in comparison with the input product.

Each machine in the spinning process increases the unevenness, thus increasing the unevenness of the final yarn. The resultant unevenness at the output of any spinning process is equal to the square root of the sum of the squares of the irregularities of the material and the irregularity introduced in the process.

<table>
<thead>
<tr>
<th>Machines at manufacturing steps</th>
<th>Calculated hypothetical unevenness, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>WIRKBAU carding machine (card sliver)</td>
<td>0.8</td>
</tr>
<tr>
<td>L2-50-1 draw frame (sliver 1)</td>
<td>0.8</td>
</tr>
<tr>
<td>L2-50-220 draw frame (sliver 2)</td>
<td>1.2</td>
</tr>
<tr>
<td>BD -200-RC rotor spinning machine (yarn)</td>
<td>8.2</td>
</tr>
</tbody>
</table>

The lower the unevenness index is, the lower the actual unevenness, and the better the adjustment of the technological process. In the ideal case the index is equal to 1. Thus, the higher the unevenness index, the greater the fluctuations that occur during
the technological process. The results of estimation of this parameter are shown in Table 4.4.

Table 4.4 Indexes of irregularity

<table>
<thead>
<tr>
<th>Machines used</th>
<th>Index of unevenness</th>
</tr>
</thead>
<tbody>
<tr>
<td>WIRKBAU carding machine (card sliver)</td>
<td>8.0</td>
</tr>
<tr>
<td>L2-50-1 draw frame (sliver 1)</td>
<td>8.4</td>
</tr>
<tr>
<td>L2-50-220 draw frame (sliver 2)</td>
<td>5.8</td>
</tr>
<tr>
<td>BD -200-RC rotor spinning machine (yarn)</td>
<td>2.4</td>
</tr>
</tbody>
</table>

The index of irregularity decreases steadily as the product becomes finer due to adjustment of the technological process and the spinning equipment being maintained in good condition. Figure 4.1 shows the change of irregularity index for 71.4 tex cotton-flax yarn.

![Graph showing changes in index of irregularity and coefficient of variation](image)

Figure 4.1 Variation of the coefficient of variation in linear density and the index of unevenness at carding spinning system manufacturing steps.

It can be seen on the chart that the index is decreasing gradually during the technological process; a lower index could be achieved by better adjustment of the equipment.
4.5 A comparison of actual and standard parameters of unevenness

Currently there are few methods to calculate the standard parameters of unevenness of intermediate products. It was therefore necessary to develop guidelines for the measurement of irregularity of intermediate products, in order to ensure required yarn evenness. Prof. Solov'ev's method (1966) provides a better estimation for the unevenness which is closer to the experimental data.

The unevenness of spinning products was estimated using data obtained from the Keisokki KET 80/III B tester as an average of two manufacturing batches taking into consideration the experiment confidence error (3 %) (see Table 4.5). In the same table guidelines of unevenness characteristics at different stages of the spinning process for production of cotton yarn are shown for comparison (Uster Statistics, 1989).

<table>
<thead>
<tr>
<th>Technical characteristics</th>
<th>Machines at manufacturing steps</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Carding machine</td>
<td>1st stage drawing frame</td>
<td>2nd stage drawing frame</td>
<td>Rotor spinning machine</td>
</tr>
<tr>
<td>Linear density, $T$, tex</td>
<td>3570</td>
<td>4000</td>
<td>4000</td>
<td>71.4</td>
</tr>
<tr>
<td>Doubling number, $n$</td>
<td>1</td>
<td>8</td>
<td>6</td>
<td>-</td>
</tr>
<tr>
<td>Draft, $E$</td>
<td>90</td>
<td>7.14</td>
<td>6</td>
<td>56</td>
</tr>
<tr>
<td>Measured variation coefficient, $CV$, %</td>
<td>6.5</td>
<td>6.9</td>
<td>7.0</td>
<td>19.6</td>
</tr>
<tr>
<td>Index of unevenness, $I$</td>
<td>8.0</td>
<td>8.4</td>
<td>5.8</td>
<td>2.4</td>
</tr>
<tr>
<td>Uster Statistics for cotton yarn:</td>
<td>$CV$, %</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>$I_{cot}$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>4.0</td>
<td>4.5</td>
<td>4.3</td>
<td>15.0</td>
</tr>
</tbody>
</table>

Comparing the test results of cotton-flax spinning products with Uster guidelines for cotton yarn it can be affirmed that actual level of unevenness of cotton-flax products at all stages of the technological process, excluding sliver from the 2nd drawing frame, are above the limit for the level of variation coefficient of 100 % cotton products.

In order to analyse the level of unevenness index of cotton-flax products Uster recommendations (Uster Statistics, 1989) at 50 % level were accepted as a basis. For
example, according to Uster Statistics the coefficient of variation of the yarn mass of an 71 tex 100 % carded cotton open-end spun yarn has an evenness of CV = 15 %; this means that 50 % of all 71 tex carded cotton rotor spun yarns produced worldwide have a CV of 15.0 % or better.

Based on this data, the unevenness guidelines for cotton-flax yarn were rated using the recommended unevenness index and the calculated ideal unevenness for cotton yarn. The recommended norm of irregularity of ready to use first-grade cotton-flax rotor spun yarn is 15 %, and second-grade yarn is 18 %.

4.6 Investigation of periodic unevenness and analysis of the spectrograms obtained on the evenness tester

Variations in the thickness of a product along its length follow a certain pattern. Recorded mass diagrams of any spinning product include waves with different amplitude and length, which are combined and superimposed on each other. As a rule wavelength and amplitude values vary. Such a complicated pattern of change in spinning product thickness is explained by continuously changing conditions during technological processes. These conditions are determined by fibre unevenness, various types of structural irregularity, incorrect setup parameters, imperfections in the machine working parts, etc.

Therefore, it is obvious that neither linear unevenness nor the variation coefficient can fully describe and/or estimate the nature of unevenness. Two products can have identical values of variation coefficients in linear density, but one of them has periodic faults, while another may have random unevenness. These two types of unevenness lead to a difference in the appearance of end-products produced from the same fibres and to the same technical specification.

Many workers have confirmed that oscillations in the thickness of spinning products can be characterized by random functions. Application of such characteristics of random function as correlation function, spectral density, unevenness gradient, etc. enables the character and structure of unevenness to be fully described and understood.

Quantitative assessment of the pattern of unevenness in spinning products, i.e. determination of unevenness wavelength and amplitude, detection of the periodic faults
and other parameters, help to investigate the effect of operating regime and construction of machine working parts on product properties.

Testing the evenness of yarn, roving or sliver by means of capacitance methods produces a mass distribution of fibre material relative to the length examined which can be represented in the form of a diagram (Figure 4.2). It is understood that random deviations are caused by a non-uniform distribution in a cross-section of the fibre material relative to the length examined, while periodic deviations are often attributable to machine faults or incorrect setting of drawing mechanisms.

In most cases, random oscillations are superimposed on periodic variations, this makes it difficult to define the source of unevenness of the examined material.

![Diagram](image)

Figure 4.2 Typical diagram of yarn unevenness

Figure 4.2 is a representation of the mass variations in the wavelength domain, whereas the spectrogram is a representation of the mass variation in the frequency domain. A spectrogram helps to recognize and analyse the periodic faults in spinning products.

The frequency spectrum is not of practical use for textile applications. A representation which makes reference to the wavelength is preferred. Wavelength directly indicates the distance at which the periodic faults repeat. A more correct indication of the curve produced by the spectrograph is the wavelength spectrum. Frequency and wavelength are related as follows:
frequency = (wavelength)/(material speed).

In the spectrogram, the x-axis represents the wavelength. In order to cover a range of wavelengths, a logarithmic scale is used for the wavelength representation. The y-axis represents the amplitude of the faults in yarn.

The spectrogram consists of shaded (critical section - CS) and non-shaded areas (general section - GS). If a periodic fault occurs minimum 25 times within the test length of the material, then it is considered as significant and it is shown in the shaded area. Wavelength ranges which are not statistically significant are not shaded. In this range the faults are displayed but not hatched. This happens when a fault repeats for about 6 to 25 times within the tests length of the material.

As far as those faults in the non-shaded area are concerned, it is recommended to first confirm the seriousness of the fault before proceeding with the corrective action. This can be done by testing a longer length of yarn. Faults, which occur less than 6 times, will not appear in the spectrogram.

Deviations in mass are registered in accordance with the frequency of their occurrence \( H(\lambda) \) by wavelength, which is defined as the distance between two thick or thin places (Figure 4.3). The maximum (Max) peak of the spectrogram is at \( \text{Max} = 3L_F \), where \( L_F \) is average fibre length; the peak at wavelength \( \lambda \) characterizes abrupt periodic mass deviation along the product length.

![Figure 4.3 a) yarn with periodic mass deviations b) spectrogram consisting of general section (GS) and critical section (CS)](image-url)
The spectrogram enables detection of the repetition length of the periodic faults using the rule that the fault is considered as significant if that part of the bar which is above the base level is greater than a half of the base level. This is illustrated in Figure 4.4, where

\[ P > \frac{B}{2}. \]  

(4.12)

![Figure 4.4 Fault affecting end-product appearance](image)

Depending on the wavelength of the periodic fault, the mass variations are classified as

- short-term variation (wavelength ranges from 1 cm to 50 cm);
- medium-term variation (wavelength ranges from 50 cm to 5 m);
- long-term variation (wavelength longer than 5 m).

Periodic variations in the range of 1 cm to 50 cm are normally repeated a number of times within the woven or knitted fabric width, which results in the periodic thick places or thin places located near to each other. This produces, in most cases, a so-called "Moire effect". This effect is particularly visible for the naked eye if the finished product is observed at a distance of approx. 50 cm to 1 m.

Periodic mass variations in the range of 50 cm to 5 m are not recognizable in every case. Faults in this range are particularly noticeable if the length of the weft is equal to a single or double width of the fabric, or the length of the stretched yarn in one circumference of the knitted fabric is equal to an integer number of wavelengths of the periodic fault. In such cases, it is to be expected that weft stripes will appear in the woven fabric or rings in the knitted fabric.
Periodic mass variations with wavelengths longer than 5m can result in quite distinct cross-stripes in woven and knitted fabrics. This is because the wavelength of the periodic fault will be longer than the weft length within the width of the woven fabric or the yarn length required to produce the circumference of the knitted fabric. The longer the wavelength, the wider the cross-stripes will be. Such faults are quite easily recognizable in the finished product, particularly when this is observed from distances more than 1 m.

A periodic mass variation in a fibre assembly does not always result in a statistically significant difference in the \( U/V \) value. Nevertheless, such a fault will be visible in a woven or knitted fabric and impair the fabric quality. Such patterning in the finished product can become intensified after dyeing. This is particularly the case with solid colour products and products consisting of synthetic fibre filament yarns.

The degree to which a periodic fault can affect the finished product depends not only on its intensity but also on the width and type of the woven or knitted fabric, the fibre material, the yarn count, the dye up-take of the fibre, etc. A considerable number of trials have shown that the height of the peak above the basic spectrum (CS) should not exceed 50% of the basic spectrum (GS) height.

Roller eccentricity results in a sinusoidal mass variation whereby the periodicity corresponds to full circumference of the roller. One complete revolution of an oval roller results in a sinusoidal mass variation with two periodic peaks. Chimney type of faults are mainly due to mechanical faults, eccentric rollers, gears etc., improper meshing of gears, missing gear teeth, missing teeth in the timing belts, damaged bearings etc. Hill type faults are due to drafting waves caused by improper draft zone settings, improper top roller pressure, too many short fibres in the material, etc. Numerous measurements of staple-fibre materials have shown that there are rules for the correlation between the appearance of drafting waves in the spectrogram and the mean staple length. The wavelength of spinning products is equal to \( K \times \) fibre length:

- yarn: \( 2.75 \times \) fibre length;
- roving: \( 3.5 \times \) fibre length;
- combed sliver: \( 4.0 \times \) fibre length;
- drawframe sliver: \( 4.0 \times \) fibre length.
A periodic fault which occurs at some stage in the spinning process is lengthened by subsequent drafting. If the front roller of the second drawframe is eccentric, then by knowing the drafts in the further processes, the position of the peak in the spectrogram of the yarn can be calculated.

The wavelength of a defective part is calculated by multiplying the circumference of the part and the draft up to that part. Doubling is not effective for eliminating periodic faults. Elimination is only possible in exceptional cases. In most cases, doubling can, under the best conditions, only reduce the periodic faults. The influence of periodic mass variation is proportional to the draft. Because the total variance of linear density is equal to the sum of variances caused by each individual reason, the contribution of periodic faults may be very small.

Using theoretical aspects stated above the reasons for the formation of unevenness have been identified using spectrogram analysis. The following spinning products obtained from cotton-flax blend were examined:

- card sliver, linear density – 3570 tex;
- first stage draw frame sliver, linear density – 4000 tex;
- second stage draw frame sliver, linear density – 4000 tex;
- open-end yarn, linear density – 71.4 tex.

Analysis of the data obtained was aimed to define possible faults which lead to the appearance of the peaks on the spectrograms in order to get general information about the technical condition of the spinning equipment employed. This analysis may also help to understand whether or not the introduction of flax fibre into the blend has an effect on the unevenness of spinning products.

Figure 4.5 represents the spectrogram of the card sliver obtained on the Wirkbau carding machine.

![Figure 4.5 Spectrogram of carding machine sliver](image-url)
Analysis of the data obtained during testing of the sliver (Table 4.6) enables the following conclusions about the technical condition of the carding machine to be drawn:

**Sliver laying fault**

The spectrogram contains a peak at the wavelength mean 1 m. It can be assumed that the peak is evidence of the material’s periodic unevenness that is generated by the so-called “can effect”, i.e. overflow of can with card sliver. One more possible reason of the fault is incorrect installation of the lower plate with respect to the upper. Hence the sliver laying method and coiler should be controlled and corrected. Expediency of the fault clearing is confirmed by proviso 4.12.

**Calender roll fault**

The peak at 28 cm (Table 4.6) comes from an incorrect arrangement of roller or spreading knife damage; insufficient pressure to rollers; misadjustment of calender rollers loading; damages of work surface of calender rollers; insufficient draft between doffer and calender rollers. Fault identification and fixing is necessary and worthwhile, because periodic unevenness of card sliver caused by this fault will have an influence on end-product appearance (according to condition 4.12).

**Doffer fault**

The peak at 9.5 m wavelength indicates a doffer fault. The reasons for the fault could be as follows: incorrect setting between the doffer and the main card cylinder, or between the doffing roller and the doffing drum, presence of burrs, impurities or oil on the card, damages and defects of the card, insufficient draft between calender rolls and doffer; wrong adjustment of doffer comb; air temperature and humidity mismatches to standard conditions (temperature 22-25 %, relative humidity 55-60 %).

