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Study on Woven Fabric Structure Using 3D Computer Image Analysis for In-Depth Identification of Thread Channels

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Abstract
A computer program - Textile3D to study the structure and identify the channels in woven fabrics in a 3D system was developed. Adaptation of a stand for computer image analysis was performed and a not-destructive method of testing channels between threads for woven fabrics (clothing) of low value of thickness and surface mass was developed. The following parameters of channels were determined: channel height Z in µm, spacing surface area P in µm^2, and the angle of channel deviation from the vertical position α in °. The woven fabric spacing surface area factor ξ (ksi) was introduced, which determines the ratio of the channel spacing surface area to the total area of woven fabric, taking into consideration channels in the 3D system. For a single channel and for the entire image of woven fabric observed, the approximate volume based on the channel spacing surface area and the angle of channel deviation from the vertical position as well as the very channel length were defined. Various channel spacing surface areas were obtained for the same woven fabrics. The median value of the angle of channel inclination for the woven fabrics tested ranged unit 19.300-36.510. Channel lengths are proportional to the thickness of woven fabric and are greater than the said thickness. The approximate size of the channel volume depends more on the size of the spacing surface area, and to a lesser extent, on the channel length. The method of channel analysis developed allows to refer to a greater diversity of fabric structures