Scheme of carding machine and the calculations carried out to found out the necessity of faults tracing are presented in the Figure 4.6 and the Table 4.6.
Figure 4.6 Scheme of Wirkbau carding machine

Table 4.6 Calculation of wavelengths of carding machine defective parts

<table>
<thead>
<tr>
<th>N</th>
<th>Cause of fault</th>
<th>Wave-length calculation</th>
<th>Fault tracing</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Licker-in</td>
<td>( \lambda_1 = \frac{V_p}{n_1} = \frac{95}{600} = 15.8 \text{ cm} )</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Card cylinder</td>
<td>( \lambda_2 = \frac{V_p}{n_2} = \frac{95}{360} = 26.4 \text{ cm} )</td>
<td>Necessary</td>
</tr>
<tr>
<td>3</td>
<td>Doffing drum</td>
<td>( \lambda_3 = \frac{V_p}{n_3} = \frac{95}{10} = 9.5 \text{ m} )</td>
<td>Necessary</td>
</tr>
<tr>
<td>4</td>
<td>Flats</td>
<td>( \lambda_4 = \frac{V_p}{n_4} = \frac{95}{2.1} = 45.2 \text{ m} )</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>Calender roll</td>
<td>( \lambda_5 = d_5 \times \pi = 8.9 \times 3.14 = 28 \text{ cm} )</td>
<td>Necessary</td>
</tr>
<tr>
<td>6</td>
<td>Basin effect (diameter of laying is 35 cm)</td>
<td>( \lambda_6 = d_b \times \pi = 35 \times 3.14 = 1 \text{ m} )</td>
<td>Necessary</td>
</tr>
</tbody>
</table>

Note: \( V_p = 95 \text{ m/min} \) is an output speed of carding machine sliver.

The spectrogram of sliver obtained at the first stage draw frame is represented in the Figure 4.7.
Analysis of the spectrogram enabled the following technical faults to be identified (Table 4.7):

**Intermediate pair fault**

The peak at 42 cm points to a fault of the intermediate pair presser roller. Possible defects are radial motion variation; axial movement is higher than standard; damages of elastic coating; load misplacement; roller is not degreased. According to condition (4.12) the periodic unevenness caused by this fault will affect the end-product appearance. Fault fixing is necessary.

**Fault of feed cylinders pair**

Feed and hump at wavelengths of 68 and 11 cm are caused by the presser roller of the feed pair and incorrect setting between fixtures lines of drafting pairs. Possible defects are incorrect roller loading; roller is not degreased; air humidity differs from standard. Fault of feed cylinders pair will not influence the end-product appearance in this instance.

**Calender roll fault and card “can effect”**

There are faults caused by the carding machine in the sliver under study. 2 m wavelength peak is caused by periodic unevenness caused by card calender roller. Peak with 7 m wavelength is caused by periodic unevenness generated by the “can effect” of the card.

Figure 4.8 represents the spectrogram of sliver obtained at the second draw frame.
Figure 4.8 Spectrogram of second stage draw frame sliver

Using the sliver spectrogram (Figure 4.8 and Table 4.7) the following technical faults have been identified:

Fault of drawing rollers pair

It is likely that there are faults of the presser roller of the drawing pair: it rotates eccentrically or it exerts insufficient pressure on the products, axial movement is higher than standard. It is pointed out by the 7 m wavelength peak. Elimination of the defect is recommended (Formula 4.12).

Fault of feed cylinders pair

The peak at 1 m wavelength is caused by a fault of the lower feed cylinder. Possible reasons are nonuniform rotation (drive to feed cylinder of drawing mechanism should be examined) or runout of the cylinder. Identification and fixing of the fault in this zone is advisable, since this fault will affect the appearance of the end-product.

Fault of carding machine calender roller

Periodic unevenness caused by the calender roller of the card became apparent at this stage in the same way as in the preceding stage. It is indicated by a peak at 12.5 m.

Fault of intermediate pair of cylinders

The intermediate pair presser roller of the first draw frame is a cause of a spike with approx. 3 m wavelength.

Scheme of draw frames and the calculations carried out to found out the necessity of faults tracing are presented in the Figure 4.9 and the Table 4.7.
Table 4.7 Calculation of wavelengths of draw frames defective parts

<table>
<thead>
<tr>
<th>N</th>
<th>Cause of the fault</th>
<th>Wave-length calculation</th>
<th>Fault tracing</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Presser roller d1</td>
<td>$\lambda_1 = d_1 \times \pi \times V_1 \times V_2 = 2.9 \times 3.14 \times 7.54 = 68.6 \text{ cm}$</td>
<td>Recommended</td>
</tr>
<tr>
<td>2</td>
<td>Cylinder d2</td>
<td>$\lambda_2 = d_2 \times \pi \times V_1 \times V_2 = 4.4 \times 3.14 \times 7.54 = 104.1 \text{ cm}$</td>
<td>Necessary</td>
</tr>
<tr>
<td>3</td>
<td>Presser roller d3</td>
<td>$\lambda_3 = d_3 \times \pi \times V_2 = 2.3 \times 3.14 \times 5.8 = 41.8 \text{ cm}$</td>
<td>Necessary</td>
</tr>
<tr>
<td>4</td>
<td>Cylinder d4</td>
<td>$\lambda_4 = d_4 \times \pi \times V_2 = 2.8 \times 3.14 \times 5.8 = 51 \text{ cm}$</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>Presser roller d5</td>
<td>$\lambda_5 = d_5 \times \pi = 2.3 \times 3.14 = 7.2 \text{ cm}$</td>
<td>Necessary</td>
</tr>
<tr>
<td>6</td>
<td>Cylinder d6</td>
<td>$\lambda_6 = d_6 \times \pi = 5 \times 3.14 = 15.7 \text{ cm}$</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>Drowing waves</td>
<td>$\lambda_7 = 3 \times 3.66 \text{(average fibre length)} = 11 \text{ cm}$</td>
<td></td>
</tr>
</tbody>
</table>

Faults caused by previous technological stages

Card (appeared in 1-st draw frame sliver)

<table>
<thead>
<tr>
<th>N</th>
<th>Cause of the fault</th>
<th>Wave-length calculation</th>
<th>Fault tracing</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Calender roller</td>
<td>$\lambda_5 = d_5 \times \pi \times V_5 = 6.8 \times 3.14 \times 1.32 \times 7.54 = 2.1 \text{ m}$</td>
<td>Necessary</td>
</tr>
<tr>
<td>2</td>
<td>Basin effect</td>
<td>$\lambda_{10} = d\text{(laying)} \times \pi = 35 \times 3.14 \times 7.54 = 7.5 \text{ m}$</td>
<td>Necessary</td>
</tr>
</tbody>
</table>

Card (appeared in 2-nd draw frame sliver)

<table>
<thead>
<tr>
<th>N</th>
<th>Cause of the fault</th>
<th>Wave-length calculation</th>
<th>Fault tracing</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>Calender roller</td>
<td>$\lambda_5 = d_5 \times \pi \times V_5 = 6.8 \times 3.14 \times 1.32 \times 7.54 \times 6 = 12.6 \text{ m}$</td>
<td>Necessary</td>
</tr>
</tbody>
</table>

Drawing (appeared in 2-nd draw frame sliver)

<table>
<thead>
<tr>
<th>N</th>
<th>Cause of the fault</th>
<th>Wave-length calculation</th>
<th>Fault tracing</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>Presser roller d3</td>
<td>$\lambda_3 = d_3 \times \pi \times V_2 = 2.3 \times 3.14 \times 5.8 \times 6 = 2.5 \text{ m}$</td>
<td>Necessary</td>
</tr>
</tbody>
</table>

Spectrogram of the yarn obtained on BD-200-RC rotor spinning machine is shown in Figure 4.10.
Figure 4.10 Spectrogram of cotton-flax yarn (BD-200-RC rotor spinning machine)

The analysis of the yarn spectrogram (Figure 4.10 and Table 4.8) did not indicate any faults in the rotor spinning frame. Nevertheless, yarn contains defects caused by the technical condition of the machinery at the preceding stages, namely:

- fault of feed cylinder of the second draw frame. It is indicated by a 3.5 m wavelength peak;
- fault of intermediate pair presser roller of the second draw frame. It corresponds to a peak at 42 m;
- fault of presser roller of drawing pair (second stage draw frame). It is indicated by a peak at 7.2 m.

Scheme of spinning machine and the calculations carried out to found out the necessity of faults tracing are presented in Figure 4.11 and Table 4.8.
Figure 4.11 Scheme of BD-200-RC rotor spinning machine

Table 4.8 Calculation of wavelengths of spinning machine defective parts

<table>
<thead>
<tr>
<th>N</th>
<th>Cause of the fault</th>
<th>Wave-length</th>
<th>Fault tracing</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Spinning head</td>
<td>( \lambda_1 = 10 - 20 \text{ cm} )</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Spinning head bearing</td>
<td>( \lambda_2 = 60 - 100 \text{ cm} )</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Yarn winding looper</td>
<td>( \lambda_3 = 20 - 30 \text{ cm} )</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>Structural unevenness of the sliver</td>
<td>( \lambda_4 = 2 \text{ m} )</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>Draw frame coiler</td>
<td>( \lambda_5 = 10 - 20 \text{ m} )</td>
<td></td>
</tr>
</tbody>
</table>

Faults caused by previous technological stages

<table>
<thead>
<tr>
<th>Drawing (2-nd draw frame sliver)</th>
<th>Necessary</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Cylinder d2 ( \lambda_2 = d_2 \pi V_1 V_2 = 4.4 \times 3.14 \times 7.54 \times 100 = 100 \text{ m} )</td>
<td></td>
</tr>
<tr>
<td>2 Presser roller d3 ( \lambda_3 = d_3 \pi V_2 = 2.3 \times 3.14 \times 5.8 \times 100 = 42 \text{ m} )</td>
<td>Necessary</td>
</tr>
<tr>
<td>3 Presser roller d5 ( \lambda_5 = d_5 \pi = 2.3 \times 3.14 \times 100 = 7.2 \text{ m} )</td>
<td>Necessary</td>
</tr>
</tbody>
</table>

In summary, the spectrograms of flax-containing spinning products contain many waves and surges that are due to yarn blend composition and the individual components of the manufacturing machinery. This makes it possible to identify with
confidence an area of possible faults in such textile machinery.

Spectrogram of the 70 tex cotton open-end yarn obtained on the same plant described in the section 4.2 is shown in Figure 4.12.

![Overall Spectrogram](image)

**Figure 4.12** Spectrogram of cotton yarn (BD-200-RC rotor spinning machine)

In order to compare the spectrograms they were digitised (Figure 4.13). Spectrograms of cotton (Figure 4.12) and cotton-flax (Figure 4.10) yarns were considered as two different distributions. The aim of this comparison was to see that unevenness is caused by blend composition as well as the machinery.

![Digitised Spectrograms](image)

**Figure 4.13** Digitised spectrograms (Figures 4.10, 4.12)

To estimate the significance of difference between the distributions (Figure 4.13) the Pearson $\chi^2$ criterion was applied. Since the calculated value $\chi^2_{(n-1)} = 39.83$ is larger than the critical tabular value $\chi^2_{ibl} = 36.42$ (Fisher and Yates, 1963) for the pre-selected
level of significance $\alpha = 0.05$, the assumption is made that the difference between the distributions is significant with 95% probability. With the reference to the spectrograms (Figures 4.10 and 4.12) it should be noticed that cotton yarn is more uneven in terms of short-wave unevenness whereas the cotton-flax yarn is more uneven in terms of long-wave unevenness.

4.7 Enzyme treatments for flax fibre and flax-containing yarns

4.7.1 Appropriateness of enzyme treatments

Literature suggests that further improvement of cotton-flax yarn properties by optimisation of current processing methods poses a difficulty. That is why it was suggested to involve other methods to improve yarn performance characteristics. Enzyme application is one of the methods recommended (Lipp-Symonowicz, 2004).

Modification of the structure of flax fibres and flax containing materials under the influence of enzyme treatments was described in Chapter 2. It was decided to investigate the effects of cellulose based enzymes on the mechanical and surface properties of cotton-flax yarn by application to flax fibre.

The biochemical treatments were carried out by the author under the supervision of Prof. Shamolina (St-Petersburg State University of Technology and Design, Russia).

Four experimental treatments were conducted (Table 4.9). Three of them (experiments 1, 2, 3) included processing of flax fibre in a Scour Tester, and the fourth experiment consisted of spray treatment of cotton-flax lap with the enzyme solution by means of a pulveriser.
Table 4.9 Experimental treatments of cottonised flax fibres with enzyme complex preparations

<table>
<thead>
<tr>
<th>Treatment No</th>
<th>Substrate</th>
<th>Enzyme preparation</th>
<th>Treatment conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Flax fibre</td>
<td><em>Aspergillus Japonicus</em></td>
<td>Treatment in Scour Tester apparatus</td>
</tr>
<tr>
<td>2</td>
<td>Flax fibre</td>
<td><em>Trichoderma Viride</em></td>
<td>Treatment in Scour Tester apparatus</td>
</tr>
<tr>
<td>3</td>
<td>Flax fibre (pre-treated at Labor Mixer device)</td>
<td><em>Aspergillus Japonicus</em></td>
<td>Treatment in Scour Tester apparatus</td>
</tr>
<tr>
<td>4</td>
<td>Cotton-flax lap</td>
<td>Celloviridin G2X</td>
<td>Spray treatment</td>
</tr>
</tbody>
</table>

In experiments 1 and 2 the original flax fibres were subjected to biochemical treatment and in the case of experiment 3 fibre mass was pre-processed with a Labor Mixer device to remove impurities.

In the case of experiments 1 and 3 the fibres were treated with a multi-enzyme complex based on *Aspergillus Japonicus*. Experiment 2 used a multi-enzyme complex produced from *Trichoderma Viride*. The treatment with the latter preparation led to significant fibre destruction and disintegration, therefore experiment 2 is not considered in the following analysis.

Working solutions were prepared by dissolving liquid enzyme preparation in acetate buffer (pH 4.4), which was prepared according to Dawson et al., 1986 (37.0 ml of 0.2M NaOAc + 63.0 ml 0.2M HOAc). Enzyme concentrations were 0.5 g/l. The treatment was carried out in a Scour Tester device by agitating at 40 rev/min for 30 min at 50°C, bath module being 30. After that the samples were rinsed by water and dried in a desiccator at 95°C for 3 hours. In the case of experiment 2 an attempt to dry the sample in the convection drier was made, however it did not prevent fibre destruction.

Treatment 4 was carried out in the following way: cotton-flax lap meant for carding was pulverized with a buffer solution (pH 4.4) containing 0.1-% Celloviridin and 0.001-% Catopol in 0.1molar nutria acetate buffer.
Celloveridin G2X (produced by PromFerment LLC, Moscow) is a complex enzyme preparation of cellulolytic action. It is applied in production of wines and spirits, in cattle-rearing and poultry farming, textile and food industry. The preparations catalyze splitting of plant cell cellulose and hemicellulose to oligosaccharides, mono- and disaccharides.

Multienzyme complex produced from *Aspergillus Japonicus* was donated by Moscow State University; this preparation is not a commercial enzyme.

Characteristics of the enzyme preparations are shown in Table 4.10.

<table>
<thead>
<tr>
<th>Component enzyme</th>
<th>Activity, U/ml</th>
<th>Multienzyme complex produced from <em>Aspergillus Japonicus</em></th>
<th>Celloveridin G2X (protein 346 mg/l)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carboxymethylcellulase</td>
<td>276</td>
<td>5187</td>
<td></td>
</tr>
<tr>
<td>Glucanase</td>
<td>636</td>
<td>4822</td>
<td></td>
</tr>
<tr>
<td>Xylanase</td>
<td>1807</td>
<td>1750</td>
<td></td>
</tr>
<tr>
<td>Polygalacturonase</td>
<td>473</td>
<td>-</td>
<td></td>
</tr>
</tbody>
</table>

An experiment to study cotton-flax ring spun yarn production using a carding spinning system was conducted. Four samples of 72 tex yarn were produced on Shirley Platt spinning plant from the blends of 70 % of cotton to 30 % of cottonised flax as follows:

- original fibres (control);
- cotton and treated flax fibres (treatment 1);
- cotton and treated flax fibres (treatment 3);
- treated cotton and flax fibres (treatment 4).

The results of tensile tests of the yarn samples produced are shown in Figures 4.14 and 4.15. Statigraph L tester was applied; the number of tests for a sample was 100. The data obtained showed that the yarn produced from flax fibres subjected to treatment 4 is the strongest in comparison with other samples examined. Its tenacity is 10 % higher than that of the control experiment produced from original fibres (Figure 4.14); the difference is statistically significant according to one-way ANOVA (Calculated
value \( F = 88.1 \) is larger than the critical value \( F_{crit} = 2.6 \) for the degree of freedom \( df = 395 \) and level of significance \( \alpha = 0.05 \).

![Diagram showing tenacity comparison](image)

**Figure 4.14 Tenacity of cotton-flax ring spun yarn samples**

In addition, there is an insignificant increase in breaking elongation of the yarn (treatment 4) of 4% (Figure 4.15). The poorest breaking characteristics were exhibited by the yarn produced from flax treated with the *Aspergillus Japonicus* multi-enzyme complex that had been pre-processed at the Labor Mixer device (treatment 3).
Figure 4.15 Relative breaking elongation of cotton-flax ring spun yarn samples

The mechanical properties of the cotton-flax ring spun yarn samples were characterised in order to estimate yarn breaking energy and potential breakage in weaving, knitting or knitting thread manufacture. To facilitate this equal-probability ellipse method was applied (Abezgaus et al., 1970).

Yarn strengths and the corresponding extensions depend on a range of factors that cause their variation. Standard deviation and coefficient of variation of strength and strain are usually used to estimate variations. These estimations cannot provide sufficient information about yarn behaviour in subsequent processes, because under real processing conditions various load and elongation combinations can occur. Each part of any continuous yarn can possess strength and strain properties that vary within a known range with a given probability. From this point of view, it is much more important to know the distribution of yarn strength and strain (Truevtsev et al., 1997).

It is obvious that the application of the equal-probability ellipse method is appropriate in the case under consideration since values of breaking load $P$ and breaking
elongation $e$ (or $E$) are not independent. They are directly interrelated, with the value of the correlation coefficient $r$ being $0.72 - 0.8$ (Pozdniakov, 1978; Perpelkin, 1991; Truevtsev et al., 1997).

It is reasonable to use normal (Gauss's) law for the description of the yarn strength and extension distributions, because of an acceptable level of coincidence of the experimental data set with a theoretical Gaussian distribution at a 5% significance level. Thus, breaking load ($P = x$) and elongation ($e = y$) should be considered as a system of two random dependent values having Gaussian distributions. Hence the function $z = r_{xy}(x, y)$ can be represented in the three-dimensional $x$, $y$, $z$ Cartesian coordinate system as the normal distribution surface (Figure 4.16) (Pozdniakov, 1978).

![Figure 4.16 The two-dimensional normal distribution surface](image)

This surface can be described by the probability distribution density function, which has the following form:

$$
\phi(\mathbf{xy})\,dx\,dy = \frac{1}{2\pi\sigma_x\sigma_y\sqrt{1-r_{xy}^2}} \cdot \exp \left[ -\frac{1}{2(1-r_{xy}^2)} \left( t_x^2 - 2r_{xy} \cdot t_x \cdot t_y + t_y^2 \right) \right] dt_x \cdot dt_y, \quad (4.13)
$$

where $t_x = (x - \mu_x) / \sigma_x$;

$t_y = (y - \mu_y) / \sigma_y$.
\( \sigma_x \) and \( \sigma_y \) are average values of \( x \) and \( y \), respectively;
\( \sigma_x \) and \( \sigma_y \) are standard deviations of \( x \) and \( y \), respectively.

Intersections of the surface (Figure 4.16) by planes \( x = x_0 \), which are perpendicular to the \( x \) axis, yield a number of Gaussian curves with the extreme points lying at the regression line described by the following equation:

\[
M(y | x) = \gamma_{y|x} = \nu_y + r_{xy} \sigma_y (x - \nu_x) / \sigma_x.
\]  

(4.14)

This is an equation of normal regression line \( y \) to \( x \).

Dissecting the surface represented in Figure 4.16 by a plane \( z = z_0 = \text{const} \) which is parallel to the \( x-y \) plane one can obtain an area that is limited by the equation of an equal-probability ellipse:

\[
(t_x^2 - 2r_{xy} t_{xy} + t_y^2) / (1 - r_{xy}^2) = \lambda^2 = \text{const}.
\]  

(4.15)

Having set a value of probability \( p \) such that the yarn being tested will have a 95% probability of breaking, we can find the value of \( \lambda \) from the table of \( \chi^2 \) distribution (Korn and Korn, 1968).

This ellipse bounds an area on the \( x-y \) plane such that any yarn with the measured values of \( x = P \) and \( y = E \) which fall within the ellipse, will have a 95% probability of rupture. Consequently, if a yarn is loaded with force \( x_i \) and the corresponding extension is \( y_i \), and the point \( (x_i; y_i) \) falls within the ellipse, then the probability that the yarn sample will break under this combination of load and extension is equal to the chosen value of \( p \). Thus the yarn will normally be ruptured in 95% of cases if loaded and (or) extended such that the point \( (x_i; y_i) \) falls within the ellipse. However, 5% of yarn samples can fail under the combination of load and extension which are less than any of the \( x_i \) and \( y_i \) that fall within the ellipse (Truevtev et al., 1997).

Figure 4.17 shows the equal-probability ellipses representing the characteristics of ring and rotor spun cotton yarns calculated using data provided by Smirnov and Dunin-Barkovski, 1959.

The sample would not be of acceptable quality, since the maximum load and extension that occur during a manufacturing operation cause unacceptable levels of yarn

86
breakage. The areas $S_P$ and $S_E$ bounded by $P_{min}$ and $E_{min}$, respectively, are the zones of potential yarn breakage (Figure 4.17). The probability of a yarn breakage depends on the position, orientation, and dimensions of the ellipse describing the experimental data with respect to the zone that is bounded by the values of $P_{min}$ and $E_{min}$.

The probability that a yarn sample will be ruptured under a given load and (or) extension that is usually found during manufacturing operations can be expressed by the following equations, according to Abezgaus et al. (1970):

$$\Phi\{N \notin S_P\} = \Phi_0 \left( \frac{d_{1P}}{\sigma_a} \right) - \Phi_0 \left( \frac{d_{2P}}{\sigma_a} \right),$$  \hspace{1cm} (4.16)

$$\Phi\{N \notin S_E\} = \Phi_0 \left( \frac{d_{1E}}{\sigma_\beta} \right) - \Phi_0 \left( \frac{d_{2E}}{\sigma_\beta} \right).$$  \hspace{1cm} (4.17)

where $\Phi\{N \notin S_P\}$ is a probability that $P_i$ will fall to $S_P$ area;

$\Phi\{N \notin S_E\}$ is a probability that $E_i$ will fall to $S_E$ area;

$$\Phi_0(x) = \frac{P}{\pi} \int_0^x e^{-r^2} \, dr$$ \hspace{1cm} is a tabulated function;

$\sigma_a$ and $\sigma_\beta$ are standard deviations determined as

$$\sigma_a = \sqrt{\sigma_p^2 \cos^2 \alpha + \sigma_\epsilon^2 \sin^2 \alpha},$$  \hspace{1cm} (4.18)

$$\sigma_\beta = \sqrt{\sigma_\epsilon^2 \cos^2 \beta + \sigma_p^2 \sin^2 \beta}.$$  \hspace{1cm} (4.19)
Figure 4.17 Equal-probability ellipses representing the characteristics of ring and rotor spun cotton yarns

The values of the semi-axes $a$ and $b$ of an equal-probability ellipse are defined by the formulae as follows:

$$a = \left[ \frac{2(1-r_m^2) \cdot \lambda^2}{(s_1+s_2)} \right]^{1/2},$$  (4.20)

$$b = \left[ \frac{2(1-r_m^2) \cdot \lambda^2}{(s_1-s_2)} \right]^{1/2},$$  (4.21)

where

$$s_i = \frac{1}{(m_p \cdot \sigma_p)^2} + \frac{1}{(m_c \cdot \sigma_c)^2},$$  (4.22)
\[ s^2 = \left[ \frac{1}{(m_p \cdot \sigma_p)^2} - \frac{1}{(m_e \cdot \sigma_e)^2} \right]^2 + \frac{4 \nu^2}{(m_p \sigma_p m_e \sigma_e)^2}. \]  

(4.23)

The fact that during manufacturing operations a yarn is not usually subjected to loads higher than 100 cN and an extension of 3% enables the zones of potential breakage \( S_p \) and \( S_e \) to be defined and to determine the probability that \( P_j \) and \( E_j \) fall within these breakage areas.

The appearance of the plotted ellipse enables the yarn performance (breaking energy) and potential breakage in its further processing to be predicted. The higher the ellipse area, the higher is the variation of yarn tenacity and elongation; the lower the tilting angle of the ellipse axis to the vertical or horizontal axis, the lower is the correlation between tenacity and elongation; the closer the ellipse comes to intersecting with \( P_{min} \) and \( E_{min} \) lines, the more likely that yarn will break during manufacturing processes.

This method is recommended for comparing yarns those mechanical characteristics are very close in order to find out the effect of pretreatment on the yarn mechanical properties (Truevtsev et al., 1997).

Statistical processing of the data obtained from estimation of the mechanical properties of the yarn samples enabled the corresponding equal-probability ellipses to be plotted, which are shown in Figure 4.18.

A multivariate Hotteling’s \( T^2 \) statistics for testing the difference in properties of the yarn samples has been applied (Manly, 1986) which can be calculated using formula as follows:

\[ T^2 = \frac{n_1 n_2}{n_1 + n_2} \sum_{i=1}^{p} \sum_{k=1}^{p} (\bar{x}_{1i} - \bar{x}_{2i}) c^{ik} (\bar{x}_{1k} - \bar{x}_{2k}), \]

where \( x_{ij} \) is the mean of variable \( x_i \) in the \( j \)th sample,

\( c^{ik} \) is the element in the \( i \)th row and \( k \)th column of the inverse co-variance matrix.
The normality test on the experimental data showed that the conditions for applying the Hotteling’s test were met. Significantly large values of $T^2$ for the Hotteling’s statistic were evidence that the samples are different in mechanical properties.

The significance of $T^2$ has been determined by using the fact that in the null hypothesis case of samples having equal properties means the transformed statistic $F_c$ (Formula 4.24) follows an $F$ distribution with $p$ and $(n_1+n_2-p-1)$ degrees of freedom.

\[
F_c = \frac{T^2 (n_1+n_2 - p - 1)}{p (n_1+n_2 - 2)}, \tag{4.24}
\]

where $n_1$ and $n_2$ are the number of observations;

$p$ is a number of variables.

In all cases the values of $F_c$ were greater than their critical tabulated values, thus the four samples examined are different in their mechanical properties.
Ellipse N1 corresponds to the sample of yarn produced using enzyme treatment (experiment 1). It possesses the smallest area in comparison with other ellipses; consequently, the yarn is characterized by the highest uniformity in tenacity and elongation. The location of the ellipse centre proves that the yarn is stronger than all other samples. Thus, breaking load is 10% higher than that of the control. The breaking energy value of the yarn N1 is the highest too. The control, the yarn sample produced without any enzyme treatment, exhibits the poorest mechanical characteristics.

If an equal-probability area overlaps with part of the area bounded by $P_{min}$ and $E_{min}$ it would indicate a high probability of yarn breakage during subsequent processing, for example, in winding. The greater the extent of intersection, the greater the number of breakages would occur. The ellipses of all four samples (at the 5% significance level) do not intersect the breaking zones. Hence, the yarns can withstand loads and extensions in manufacturing operations at an acceptable level. Though the ellipses representing the samples are close to each other the variant N1 is preferable, because it is characterized by the greatest breaking energy and the lowest deviation in breaking load and elongation, i.e. it has the lowest probability of tensile parameters to fall into the zones of potential breakage $S_P$ and $S_E$ among those that are presented in Figure 4.18.

It should be noted that the yarn produced by application of the spray treatment of cotton-flax blend with enzymes (experiment 4) was close in mechanical properties to the “best” sample of the yarn (experiment 1) that was obtained by treatment of flax in the Scour Tester. Since the spray method of enzyme application to substrate requires minimum water and energy, it is suggested that spray techniques should be developed for enzyme modification of fibres.

It was observed that enzyme treatment can significantly reduce the yarn hairiness (Figure 4.19). Maximum reduction was observed in the case of treatment 1.
Figure 4.19 Hairiness of cotton-flax ring spun yarn samples

This tendency is positive from a technological point of view. The correlation between hairiness and tensile characteristics has been determined, the breaking load:hairiness correlation coefficient being $R_{H-P} = -0.58$, and the elongation:hairiness correlation coefficient being $R_{H-E} = -0.72$.

Thus, the results obtained show that the application of enzyme treatments (experiments 1 and 3) in the processing of cotton-flax blends enables cotton-flax yarn with reduced hairiness and improved mechanical properties to be produced.

4.7.2 The influence of enzyme treatment on the properties of short flax fibre

The methods of short flax fibre biochemical modification described in the literature (Section 2.6) have been designed to achieve two main objectives. These are flax fibre cottonising and the removal of shive and impurities. Unfortunately these methods have not found wide application in industry. Cotton-spinning factories are used to process mostly mechanically cottonised flax. However, the raw material
requires purification from the fine dust that is the remainder of shive and impurities removed by mechanical actions. The size of this dust is 0.25-10 μm.

Recently it has been reported that the number of diseases caused by organic dust has risen dramatically. The diseases provoked by cotton and flax dust are among bysinossis (Pivovarov et al., 2002).

At present there is a tendency to apply fibre treatments with water at the preparation stage of spinning to remove dust, toxins, pigments and metals.

The aim of this part of the research work was to evaluate the potential of fine dust removal with simultaneous improvement of hygroscopic properties of cottonised flax by means of enzyme treatment.

Cottonised flax fibre processed at the Fibre Development Ltd Plant, Launceston, Cornwall, was used as an object of investigation. The fibre was treated under the conditions shown in Table 4.11.

Table 4.11 Variants of treatment of cottonised flax fibres with Celloviridin G2X multi-enzyme complex

<table>
<thead>
<tr>
<th>Sample number</th>
<th>Water</th>
<th>Acetate buffer</th>
<th>Enzyme concentration, g/l</th>
<th>Agitation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>yes</td>
<td>no</td>
<td>no</td>
<td>no</td>
</tr>
<tr>
<td>2</td>
<td>yes</td>
<td>yes</td>
<td>no</td>
<td>no</td>
</tr>
<tr>
<td>3</td>
<td>yes</td>
<td>yes</td>
<td>0.3</td>
<td>yes</td>
</tr>
<tr>
<td>4</td>
<td>yes</td>
<td>no</td>
<td>no</td>
<td>yes</td>
</tr>
<tr>
<td>5</td>
<td>yes</td>
<td>yes</td>
<td>no</td>
<td>yes</td>
</tr>
<tr>
<td>6</td>
<td>yes</td>
<td>yes</td>
<td>0.3</td>
<td>no</td>
</tr>
<tr>
<td>7 (original)</td>
<td>no</td>
<td>no</td>
<td>no</td>
<td>no</td>
</tr>
</tbody>
</table>

The fibre treatment with the Celloviridin G2X multi-enzyme complex was carried out in the Scour Tester at 40 rev/min mixing for 1 hour, module 30, at 50°C. Characteristics of the enzyme preparation are presented in Table 4.11. In the case of variants 3 and 6 solutions were prepared by dissolving 0.3 g/l enzyme preparation in acetate buffer (pH 4.4; 37.0 ml of 0.2M NaOAc + 63.0 ml 0.2M HOAc). After the treatments the samples were rinsed by water and dried in the convection drier for 2 hours.

The effect of the treatments presented in Table 4.11 was estimated by method described on the page 35. Fibre length distributions are shown in Figure 4.20.
Figure 4.20 Flax fibre length distribution

In order to estimate the significance of difference between the distribution curves (Figure 4.20) the Pearson $\chi^2$ criterion was applied. It was found that there is a considerable difference between the length distribution of N3 fibre and other six curves. Actually, treatment 3 led to a considerable fibre destruction visible by the naked eye. The destruction could be caused by the combination of two treatment conditions, namely presence of enzymes in solution and hydro mechanical impact.

In order to obtain additional data concerning the influence of the treatments on flax the Sirolan-Laserscan instrument was used (Figure 4.21). The results of relative fibre fineness estimation showed that the treatments did not lead to a significant difference in splitting of complex fibres and changes in fibre diameter (calculated values of the Pearson criterion $\chi^2=1.5\div6.0$ were lower than the tabulated value $\chi^2=101.9$).
The estimation of the tensile characteristics of fibre samples N1, 2, 4, 5, 6, 7 showed that the treatments applied did not significantly affect fibre strength (staple tenacity was $49.3 \pm 3.0$ N/tex, staple extension $4.6 \pm 0.5\%$). In the case of yarn sample N3 decreased tensile characteristics were observed (staple tenacity was $34.2 \pm 2.0$ N/tex, staple extension $3.7 \pm 0.4\%$). The decrease in strength was caused by fibre destruction by the influence of treatment N3.

Enzyme treatment led to fibre weight loss (Table 4.12), but at the same time the fibre geometrical characteristics did not change significantly.

Table 4.12 Weight loss of flax fibres during the treatment with Celloviridin G2X multi-enzyme complex

<table>
<thead>
<tr>
<th>Sample number</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weigh loss, %</td>
<td>3.5</td>
<td>5.7</td>
<td>10.4</td>
<td>6.0</td>
<td>6.4</td>
<td>6.7</td>
</tr>
</tbody>
</table>

Maximum weight loss took place in case of the treatments enzymes were applied in. The most considerable weight loss was caused by the treatment N3 that led to fibre destruction. Treatment N6 was accompanied by $6.7\%$ weight loss that is higher
then that of treatments N 1, 2, 4 and 5. This increased weight loss could be explained by fine dust removal that was found out by SEM-investigation. The results of SEM-investigation of the fibre surface showed that the most noticeable fibre purification from fine dust takes place following treatment N6 (Figure 4.22).

![Figure 4.22 a - SEM image of untreated flax fibre](image1.png) ![b - SEM image of enzyme treated flax fibre (variant N6)](image2.png)

Figure 4.22 a - SEM image of untreated flax fibre  
b - SEM image of enzyme treated flax fibre (variant N6)

In order to study the influence of enzyme treatment on fibre weight loss the original fibre (variant N7) was subjected to wet treatments at conditions similar to those of variant N6 presented in Table 4.11, varying the concentration of enzyme preparation (see Table 4.13).

<table>
<thead>
<tr>
<th>Sample number</th>
<th>Enzyme concentration, g/l</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>0.00</td>
</tr>
<tr>
<td>6 (1)</td>
<td>0.24</td>
</tr>
<tr>
<td>6 (2)</td>
<td>0.48</td>
</tr>
<tr>
<td>6 (3)</td>
<td>0.72</td>
</tr>
<tr>
<td>6 (4)</td>
<td>0.96</td>
</tr>
<tr>
<td>6 (5)</td>
<td>1.20</td>
</tr>
</tbody>
</table>

Table 4.13 Concentration of enzyme preparation in solution (pH = 4.4)

The effect of treatment N6 for removal of the fine dust recognized by the SEM-investigation was confirmed by fibre weight loss of 6-9 %. The dependence of the weight loss on enzyme concentration is represented in Figure 4.23.
As a result of the treatment the hygroscopic properties of the substrate were improved (Figure 4.23) – moisture absorption and speed of wetting increased considerably. Water molecules may be adsorbed on cellulosic fibres in orderly or random arrays depending on the degree of crystallinity of the cellulose because the water molecules are associated with polar sites on the polymer chains. The absorption of water takes place in the amorphous regions as multiple layers of water molecules built up on the absorbed monolayer. Eventually further absorption leads to condensation of liquid water in pores and capillaries (Kornuhin et al., 1997).

Figure 4.23 Flax fibre weight loss, moisture absorption and wettability variations with enzyme concentration.

Considering the effect of treatments it can be assumed that major changes result from the partial removal of non-cellulose substances from the fibres and cellulose decomposition and its partial elimination from fibres. These changes are followed by the modification of the fibre’s morphological structure and surface properties which led to changes in hygroscopic properties of substrate.
Figure 4.23 shows the effect of enzyme concentration on wettability and moisture absorption. Depending on enzyme concentration moisture absorption increased by up to 3%. Time of wetting was decreased from 33 minutes (in case of untreated fibre) down to 6 minutes (in case of treatment with 1.2 g/l enzyme concentration).

The results show the potential for the removal of fine dust by biochemical means whilst simultaneously improving the hygroscopic properties of flax fibre. The treatments applied (Table 4.12) did not considerably affect mechanical properties of fibre samples (staple tenacity - 48.9 ± 2.5 N/tex, staple extension - 4.5 ± 0.6 %).

The aim of this part of the research work was to evaluate the potential for fine dust removal with simultaneous improvement of hygroscopic properties of cottonised flax by means of enzyme treatment. The chosen conditions of flax fibre treatment using the enzyme preparation Celloviridin G2X did not have a significant effect on fibre tenacity, fibre diameter and fibre length distributions.

4.8 Conclusions

Estimations of hypothetical and actual irregularity, and the index of spinning products irregularity were made. The reasons for the unevenness formation were investigated using spectrogram analysis. The unevenness guidelines for cotton-flax yarn were rated using the recommended unevenness index and the calculated ideal unevenness. The recommended norm of irregularity of ready to use first-grade cotton-flax yarn is 15 %, and second-grade yarn is 18 %.

Application of enzyme treatments comprising a cellulase complex for processing of cotton-flax blends enables cotton-flax yarn with reduced hairiness and improved mechanical properties to be produced.

The results obtained showed the potential for biochemical removal of fine dust with simultaneous improvement of flax hygroscopic properties. The chosen conditions of flax fibre treatment using the enzyme preparation Celloviridin G2X did not have a significant effect on fibre tenacity, fibre diameter and fibre length distributions.

In order to study structure and properties of the cotton-flax yarn it was decided to investigate the topics as follows:
- flax fibre content in yarn;
- fibre migration in yarn;
- yarn surface and mechanical properties;
- influence of twist on strength and unevenness of open-end flax blended yarn;
- complex assessment of the quality of cotton-flax yarn for knitting.
CHAPTER 5 FLAX FIBRE BEHAVIOUR IN COTTON-FLAX YARN

The objectives of this part of the research were as follows:
- to determine flax fibre content in yarn;
- to investigate fibre migration in yarn;
- to define effect of spinning methods on fibre migration pattern in cotton-flax yarn;
- to investigate yarn hairiness, winding friction coefficient, unevenness in diameter and linear density, tenacity and elongation;
- to define influence of twist on strength and unevenness of open-end flax blended yarn;
- to consider the possibility to apply airflow method (Micronaire) for short flax fibres;
- to conduct complex assessment of the quality of cotton-flax yarn for knitting.

5.1 Determination of flax fibre content in the blended yarn

In order to produce a yarn of the quality required and at high productive efficiency it is necessary to use the most efficient technology and required quality of raw material. Practical experience of textile fibre processing is needed to determine with a sufficient degree of accuracy the influence of various spinning systems on the range, cost and quality of the yarns produced. To produce a yarn a blend of fibres is usually used. The blend of homogeneous fibres is generally used to stabilize the quality and the technological process of monocomponent yarn production, whereas mixtures of heterogeneous components are used to attain certain specific properties of yarn.

In the case of blended yarns, the following factors must be addressed: the difficulty of combined processing of heterogeneous fibres; the acceptable level of difference in their properties and their effect on the quality of yarn and semi-products and on spinning processes.
It is generally recognized that the cost-performance ratio of cotton-flax blend processing decreases because of significant loss of cottonin at different stages of the spinning process. The greatest waste yield in cotton-flax yarn manufacture occurs at carding machines.

There is no standard method to determine the flax component percentage in cotton-flax yarn. For this purpose the method described in Section 3.2.3 has been applied.

In the course of the experiment a high variation in the number of fibres of different components in cross-sections of blended yarn was observed. It was characterized by a coefficient of variation equal to 34 % for ring spun yarn, and 29 % for open-end yarn. Such a high non-uniformity is hypothetically caused by insufficient mixing of components and a significant difference in their properties.

Table 5.1 presents an estimation of flax fibre percentage in two variants of cotton-flax yarn obtained using different spinning methods.

<table>
<thead>
<tr>
<th>Yarn variant</th>
<th>Average number of fibres in yarn cross-section</th>
<th>Fibre linear density, tex</th>
<th>Flax percentage (by mass), %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Open-end yarn 71.4 tex</td>
<td>Cotton 396</td>
<td>Cotton 0.138</td>
<td>25.0</td>
</tr>
<tr>
<td></td>
<td>Flax 71</td>
<td>Flax 0.28</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Cotton + Flax 467</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ring spun yarn 72.0 tex</td>
<td>Cotton 412</td>
<td>Cotton 0.138</td>
<td>23.1</td>
</tr>
<tr>
<td></td>
<td>Flax 61</td>
<td>Flax 0.28</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Cotton + Flax 473</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Flax fibre mean linear density was determined using the formula:

\[
T = \frac{d \delta^2}{0.13},
\]  

(5.1)
where $\delta$ – fibre volume weight, accepted as equal to 0.95 mg/mm$^3$;

$d_c$ – average diameter of flax fibre in yarn sample (19.2 $\mu$m) determined using microscope.

Thus, the calculated linear density of flax fibre in the yarn samples investigated was 0.28 tex. The difference in linear densities of non-processed flax fibres (Table 3.1) and flax contained in yarn samples (Table 5.1) could be explained by the fact that the fibres have been subjected to intensive mechanical impacts in processing that caused splitting of technical fibres.

Data obtained by estimation of flax fibre percentage in different samples of cotton-flax and flax-polyester yarns is presented in Table 5.2. Flax-polyester yarn samples (Krylova, 2004) were considered for comparison.

<table>
<thead>
<tr>
<th>Yarn linear density, (spinning method)</th>
<th>Blend composition</th>
<th>Actual percentage of flax in yarn by mass, %</th>
<th>Flax loss based on initial mass of component in the blend, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>71.4 tex (OE)</td>
<td>70% cotton, 30% flax</td>
<td>25.0</td>
<td>16.7</td>
</tr>
<tr>
<td>72.0 tex (R)</td>
<td>70% cotton, 30% flax</td>
<td>23.1</td>
<td>23.0</td>
</tr>
<tr>
<td>25.0 tex (R)</td>
<td>80% PE, 20% flax</td>
<td>18.9</td>
<td>5.5</td>
</tr>
<tr>
<td>25.0 tex (R)</td>
<td>70% PE, 30% flax</td>
<td>27.7</td>
<td>7.7</td>
</tr>
<tr>
<td>25.0 tex (R)</td>
<td>60% PE, 40% flax</td>
<td>34.0</td>
<td>15.0</td>
</tr>
</tbody>
</table>

Note: OE - open-end yarn, R - ring spun yarn.

The data suggests that the increase of flax content in a blend is accompanied by an increase in flax loss in the blended yarn. In the case of ring spun cotton-flax yarn the loss is the most noticeable. In the case of flax-polyester blends loss of flax during the spinning processes is considerably lower. Investigation of 25 tex flax-polyester yarns has shown the dependence of flax component loss not only on its percentage in blend but on its linear density.
5.2 Investigation of fibre migration in cotton-flax yarn

5.2.1 Theory of fibre migration in a yarn

Fibre properties alone cannot explain the characteristics of a yarn without some knowledge of its structure, i.e. the spatial distribution of the fibres.

It is now generally recognized that blending of dissimilar fibres in spun yarns may lead to an uneven distribution of fibres throughout the yarn cross-section. It is known that particular fibre components may migrate towards the surface or to the core of the yarn (Morton, 1952). Furthermore, fibre migration theories indicate that this preferential distribution of blend components is a direct result of fibre migration effects at certain stages during the yarn production process. These effects are dependent on both fibre properties and the spinning methods employed (Hamilton, 1958). Migration of heterogeneous fibres during the process of yarn formation caused by differences in their properties can cause yarn structural unevenness.

Uniformity of fibre distribution in yarn cross-section and along its length characterizes the efficiency of mixing of heterogeneous fibres in a blended yarn. The appearance and the properties of the end-product can be determined by knowledge of the radial distribution of fibre components in a yarn cross-section.

The change in the radial position of fibres in a yarn recognized by Peirce (1947) continues to be of interest to many researchers. El-Behery (1968) studied fibre migration in yarns spun from different types of fibre on different spinning systems. According to Townend and Dewhirst (1964) longer and finer fibres tend to dominate in the yarn core, whereas shorter and coarser fibres migrate towards the yarn surface.

The term "migration", which refers to changes in the spatial position of a single fibre along the length of a yarn in comparison to its expected position defined by an ideal helical path, was introduced by Morton (1952). He also developed the tracer fibre technique and defined the "coefficient of migration" to express the degree of fibre migration based on the area according to a radial distance over a yarn length (Morton, 1956).

The main features of migrational behaviour are usually characterized by the following parameters (Hearle et al., 1965 a, b, 1972; Morton and Yen, 1952): (i) the
helix profile, (ii) the mean fibre position, (iii) the root mean square (r.m.s.) deviation, (iv) the mean migration intensity, and (v) the equivalent migration frequency.

There have been many studies of fibre migration and structures of twisted yarns (Mu et al., 1966; Riding, 1964; Hearle and Goswami, 1968; Hearle and Bose, 1965; Hearle et al., 1965 a, b, 1969, 1987; Huh et al., 2001; Lord, 1971; Lord and Grady, 1976, Grishanov et al, 1999). Some experts studied the character of yarn twist. However, most works are concerned with twist distribution along the yarn axis (Grosberg, et al., 1987; Guo et al., 2000; Lord and Rust, 1990). Zhang et al. (2003) researched the twist radial distribution in rotor spun yarns.

The influence of twist on the migrational behaviour of fibres in ring-spun yarns has been described by Morton (1956), Hearle (Hearle et al., 1965 b), and Gupta (1972). They showed that, in general, the rate of migration increases with twist. Hearle and Gupta (1965 a) further observed the existence of long-term migration, on which short-term migration was superimposed.

Existing literature recognizes that the linear density of the yarn and its twist level are the most influential factors that affect fibre migration in staple yarns (Gupta and Hamby, 1969; Gupta, 1970).

Most fibres in single spun yarns do not follow the perfect coaxial helical path. In ring spun yarns, the fibres move from the yarn center to the yarn surface, following the path of migrating helices. Fibre migration is essential in the ring spun structure because it provides integrity to the structure. In addition to tensile strength, fibre migration affects performance and other yarn properties. Variation in the fibre migration pattern imposes significant influences on torsional and flexural properties of yarns, although the effects on yarn tensile strength are less obvious (Postle et al., 1988).

The deviation from the perfect helical path is more evident in yarn structures produced by unconventional spinning methods, for instance, rotor and friction spun yarns. The core-sheath structure and non-uniform distribution of fibres in the yarn cross section are common in these yarns. The geometry and mechanical properties of these yarns are closely related to fibre configuration. For instance, rotor yarns are known to have better abrasion resistance and less snarling tendency than ring spun yarns, whereas friction spun yarns have higher snarling tendency than rotor and ring
spun yarns. However, the fundamental understanding of the relationship between yarn structure and properties is rather poor (Tao, 1996).

It is now widely known that open-end spun yarns are weaker and bulkier than ring-spun yarns. The reasons for the difference in properties lie in the respective structures of the yarns; fibres are assembled in different ways according to the method of manufacture. In ring-spinning a ribbon-like assembly is twisted into a roughly cylindrical shape, and, because the nip of the front roller restrains fibre movement, there is a wide range of fibre tensions generated, which causes migration (Morton, 1956). In open-end spinning fibres are usually wrapped sequentially onto the forming yarn under very low tensions, and little fibre migration is generated. There are also differences in fibre configuration. In ring-spinning the fibre configurations in the yarn are determined to a large extent by prior processes. In open-end spinning the fibres are separated to such an extent that prior processes have a smaller effect; however, many types of open-end spinning generate hooks or other fibre configurations as part of their operation (Lord, 1970). These mechanisms affect the strength and bulk of the yarn.

Fibre migration in an open-end-spun yarn is more local, and there is a tendency for the yarns to be made up of layers. In the open-end spun yarn samples the magnitude of migration (as determined by the r.m.s. deviation) is observed to be as low as one-sixth of the typical values that have been observed in ring spun yarns. This difference in structure is important because it affects the degree of fibre-interlocking within the yarn, which in turn can affect the properties of the yarn.

The observed low strength of most open-end spun yarns can therefore be attributed to the poor fibre extent and inferior fibre migration within the yarn body. On the other hand, the relatively high elongation of these yarns may be explained in terms of the folded and entangled nature of the fibres, which act as extensible components of the system (Hearle et al., 1987).

Literature describes a number of methods to estimate fibre distribution in blended yarn, which can be classified into four groups.

Group 1 – the methods used to obtain a quantitative estimation of fibre radial distribution in a yarn cross-section. This group includes the methods of Hamilton (1958), Maillard (1961), Rudolph (1955), Townend (Onions et al., 1960), Kirschner (1963) and Sevostyanov (1962).
Group 2 – the methods that provide a quantitative estimation of fibre sectorial distribution in a yarn cross-section. The number of such investigations is considerably lower than for Group 1 and includes the methods of Coplan and Bloch (1955), and Sevostyanov (1962).

Group 3 - consists of the methods for quantitative estimation of fibre distribution along the yarn; these methods been developed by Coplan and Klein (1955) and Sevostyanov (1962).

Group 4 – the methods in which the quality of mixing is determined by the size and number of fibre bundles of different components. This group contains methods developed by De Bass and Walker (1957), Kirschner (1963), Coplan and Klein (1955), and Onions and Hampson (1955).

The choice of method to estimate mixing of heterogeneous fibres in a yarn should be made according to the research objectives. Investigation of a large number of cross-sections enables the actual distribution of different components in a yarn to be determined.

The fundamental requirement for any investigation of specific factors affecting preferential migration, and subsequently the effects of the resulting preferential distribution of fibres on yarn and fabric properties, is to produce a quantitative method of expressing the arrangement of blend components relative to the yarn axis. An obvious approach is to divide the yarn cross-section into a series of zones concentric with the axis and attempt some interpretation of an appropriate fibre count.

All methods estimating radial distribution have a common feature, which consist of dividing the yarn cross-section into radial zones and counting component fibres in the zones.

One of the most widely applied and mathematically sound methods is that of Hamilton (1958).

The method is based on the interpretation of a fibre count taken from zoned yarn cross-sections in an attempt to represent the overall core-to-surface distribution of a particular blend component by a single numerical parameter. The advantage of such a parameter is its capacity for direct quantitative comparison, and for correlation with other yarn and fabric properties.
The parameter proposed by Hamilton is termed the "migration index" and may be calculated for any given component in a blend of any number of components. It is based on certain first moments of the given component about the centre of the yarn cross-section and relates the moment \( FM_a \) corresponding to the actual distribution, to moments \( FM_u, FM, \) and \( FM_o \) corresponding to three hypothetical distributions, i.e. uniform distribution, and those which would result from maximum inward and outward migration, respectively.

Determination of the migration index is carried out in three stages:

1) the preparation and examination of a suitable number of yarn cross-sections. The section-to-section variability and the ultimate statistical significance require a large number of cross-sections to be examined; usually it is recommended to have 100 cross-sections;

2) the concentric zoning of these sections and fibre counting;

3) the derivation of the migration index itself from the fibre count.

In the experiment the yarn cross-sections were divided into five concentric zones with equal increments in radius (Figures 5.1 - 5.2). This method of dividing the section is considered to be a preferential alternative to division into five zones of equal area (Hamilton, 1958).

The migration index is calculated from the actual fibre moment \( FM_a \), the uniform moment \( FM_u \), and the appropriate other hypothetical moment (inward or outward), and is expressed as a percentage. It is given by the ratio of the deviation of the actual fibre moment \( FM_a \) from the uniform moment \( FM_u \), to the deviation of either the maximum inward or maximum outward moment \( FM_o \) or \( FM_i \) from the uniform moment. If the preferential migration of the component has been inward, \( FM_a < FM_u \), \( FM \) is used; whilst if the migration has been outward, \( FM_a > FM_u \), \( FM_o \) is used.

Thus, if \( FM_a < FM_u \) the migration index is negative:

\[
M = \frac{FM_u - FM_a}{FM_u - FM_i} \times 100 \; (\%);
\]

whilst if \( FM_a > FM_u \), the migration index is positive:
\[ M = \frac{FM_u - FM_s}{FM_o - FM_u} \times 100 \% \]

The migration index characterises the uniformity of radial distribution of fibres over the yarn cross-section.

A migration index of zero represents a uniform distribution of the component between core and surface.

A migration index of ±100 % may be taken to represent complete separation of the component from the other fibres, except possibly in the zone where they meet, since mixing in this zone will not affect the migration index.

The migration index is positive or negative according to whether the preferential migration has been outward or inward.

The migration index of the second fibre component in a binary blend is equal in value, but opposite in sign, to the migration index of the component under consideration – i.e., the sum of the migration indices of the components in a binary blend is equal to zero.

It should be noted that the numerical value of the migration index does not depend on taking fibre moments relative to the middle zone.

Hamilton's method provides a sufficiently objective estimate of distribution uniformity of fibre components in yarn (Hearle et al., 1965).

5.2.2 Fibre migration in cotton-flax yarn

This research work included the investigation of flax fibre migration in rotor- and ring-spun yarns produced from a blend containing 70 % cotton and 30 % flax. According to the literature the effect of spinning method on fibre migration pattern in cotton-flax yarn has not been previously studied.

The analysis of cotton-flax yarn cross-sections is hampered by the fact that it is quite difficult to distinguish between these two fibres. Therefore, at the initial stage of the research work cotton-flax yarn dyeing experiments were carried out in order to facilitate the identification of different fibres in the yarn cross-section. The cotton-flax yarn was stained in order to colour the components differently, because it seemed possible that similar cross-section characteristics might lead to difficulties in the
subsequent identification and counting of fibres. A number of stains were applied in accordance with the recommendations of Lamb (1957). Dyeing conditions were aimed at minimizing the influence on yarn structure. The best results were obtained using two variants of mixture. The first solution contained the following ingredients:

- C.I. Acid Red III (5 ml 0.5 % solution);
- C.I. Basic Red 18 (5 ml 0.5 % solution);
- C.I. Direct Yellow 50 (5 ml 0.5 % solution);
- C.I. Disperse Blue 26 (10 ml 0.5 % suspension);
- Synpheronic NP9 (2 ml 5 % solution);
- acetic acid (6 ml 5 % solution);
- sodium sulphate (20 ml 5 % solution),

made up to a total volume of 400 ml with distilled water.

The second mixture that proved to be the most effective was Shirlastain C (Shrilastain, 2001).

Representative sampling was carried out in such a way that the distance between adjacent cross-sections exceeded the average fibre length in the blend. The necessity to sample in this way has been confirmed by the results of other researchers (Kirschner, 1963; Coplan and Bloch, 1955).

A number of experiments to characterise the radial distribution of fibres in the yarn cross-section of rotor and ring cotton-flax yarn were conducted. The main aim of this experiment was to study the migration pattern of flax fibres. Hamilton’s Migration Index was applied as a single numerical parameter to represent a preferential radial distribution of a particular fibre component in a blended yarn, relative to the yarn axis. The migration index is based on zoned fibre counts taken from a suitable number (100) of yarn cross-sections and expresses the actual migration of the component in terms of the maximum possible that could have occurred in the given yarn.

The results of this experiment showed that flax fibres (marked by green in Figures 5.1 and 5.2) in both cases are mainly located in outer layers of yarn cross-section, while cotton fibres are in internal layers.
Figure 5.1 Cotton-flax rotor yarn (71.4 tex) cross-section (flax fibres are marked green, cotton fibres red)

Figure 5.2 Cotton-flax ring yarn (72.0 tex) cross-section (flax fibres are marked green, cotton fibres red)

The migration index of flax fibre in cotton-flax rotor yarn cross-sections is \( M_{\text{flax}}^{\text{rotor}} = +19.19 \) (\( M_{\text{cotton}}^{\text{rotor}} = -19.19 \), accordingly). In comparison with open-end yarn the migration pattern in ring-spun yarn showed more significant radial migration of flax component to outer layers of yarn cross-section: \( M_{\text{flax}}^{\text{ring}} = +27.3 \) (\( M_{\text{cotton}}^{\text{ring}} = -27.3 \)).

A more uniform fibre distribution in open-end cotton-flax yarn is evidence of more effective mixing of the blend components during processing.
Investigation of the rotor yarn produced from the blend of less heterogeneous fibres (25 % - polyacrylonitrile fibres, 75 % - cotton) show that the fibres of PAN are insignificantly displaced to external layers. There is no significant evidence for radial migration of components in the yarn cross-section ($M_{PAN} = 0.94$). Therefore, it can be concluded that the fibres are uniformly distributed over the cross-section.

Figure 5.3 Polyacrylonitrile-cotton rotor yarn (50.0 tex) cross-section (PAN fibres are marked by star tokens, cotton fibres – by circles)

In this way quantitative assessments of the radial distribution of fibres in cotton-flax yarns cross-section have been carried out. Results show that flax fibres are preferentially located in the outer layers of yarn cross-sections. The effect of rotor and ring spinning methods on fibre migration pattern in cotton-flax yarn has been defined
5.3 Investigation of surface properties of flax-containing yarn

The relative position of different fibre components changes between yarn cross-sections. Accordingly, fibre migration will change yarn hairiness and surface properties, and affect yarn friction characteristics.

Two- and three-component yarns obtained using different spinning methods have been investigated to understand the influence of blend composition on yarn hairiness, winding friction coefficient and other properties.

The characteristics of the yarn samples investigated are represented in Table 5.3. The experiments have been conducted using the equipment of MTFM department laboratory (SPSUTD).

Table 5.3 Characteristics of the yarn samples investigated

<table>
<thead>
<tr>
<th>Number of the sample</th>
<th>Linear density, tex</th>
<th>Type of the yarn, blend composition</th>
<th>Spinning method employed</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>25.0</td>
<td>Blended, three-component : 52 % cotton, 35 % flax, 13 % polyester</td>
<td>Ring spun</td>
</tr>
<tr>
<td>2</td>
<td>25.0</td>
<td>Blended, three-component: 52 % cotton, 35 % flax, 13 % polyester</td>
<td>Open-end</td>
</tr>
<tr>
<td>3</td>
<td>84.0</td>
<td>Blended, three-component: 52 % cotton, 35 % flax, 13 % polyester</td>
<td>Open-end</td>
</tr>
<tr>
<td>4</td>
<td>35.5</td>
<td>Blended, bi-component: 70 % cotton, 30 % flax</td>
<td>Open-end</td>
</tr>
<tr>
<td>5</td>
<td>71.4</td>
<td>Blended, bi-component: 70 % cotton, 30 % flax</td>
<td>Open-end</td>
</tr>
<tr>
<td>6</td>
<td>71.4×2</td>
<td>Blended, bi-component, twisted: 70 % cotton, 30 % flax</td>
<td>Open-end</td>
</tr>
<tr>
<td>7 (control)</td>
<td>29.0</td>
<td>Homogeneous – 100 % cotton</td>
<td>Ring spun</td>
</tr>
</tbody>
</table>

Unevenness in the linear density of yarn samples was measured on Keisokki KET 80-III B evenness tester. The results of the measurements are represented in Table 5.4.

Yarn hairiness has a significant influence on the stability of technological processes in weaving and knitting. It affects properties of the materials produced from the yarn (air permeability, electric conductivity, dirt retention, etc.) and the appearance of faults.
Yarn hairiness depends on fibre properties, the degree of fibre straightness, the spinning method employed, yarn twist and many other factors.

Until recently hairiness characteristics have not been required to be standardized. However, the problems that arise during processing of highly hairy yarn in knitting and weaving, and the additional processing costs associated with the elimination of hairiness in ready-made materials, require these characteristics to be controlled.

To examine yarn samples Laserspot LST II has been used. It enables the yarn unevenness in diameter and hairiness to be estimated simultaneously.

The main hairiness characteristic $Ha$ represents the hairiness equal to the total length of hairs (in mm) in 1 cm of yarn (Figure 5.4).

Figures 5.5 and 5.6 illustrate the minimum and maximum hairiness inherent to all yarn samples. Minimum hairiness is the number of piles shorter than 1 mm in a 10 cm yarn length. Maximum hairiness is accordingly the number of 3-5 mm long piles in a 10 cm length of yarn.

![Figure 5.4 Yarn hairiness of the samples](attachment:image.png)
Figure 5.5 Maximum hairiness of the samples

It is obvious that the presence of long piles (less than 5 mm) is more typical for ring spun yarns: yarn No 1 (a three component flax-containing ring spun yarn) and for yarn No 7 (a pure cotton ring spun yarn). Open-end yarns have long hairs to a lesser degree (Figure 5.5).

The appearance of short pile (length of hairs is less than 1 mm) could be observed on the surface of all samples investigated (Figure 5.6). Results suggest that the difference between the variants depends on the spinning method to a greater extent, than on fibre content and linear density of the yarn.
Figure 5.6 Minimum hairiness of the samples

It should be noticed that there is a close correlation between the total hairiness and both minimum (Figure 5.6) and maximum (Figure 5.5) hairiness: $R_{1A-H_{max}} = 0.80$ and $R_{1A-H_{min}} = 0.89$, respectively. However the correlation between hairiness and WIRA friction coefficient ($r_{1A-\mu} = 0.29$) or between hairiness and yarn diameter variation coefficient ($r_{1A-CVD} = 0.27$) is insignificant.

The data obtained from Laserspot - LST – II is given in Table 5.4. In the same table the values of friction kinetic performance (moving yarn to steel) for all variants are shown.

Comparing the yarn samples No 1 and No 2 (Table 5.4), which differ in their production method (ring and rotor spinning methods), the assertion that open end spun yarn exhibits reduced hairiness and irregularity in comparison with ring spun yarn (Lord and Suzami, 1974) can be proved.
Table 5.4 Hairiness, WIRA friction coefficient, variations in linear density and diameter of a range of yarns

| Sample | Blend composition (%) | Linear density spinning method | WIRA friction coefficient μ | Hairiness Ha | Coefficient of variation |
|--------|-----------------------|--------------------------------|-----------------------------|--------------|-------------------------|------------------------|
|        |                       |                                |                             |              | in hairiness CVH, %     | in diameter CVd, %     | in linear density CVr, %|
| 1      | 35fl / 52ctn / 13PE   | 25.0 tex RS                   | 0.48                        | 64.1         | 64.2                    | 28.3                   | 33.5                   |
| 2      | 35fl / 52ctn / 13PE   | 25.0 tex OE                   | 0.46                        | 28.9         | 46.8                    | 13.2                   | 20.5                   |
| 3      | 35fl / 52ctn / 13PE   | 84.0 tex OE                   | 0.81                        | 38.1         | 57.5                    | 18.0                   | 19.2                   |
| 4      | 30 fl / 70 ctn        | 35.5 tex OE                   | 0.58                        | 80.0         | 35.4                    | 16.5                   | 21.3                   |
| 5      | 30 fl / 70 ctn        | 71.4 tex OE                   | 1.14                        | 67.9         | 36.8                    | 15.3                   | 19.0                   |
| 6      | 30 fl / 70 ctn        | 71.4×2 tex OE                 | 1.32                        | 57.4         | 57.3                    | 15.4                   | 12.4                   |
| 7      | 100 % ctn             | 29.0 tex RS                   | 0.44                        | 56.6         | 63.4                    | 20.7                   | 21.0                   |

Note: RS – is ring spun yarn, OE – is open-end spun yarn, fl – is flax, ctn – is cotton, PE – is polyester.

The increase in linear density for both two-component (No 4 and No 5) and three-component (No 2 and No 3) open-end yarns leads to an increase in the WIRA friction coefficient, while the hairiness parameter (Figure 5.4) increases only in the case of three component yarn, and for two component cotton-flax yarn it tends to decrease.

Comparison of the variation coefficients of linear density $CV_T$ and diameter $CV_d$ shows that irregularity in diameter is less than that for linear density (excluding variant No 6 –twisted), and the difference is more significant for three-component yarns.

Comparing variants No 5 and No 6 (single and twisted) it is apparent that the variation in linear density decreases considerably in the case of the twisted yarn, while the variation in diameter has not changed significantly. The increase of friction coefficient could be explained by the increase in contact area of twisted 71.4 × 2 tex yarn during winding in comparison with the single 71.4 yarn.

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This part of the research work also included investigation of the influence of load conditions in the “friction area” on the surface friction coefficient (WIRA) of yarns of different structure and composition. The results obtained are presented in Figure 5.7

![Graph showing the dependence of WIRA friction coefficient on pressure load for different yarn samples.](image)

Figure 5.7 Dependence of WIRA friction coefficient on pressure load for different yarn samples

The data obtained enables the following conclusions to be made:

- all the samples of blended yarns are characterized by higher WIRA friction coefficients and a more significant effect of normal pressure on these values in comparison with pure cotton yarn;
- increase in yarn linear density led to an increase in the WIRA friction coefficient because of the extension of contact area between winding yarn and steel, and this increase is more significant when the value of normal pressure is low;
- the introduction of flax into the cotton blend leads to an increase in friction coefficient for all spinning systems employed for yarn production;
- the introduction of polyester fibres into the cotton-flax blend decreases the values of the WIRA friction coefficient; moreover, the difference between the coefficients of two and three component yarns becomes insignificant as the force of normal pressure increases;

In the course of the research work it has been found that the open-end method is preferable to conventional ring spinning for the production of a three-component flax-containing yarn. This is confirmed by the fact that the breaking energy of ring spun yarn (variant 1) is 6% higher than that of open-end yarn (variant 2), which is a statistically significant difference.

Poor homogeneity within a blend composition has a negative effect on the mechanical properties of a yarn. Thus, the breaking energy of the pure cotton yarn exceeds that of both the blended ring and rotor yarns that are comparable in linear density (variants 1, 2) by approximately 50%. For example, the breaking energy of pure cotton yarn is 50% greater than that of blended yarn.

In summary it is suggested that to make a complex estimation of the quality of a flax-containing yarn and to predict its behavior in further processing the characteristics indicated above should be considered. This is confirmed by the results of experiments conducted.

The influence of blend composition on hairiness, WIRA friction coefficient and other yarn properties shows that it is necessary to carry out more accurate adjustment of technological processes before introducing the yarn to further industrial processing.
5.4 Strength of flax-containing yarn

Yarn tensile properties have been estimated using the automatic tensile-testing machine Statigraph L. The results of tensile tests that have been conducted in accordance with ISO 2062 are shown in Table 5.5.

Table 5.5 Strength of flax-containing yarn

<table>
<thead>
<tr>
<th>Yarn linear density, tex</th>
<th>Blend composition</th>
<th>Spinning method employed</th>
<th>Breaking load, cN</th>
<th>Tenacity, cN/tex</th>
<th>Relative elongation, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>35.5</td>
<td>70% cotton, 30% flax (I)</td>
<td>OE</td>
<td>247.8</td>
<td>6.98</td>
<td>4.22</td>
</tr>
<tr>
<td>71.4</td>
<td>70% cotton, 30% flax (II)</td>
<td>OE</td>
<td>465.1</td>
<td>6.51</td>
<td>4.73</td>
</tr>
<tr>
<td>72.0</td>
<td>70% cotton, 30% flax (III)</td>
<td>RS</td>
<td>853.7</td>
<td>11.86</td>
<td>6.45</td>
</tr>
<tr>
<td>84.0</td>
<td>52% cotton, 35% flax, 13% polyester (IV)</td>
<td>OE</td>
<td>549.1</td>
<td>6.54</td>
<td>7.19</td>
</tr>
<tr>
<td>71.4 × 2</td>
<td>70% cotton, 30% flax (V)</td>
<td>OE</td>
<td>1656.9</td>
<td>11.60</td>
<td>6.83</td>
</tr>
</tbody>
</table>

The data given in Table 5.5 show that, among all samples studied, the ring-spun cotton-flax yarn has maximum tenacity. The tenacity of the open-end yarn that has the comparable linear density and the same blend composition is 45% lower (Figure 5.8 – samples II and III). The difference in breaking elongation (Figure 5.9) of these two yarn samples is much more significant. These differences are caused mainly by the spinning methods employed.
The decrease in linear density of open-end cotton-flax yarn (samples I and II) led to a 7.2% increase in tenacity, while the relative breaking elongation was 10.8% lower. The changes were statistically significant because calculated t-distribution coefficients ($t_c = 2.75$) were higher than the tabulated value $t_T = 2.0$ (at $df = 48$ and 95% significance). The number of fibres in cross-section is the cause of the change. However, the increase in breaking load and decrease in elongation result from the twist factor of the yarn samples investigated. The twist level of the 35.5 tex yarn is twice as high as that of 71.4 tex yarn (934.7 and 476.4, respectively; twist factor: $\alpha_{35.5}=5530$, $\alpha_{71.4}=3990$)

The presence of polyester in the blend led to considerable augmentation of yarn relative elongation (40% in comparison with two-component yarn). However, the breaking load did not change significantly.
Figure 5.9 Breaking elongation of flax-containing yarn

The mechanical properties of the cotton-flax twisted yarn (71.4 × 2 tex) shown in Table 5.5 meet the Russian standard requirements for cotton threads for hand knitting.
5.5 The influence of twist on strength and unevenness of open-end flax blended yarn

It is well known that yarn twist serves as a tool for compacting the fibre "package". Fibres exert pressure on one another in the direction perpendicular to the yarn axis caused by the torsion. Under the influence of twist each fibre cross-section rotates about its axis by some angle relative to the neighboring section; as a result torsional strain takes place. Due to this strain non-twisted fibre sliver consisting of parallelized fibres transforms into a yarn with a rounded cross-section. Fibres within the yarn bend and arrange in irregular cylindrical helical lines of varied pitch and radius of curvature. The increase of twist (up to the level of critical twist) leads to the increase of the strain in fibres caused by their bending. Thereby, the total pressure exerted between fibres and, consequently the forces of friction between them, increase. This results in the yarn becoming stronger.

Tensile tests show that during yarn breakage only part of the fibres is ruptured, while the rest of the fibres are slipping relative to each other. At the same time, the higher the yarn twist the higher the quantity of fibres which are breaking. Therefore, yarn strength depends on twist level, breaking strength and the slip resistance of the fibres forming the yarn.

Analysis of the influence of twist on yarn tenacity and breaking elongation shows that a gradual increase and subsequent gradual decrease in the yarn tenacity after reaching the critical twist value is typical for open-end yarn.

The structure of the yarn obtained using the open-end spinning method is different from that of conventional ring-spun yarn. For this reason there is some difficulty in estimating rotor yarn twist. To estimate yarn twist level the following methods are usually applied:

(i) determination of the angle of inclination of the fibre coils to the yarn axis; this is carried out using a microscope;

(ii) the method of direct untwisting which involves counting the number of turns required for untwisting the yarn up to fibre parallelization; this method is not suitable for open-end yarn because of its structure;
(iii) double twisting method, which is applied as standard for cotton yarns and in all cases when determination of the moment of fibre parallel arrangement during untwisting is difficult. It is not recommended to use this method for testing the twist of open-end yarn because it underestimates the twist level;

(iv) the method of breaking twisting. It is not recommended to use this method for testing the twist of rotor yarn because it overestimates the twist level;

(v) "balanced twist" method described in Chapter 3 (section 3.2.10). It has been applied in this thesis to obtain more accurate results of measuring the open-end yarn twist.

Yarn unevenness in twist depends on a range of factors. One of them is the variable torsional rigidity of fibres, which is especially typical in the case of cotton-flax blends.

In the case of homogeneous fibre flow in a spinning rotor from the funnel surface to the output point of the channel the yarn twist increases exponentially. If the fibre of greater torsion rigidity gets to this zone, the twist considerably reduces (Larin et al., 2001). This leads to a decrease in yarn strength or even to its breakage.

The effect of twist on yarn properties is very well known for cotton yarn. However this effect has not been studied thoroughly for spinning of unconventional blends. The influence of twist on variations in yarn strength and elongation is even less known for open-end cotton-flax yarns. These factors are important for both yarn manufacturers and customers. This influence has been studied for 71.4 tex cotton-flax open-end yarn using the method of balanced twist.

To determine the value of critical twist, yarn samples of different twist level have been subjected to standard tensile tests. The data enabled definition of a relationship between twist factor and yarn tenacity and unevenness in strength. The plotted function is represented in Figure 5.10.

The regression equations for yarn tenacity and unevenness in strength against twist factor are as follows:

\[ P_o = -3 \alpha^2 10^6 + 2.87 \alpha 10^2 - 53.12, \quad DC = 0.69; \]  \hspace{1cm} (5.4)

\[ CV_p = 2 \alpha^2 - 0.17 \alpha + 361.54, \quad DC = 0.85; \]  \hspace{1cm} (5.5)
where $P_o$ is yarn tenacity, cN/tex;

$\alpha$ is a twist factor;

$CV_P$ is variation coefficient of yarn strength, %;

$DC$ is determination coefficient.

The analysis of regression equations enabled the value of critical twist factor $\alpha_c = 4200$, which provides the maximum tenacity of the yarn, to be defined.

Figure 5.10 illustrates the variation in yarn tenacity and unevenness in strength. It indicates the presence of an optimal twists zone that makes it possible to produce yarn with decreased unevenness in strength.

![Graph showing the relationship between yarn tenacity and twist factor.](image)

**Figure 5.10** The influence of twist on strength and unevenness of open-end cotton-flax yarn

Therefore the data enables recommendations on optimal twist level of open-end cotton-flax yarn to be given to industry. Considerable dependence of yarn tenacity, elongation and variation of these factors on twist level has been ascertained in the research work.
5.6 An adaptation of instrumental methods for the examination of flax fibres

The majority of the techniques employed for testing the properties of textile materials can be applied universally regardless of the type of fibres being investigated. However, some instrumental methods have been developed for so-called 'conventional' fibres and materials only, for the most part for cotton and wool. Therefore, researchers face problems when estimating some properties of short flax fibre. It appears to be economically feasible to adapt existing techniques for such fibres instead of designing new test methods.

One of the problems that arose in the course of the research work was estimation of flax fibre fineness.

There are several methods for measuring fibre fineness. They are:

(i) Gravimetric method. This is a very time consuming manual technique that enables estimation of the average fibre fineness.

(ii) Airflow (Micronaire) method. This provides an indication of fibre fineness by measurement of the pressure drop of airflow through a standard mass of cotton or wool fibres.

(iii) Image analysis of fibre. This method can give very detailed information about fibre cross-section, however, sample preparation and analysis is time consuming.

(iv) OFDA (Optical Fibre Diameter Analyser) method. This technique is based on the application of an automatic microscope that magnifies and captures images of the individual fibres using a video camera (Van Schie et al., 1990; Baxter et al., 1992). This method was developed for measuring the diameter of wool fibre, however, it has been used by Linger et al. (2002) for measuring hemp fibre fineness and showed a good correlation with the results produced by the Airflow method. Dreyer et al. (2002) applied OFDA method for the study of the fineness of enzyme treated nettle and hemp.

(v) LaserScan method. This is based on the optical measurement of 2 mm long fibre snippets suspended in an isopropanol-water mixture (Bactens, 1998; AWTA, 1999). It was designed for the measurement of single wool fibre with approximately circular cross-sections.
The fact that flax fibre samples always include a proportion of fibre bundles and single flax fibres which are not circular in their cross-section considerably affects the average fibre width estimated by the LaserScan or OFDA methods in comparison with its true value for the given fibre sample (Grishanov et al., 2006). A new method for estimating the single flax fibre diameter using data from the LaserScan and OFDA instruments was developed by Grishanov et al. (2006). The method is based on the mathematical modelling and numerical analysis of the experimental fibre and fibre bundle width distribution.

Undoubtedly, the method proposed is reliable and less time consuming in comparison with gravimetric method or image analysis of fibre. However, the application of the airflow method should not be ignored for estimation of flax fibre fineness. The time required for sample preparation and measurement on Micronaire do not exceed those on LaserScan or OFDA.

Very few attempts to apply the airflow method, originally developed for the measurement of cotton and wool fibre fineness, are mentioned in the literature (Akin et al., 1999 b; Grebenkin, 2004), the techniques used by these workers are not been described clearly in the literature.

The Micronaire method is based on the measurement of the pressure drop of airflow through a standard mass of fibres.

There is a correlation between air permeability of a fibre mass of constant volume and the average fibre fineness. This correlation is applied in instruments designed for fibre fineness estimation. The airflow method determines fibre relative surface $S$, the value of which can be used for estimating the fibre fineness.

The shapes of the cross-sections of heterogeneous fibres can differ considerably. In the case of flax and cotton they are not constant, therefore the fineness value determined using a relative surface $S$ may not correlate closely with the fibre fineness $T$ determined by the gravimetric method, as follows from the formula:

$$T = \frac{A \rho}{S^2}, \quad (5.6)$$

where $A$ is a constant determined by fibre cross-section shape;

$S$ is fibre surface area;
\( \rho \) is fibre volume density.

Formerly the Micronaire scale was calibrated in these units, which enable direct estimation of the \( S \) value. Contemporary instruments are equipped with the scale of units of weight of length. However, readings obtained using the Micronaire system are not identical to those determined by the conventional method.

Flax cottonin obtained using the rupture method was used for the tests. Image analysis of flax, cotton and wool fibres showed that flax fibre width and surface is closer to those of cotton rather than to wool. Figure 5.11 presents the images of cotton, wool and flax fibres obtained using scanning electron microscopy. To aid comparison each image shows a segment equivalent to \( 10^{-6} \) m at the magnification employed.

![SEM images of cotton, wool and flax fibres](image)

Figure 5.11 SEM images of cotton, wool and flax fibres

This investigation estimated fibre fineness by means of the airflow method. Ten variants of different linear density flax were examined. The specimen weight for all variants was 4 grams according to standard practice for cotton quality testing on the Keisokki Micronaire instrument. The same fibre samples were subjected to testing on LaserScan.

It was found that the flax fibre fineness values estimated by these methods showed poor correlation, the correlation coefficient \( r = 0.34 \) is insignificant. This could be explained by the fact that the normal Micronaire scale is designed for cotton (the second scale is for wool). The result produced by the Micronaire instrument is affected by the non-uniform porosity of the fibre mass, the specific surface area of the flax fibres and the presence of fibre bundles. Hypothetically, the application of the instrument for testing flax fibres will require special calibration. Another reason for the poor
correlation could be that a 4-gram specimen weight, standard for cotton, is inapplicable for short flax fibres due to the difference in volume density of flax and cotton fibre specimens. In actual fact experimental data obtained by airflow method greatly depends on the weight of tested specimen.

To define an appropriate specimen weight, two types of short flax fibre with linear density 0.22 and 0.26 tex (determined by the gravimetric method) were tested on the Micronaire device using different specimen weights. The results of the experiment (Figure 5.12) showed that on application of 4.7-gram specimen weight of flax the data obtained using airflow method (Keissokki Micronaire) is the closest to that obtained by conventional (gravimetric) method.

![Graph showing the influence of flax fibre specimen weight on Micronaire experimental value of fineness.](image)

**Figure 5.12** The influence of flax fibre specimen weight on Micronaire experimental value of fineness

Taking into consideration these results, ten variants of different linear density flax were examined using Micronaire. This time the specimen weight for all variants was 4.7 grams. The results obtained showed considerable correlation with fibre diameter values estimated using LaserScan, the correlation coefficient being $r = 0.72$. The correlation between the gravimetric method average and the Micronaire was better, the correlation coefficient being $r = 0.83$. 

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Nevertheless, the airflow method (Micronaire) could be applied for cottonised flax fibre testing as a quick method compare the results obtained from each system.

5.7 Complex assessment of the quality of cotton-flax yarn for knitting

Analysis of the textile market shows that flax-containing yarns are not currently available. A pilot investigation carried out jointly with JSV ‘Kvarton’, one of the biggest spinning mills in the North-West of Russia, has demonstrated a possible market for flax-containing threads for hand knitting in Russia (Truevtsev et al., 2001).

This problem may initially appear superficial. However, a yarn for hand knitting is quite a competitive business sector in Eastern Europe, which is of increasing interest in fluctuating markets.

In order to compare the properties of products various integrated quality assessments can be made. Expert methods have been designed for use in textile materials science for estimation of defined characteristics and their significance.

Numerical values of the integrated assessments are considered to characterise the quality of materials adequately. For a comparative assessment of the quality it is necessary to know from which properties the estimate has been obtained. For this purpose a graphical method for the determination of a complex assessment criterion has been used (Truevtsev et al., 1983). It gives a pictorial representation of the values of the single properties of the materials used for comparison.

To determine the significance weightings of the attributes, and to calculate the value of the integrated assessment, expert methods are most often used. To determine the significance of individual properties of yarn the expert judgement method proposed by Kendall (1970) has been applied.

The values for statistical processing were obtained by interviewing twenty respondents, who are specialists in the science of textile materials. The questionnaire (Appendix B) contained nine characteristics of knitting threads:

- $X_1$ - thread tenacity, cN/tex;
- $X_2$ - coefficient of variation in breaking load, %;
- $X_3$ - relative breaking elongation, %;
- $X_4$ - coefficient of variation in linear density, %;
- $X_5$ - relative torsional rigidity, 1/tex;
- \( X_6 \) – hairiness;
- \( X_7 \) – balance in twist;
- \( X_8 \) – abrasion rigidity;
- \( X_9 \) – coefficient of variation in twist, \%. 

The experts had an opportunity to add any characteristics which they considered important but had not been mentioned in the questionnaire.

The reliability of the results of this expert evaluation depends on the compatibility of expert judgement. The concordance coefficient (Kendall, 1970), which characterizes agreement in the respondents’ opinions, was determined using the formula 5.7:

\[
W = \frac{12 \sum_{i=1}^{n} (S_i - S_{av})^2}{m^2 (n^3 - n)},
\]  

(5.7)

where \( S_i \) is a sum of ranks;
\( S_{av} \) is a ranking sum average;
\( m \) is the number of respondents;
\( n \) is the number of characteristics considered.

In the case of complete concordance of experts opinions \( W = 1 \), in the case of total disagreement \( W = 0 \). The questionnaire data obtained showed high concordance in expert judgements \( (W = 0.89) \).

The significance of the concordance coefficient has been defined using the Pearson criterion, determined as follows:

\[
\chi^2_{(n-1)} = W \cdot m \cdot (n - 1).
\]  

(5.8)

Since the calculated value \( \chi^2_{(n-1)} = 141.8 \) is larger than the critical tabular value \( \chi^2_{tabl} = 15.5 \) (Fisher and Yates, 1963) for the pre-selected level of significance \( \alpha = 0.05 \), the assumption is made that the coefficient of concordance is significant and expert rankings are in concordance with 95 % probability.
The characteristics, whose weightings were determined by expert methods as low, were excluded. Five properties were recognized as significant for complex assessment. Their weightings are represented in Figure 5.13.

![Figure 5.13 Weightings of characteristics at complex assessment of the knitting threads quality](image)

Figure 5.13 Weightings of characteristics at complex assessment of the knitting threads quality ($X_1$ – thread tenacity, cN/tex; $X_2$ – coefficient of variation in breaking load, %; $X_3$ – relative breaking elongation, %; $X_4$ – coefficient of variation in linear density, %; $X_5$ – relative torsional rigidity, 1/tex)

Thus, the coefficients of characteristics weightings that determine the quality of knitting threads have been defined and the dependence of quality complex characteristic on the most significant properties has been equated. The equation is given as:

$$ Y = 0.28X_1 + 0.2X_2 + 0.15X_3 + 0.26X_4 + 0.11X_5. \quad (5.9) $$

A circle diagram characterizing the threads quality has been plotted using the data obtained (Figure 5.14). The characteristics of threads are represented by the length of radius-vectors. The vectors corresponding to the characteristics, whose increase lead to improvement of the quality (e.g. tenacity), are directed to the diagram centre. The origin of such a vector is located at the external concentric circle that determines the permissible level of the characteristic. The vectors that characterize those properties whose increase lead to deterioration of the quality (e.g. unevenness in linear density), radiate from the circle centre.
The scale for each characteristic is such that the point of intersection of radius-vector with interior concentric circle corresponds to the value of the relative characteristic of a control sample. Standard cotton knitting thread \(84 \times 2\) tex (according to the Russian standard GOST 8402-84) has been used as a control sample.

If the characteristics represented in the diagram (Figure 5.14) had equal weights, the quality of the threads properties would be estimated by the area of the polygon plotted by connecting the points of radius-vectors corresponding to the values of products characteristics. The higher the area of the polygon indicates higher quality of the yarn.

To compare the properties of cotton-flax knitting thread with those of analogous flax and cotton materials the Russian standards data was used. Figure 5.14 represents the diagrams of quality of three types of threads, plotted as polygons:

- the polygon plotted by a solid line corresponds to the quality of \(71.4 \times 2\) tex cotton-flax knitting thread (70 % cotton, 30 % flax);
- the polygon depicted by a dotted line corresponds to the quality of \(84.0 \times 2\) tex cotton knitting thread (Russian standard GOST 8402-84);
- a dash-dotted line was used to demonstrate the polygon characterizing the quality of \(60.0 \times 2\) tex flax knitting thread (Russian standard GOST 14961-91).

Figure 5.14 Graphical complex assessment of the threads quality
Figure 5.15 represents the complex assessment of the quality for these three materials. Computation of the assessment has been carried out in the following way: the values of characteristics $X_1$, $X_2$, $X_3$, $X_4$, $X_5$ were taken as the distance between the point of radius-vectors intersection and the point corresponding to the property value (Figure 5.15). The radius of the central concentric circle has been taken as a unit of distance.

![Bar Chart](image)

**Figure 5.15 Complex assessment of the threads quality**

Thus, it has been determined that the difference in the complex assessment of the quality between cotton-flax threads and standard flax and cotton threads of the same structure and similar linear density was small ($7.5 \pm 1\%$).

Hence, the diversification of available knitting threads by use of cottonised flax in blends with cotton is possible and expedient. The flax-like appearance of the material is in demand and the properties of the cotton-flax twisted yarn meet the standard requirements for cotton threads for hand knitting.
5.8 Conclusions

Quantitative assessments of the radial distribution in the cross section of cotton-flax yarns showed that flax fibres are preferentially located in the outer layers of yarn cross-sections. The migration index of flax fibre in cotton-flax rotor yarn cross-sections is \( M_{\text{flax}}^{\text{rotor}} = +19.19 \) (\( M_{\text{cotton}}^{\text{rotor}} = -19.19 \), accordingly). In comparison with open-end yarn the migration pattern in ring-spun yarn showed more significant radial migration of flax component to outer layers of yarn cross-section: \( M_{\text{flax}}^{\text{ring}} = +27.3 \) (\( M_{\text{cotton}}^{\text{ring}} = -27.3 \)). A more uniform fibre distribution in open-end cotton-flax yarn is evidence of more effective mixing of the blend components during processing.

The influence of blend composition on the surface properties of two- and three-component yarns obtained using different spinning methods was determined. It was established that the appearance of short (length of hairs is less than 1 mm) and long (length is 3-5 mm) piles depends on the spinning method to a greater extent, than on fibre content and linear density of the yarn. The presence of these piles is more typical for ring spun yarns. The increase in linear density in both two-component and three-component open-end yarns leads to increase of the WIRA friction coefficient, while the hairiness increases only in the case of three component yarn, and for two component cotton-flax yarn it tends to decrease. The introduction of flax into the cotton blend leads to an increase in friction coefficient for all spinning systems employed for yarn production. The introduction of polyester fibres into the cotton-flax blend decreases the values of the WIRA friction coefficient; moreover, the difference between the coefficients of two and three component yarns becomes insignificant as the force of normal pressure increases.

Comparison of the variation coefficients of linear density \( CV_T \) and diameter \( CV_d \) showed that irregularity in diameter is lower than that in linear density, and the difference is more significant for three-component yarns.

Poor homogeneity of blend composition has a negative effect on yarn mechanical properties. Thus, the breaking energy of pure cotton yarn exceeds that of both blended ring and rotor yarns that are comparable in linear density by approximately 50%.
The effect of twist level on yarn tenacity and its variation was investigated. The analysis of regression equations for yarn tenacity and unevenness in strength against twist factor enabled to indicate the presence of an optimal twists zone that makes it possible to produce yarn with decreased unevenness in strength. A twist factor equal to 4 200 is recommended as an optimal value for 71.4 tex open-end cotton-flax yarn.

It was defined that on application of 4.7-gram specimen weight of short flax fibre the data obtained using airflow method (Keissokki Micronaire) is the closest to that obtained by conventional gravimetric method.

It was shown that the difference in the complex quality criterion between cotton-flax threads and standard 100% linen and 100% cotton threads of the same structure and similar linear density is not significant.
CHAPTER 6 CONCLUSIONS AND RECOMMENDATIONS

6.1 Main results

The review of the development of spinning technology for cotton-flax blends processing and a limited application of enzymes at different stages of flax fibre processing was carried out.

Estimations of hypothetical and actual irregularity, and the index of spinning products irregularity were made. The reasons for the unevenness formation were investigated using spectrogram analysis. The unevenness guidelines for cotton-flax yarn were rated using the recommended unevenness index and the calculated ideal unevenness. The recommended norm of irregularity of ready to use first-grade cotton-flax yarn is 15 %, and second-grade yarn is 18 %.

Quantitative assessments of the radial distribution in the cross section of cotton-flax yarns showed that flax fibres are preferentially located in the outer layers of yarn cross-sections. The effect of spinning method on the fibre migration pattern in cotton-flax yarn was investigated. In comparison with open-end yarn the migration pattern in ring-spun yarn showed more significant radial migration of flax component to outer layers of yarn cross-section.

The influence of blend composition on the surface properties of two- and three-component yarns obtained using different spinning methods was determined. It was established that the appearance of short (length of hairs is less than 1 mm) and long (length is 3-5 mm) piles depends on the spinning method to a greater extent, than on fibre content and linear density of the yarn. The presence of these piles is more typical for ring spun yarns. The increase in linear density in both two-component and three-component open-end yarns leads to increase of the WIRA friction coefficient, while the hairiness increases only in the case of three component yarn, and for two component cotton-flax yarn it tends to decrease. The introduction of flax into the cotton blend leads to an increase in friction coefficient for all spinning systems employed for yarn production. The introduction of polyester fibres into the cotton-flax blend decreases the values of the WIRA friction coefficient; moreover, the difference between the coefficients of two and three component yarns becomes insignificant as the force of normal pressure increases.
Comparison of the variation coefficients of linear density $CV_T$ and diameter $CV_d$ showed that irregularity in diameter is lower than that in linear density, and the difference is more significant for three-component yarns.

Poor homogeneity of blend composition has a negative effect on yarn mechanical properties. Thus, the breaking energy of pure cotton yarn exceeds that of both blended ring and rotor yarns that are comparable in linear density by approximately 50%.

The effect of twist level on yarn tenacity and its variation was investigated. The analysis of regression equations for yarn tenacity and unevenness in strength against twist factor enabled to indicate the presence of an optimal twists zone that makes it possible to produce yarn with decreased unevenness in strength. A twist factor equal to 4 670 is recommended as an optimal value for 71.4 tex open-end cotton-flax yarn.

Application of enzyme treatments comprising a cellulase complex for processing of cotton-flax blends enables cotton-flax yarn with reduced hairiness and improved mechanical properties to be produced. The results obtained showed the potential for biochemical removal of fine dust with simultaneous improvement of flax hygroscopic properties. The chosen conditions of flax fibre treatment using the enzyme preparation Celloviridin G2X did not have a significant effect on fibre tenacity, fibre diameter and fibre length distributions.

It has been shown that the difference in the complex quality criterion between cotton-flax threads and standard 100% linen and 100% cotton threads of the same structure and similar linear density is not significant. Hence, the diversification of available knitting threads by use of cottonised flax in blends with cotton is possible and expedient. The flax-like appearance of the material is in demand and the properties of the cotton-flax twisted yarn meet the standard requirements for cotton threads for hand knitting.

Processing of cotton-flax yarn in weaving and knitting was not studied in the research work. The end-use application of the yarn produced was limited by the threads manufacturing. This field of application is of priority interest because analysis of the textile market showed that flax-containing threads are not currently available, while there is a growing demand for them in the Eastern Europe market. The application of cotton-flax yarn in weaving and knitting will be studied in further research work.
Unfortunately there was no opportunity to apply the proposed enzyme treatments on an industrial scale. The results obtained will be taken into consideration to conduct an industrial experiment in further research work.

6.2 Recommendations

The guidelines for the estimation of the quality of cotton-flax yarn were reviewed and new values for the unevenness characteristics were suggested. The recommended norm for the coefficient of variation in linear density of first-grade cotton-flax yarn is 15 %, and for second-grade yarn – 18 %.

For the reduction of yarn unevenness and better stability of the spinning process it is recommended to use flax fibre with a low linear density and limiting the flax percentage in the blend to 30%.

It is suggested that to make a complex estimation of the quality of flax containing yarn and to predict its behavior in further processing the surface characteristics (yarn hairiness, winding friction coefficient, unevenness in diameter and linear density) should be considered.

The airflow method using a specimen weight of 4.7 grams is recommended for cottonised flax fibre testing in order to compare the results obtained from each system.

The results showed that the application of enzyme treatments in the processing of cotton-flax blends enables a cotton-flax yarn with reduced hairiness and improved mechanical properties to be produced. Two variants of biochemical treatment may be recommended.

The first suggested treatment is to dissolve the multi-enzyme complex based on Aspergillus Japonicus (0.5 g/l) in acetate buffer (pH 4.4, 37.0 ml of 0.2M NaOAc + 63.0 ml 0.2M HOAc). The treatment should be carried out in a Scour Tester device at 40 rev/min mixing, for 30 min, module 30, at 50°C. Samples are then rinsed with water and dried in a desiccator at 95°C for 3 hours. The second recommended treatment is to pulverize cotton-flax lap meant for carding with a buffer solution containing 0.1-% Celloviridin G2X and 0.001-% Catopol in the acetate buffer described above.

It is recommended to treat cottonised flax with the Celloviridin G2X multi-enzyme complex which helps in fine dust removal with simultaneous improvement of hygroscopic properties of cottonised flax. The treatment should be conducted in the
Scour Tester device without mixing for 1 hour, module 30, at 50°C in 0.75 g/l enzyme solution in acetate buffer. After the treatment the fibres should be rinsed by water and dried in the convection drier for 2 hours.

The research work will be continued. Further investigations will include introduction of the enzyme treatments into industry and development of methods for measuring and estimating performance characteristics of flax blended yarns.

The application of twisted cotton-flax yarn in manufacturing of composite materials and complex structure fabrics as a warp and weft is also planned to be studied in further research, as well as processing of the yarn in knitting.
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Appendix A

Spinning plan

Linear density of the yarn, tex 71.4

Blend 70% cotton + 30% flax

Spinning frame

1. Type of frame BD-200-RC
2. Linear density of the yarn, tex 71.4
3. Linear density of the sliver processed, tex 4000
4. Draft 56
5. Direction of twist Right (Z)
6. Twist factor 3 750
7. Twist, rot/m 530
8. Output speed of the yarn, m/min 47.9
9. Rotor speed, min\(^{-1}\) 25376
10. Basin weight of the sliver, kg 3.3
11. Bobbin weight, kg 1.25
12. Yarn breakage on 1000 heads, br/h 200
13. Theoretical production rate of 1000 heads, kg/h 205.2
14. Standard operating efficiency 0.88
15. Standard production rate of 1000 heads, kg/h 180.6
16. Standard production rate of the frame (200 heads), kg/h 41.1

17. Technical downtime, % 3.50
### 2nd stage draw frame

1. Type of frame L2-50-220
2. Drawing mechanism 3×3
3. Linear density of output sliver, tex 4000
4. Linear density of input sliver, tex 4000
5. Draft 6
6. Ply 6
7. Front cylinder, mm 50
8. Rotational speed of the front cylinder, min⁻¹ 1330
9. Front cylinder speed, m/min 208.81
10. Basin dimensions (D×H), mm 220×900
11. Basin weight of the sliver, kg 3.3
12. Breakage, br/h 2
13. Theoretical production rate of one outlet, kg/h 50.11
14. Standard operating efficiency 0.81
15. Standard production rate of one outlet, kg/h 40.59
16. Standard production rate of the frame, kg/h 81.18
17. Technical downtime, % 5.0

### 1st stage draw frame

1. Type of frame L2-50-1
2. Drawing mechanism 3×3
3. Linear density of output sliver, tex 4000
4. Linear density of input sliver, tex 3570
5. Draft 7.14
6. Ply 8
7. Front cylinder, mm 50
8. Rotational speed of the front cylinder, min⁻¹ 1330
9. Front cylinder speed, m/min 208.81
10. Basin dimensions (D×H), mm 500×1000
11. Basin weight of the sliver, kg 10.7
12. Breakage, br/h 2
13. Theoretical production rate of one outlet, kg/h 50.11
14. Standard operating efficiency 0.81
15. Standard production rate of one outlet, kg/h 40.59
16. Standard production rate of the frame, kg/h 81.18
17. Technical downtime, % 5.0
Carding machine

1. Type of machine Wirkbau 1456
2. Linear density of sliver, tex 3570
3. Linear density of lap, tex Vary
4. Draft Vary
5. Ply 1
6. Doffing drum diameter, mm 668
7. Rotational speed of doffing drum, min\(^{-1}\) 39.6
8. Basin dimensions (D×H), mm 500×1000
9. Basin weight of the sliver, kg 14.0
10. Breakage per machine, br/h 0.2
11. Theoretical production rate of the frame, kg/h 30
12. Standard operating efficiency 0.86
13. Standard production rate of the frame, kg/h 25.8
14. Technical downtime, % 14.0

Scutching-machine

1. Type of machine T-16
2. Linear density of lap, ktex 384.6
3. Lap rollers diameter, mm 230
4. Rotational speed of lap rollers, min\(^{-1}\) 9.85
5. Theoretical production rate, kg/h 163.8
6. Standard operating efficiency 0.9
7. Standard production rate, kg/h 147.4
8. Technical downtime, % 6.5
Appendix B

Expert questionnaire

Dear respondent,

Please rank the characteristics of knitting threads meeting the following conditions:

- the most important characteristic is ranked first, next are arranged according to their significance – 2nd, 3rd, etc. places;

- the characteristics that have equal importance in your opinion should be assigned the same ranks, e.g. 1, 2, 2, 3...;

- if you consider that the questionnaire does not contain some important characteristic, please add it to Table B1 and give it an appropriate rank.

Table B1 – Expert questionnaire

<table>
<thead>
<tr>
<th>N</th>
<th>Characteristic</th>
<th>Rank</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Thread tenacity</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Coefficient of variation in breaking load</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Relative breaking elongation</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>Coefficient of variation in linear density</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>Relative torsion rigidity</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>Hairiness</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>Balance in twist</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>Abrasion rigidity</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>Coefficient of variation in twist</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td></td>
<td></td>
</tr>
<tr>
<td>11</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Thank you for your help!
Appendix B

Results of experts interviewing

Table B2 – Significances of the yarn single properties

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Sum of ranks $S_i$</th>
<th>Weight $\alpha_1$</th>
<th>Weight $\alpha_2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thread tenacity</td>
<td>37.5</td>
<td>0.219</td>
<td>0.28</td>
</tr>
<tr>
<td>Coefficient of variation in breaking load</td>
<td>52.5</td>
<td>0.156</td>
<td>0.20</td>
</tr>
<tr>
<td>Relative breaking elongation</td>
<td>70.0</td>
<td>0.117</td>
<td>0.15</td>
</tr>
<tr>
<td>Coefficient of variation in linear density</td>
<td>40.5</td>
<td>0.203</td>
<td>0.26</td>
</tr>
<tr>
<td>Relative torsion rigidity</td>
<td>95.5</td>
<td>0.086</td>
<td>0.11</td>
</tr>
<tr>
<td>Hairiness</td>
<td>161.0</td>
<td>0.051</td>
<td>-</td>
</tr>
<tr>
<td>Balance in twist</td>
<td>156.0</td>
<td>0.053</td>
<td>-</td>
</tr>
<tr>
<td>Abrasion rigidity</td>
<td>141.0</td>
<td>0.058</td>
<td>-</td>
</tr>
<tr>
<td>Coefficient of variation in twist</td>
<td>146.0</td>
<td>0.056</td>
<td>-</td>
</tr>
</tbody>
</table>

Note - Weights $\alpha_2$ were obtained by recalculation after excluding the characteristics that had low values of $\alpha_1$.

Table B3 – Concordance in experts’ opinions

<table>
<thead>
<tr>
<th>Sum of weights</th>
<th>$\Sigma \alpha = 1$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Concordance coefficient</td>
<td>$W = 0.89$</td>
</tr>
<tr>
<td>Pearson criterion calculated</td>
<td>$\chi^2_{calc} = 141.8$</td>
</tr>
<tr>
<td>Pearson criterion tabular</td>
<td>$\chi^2_{tab} = 15.5$</td>
</tr>
</tbody>
</table>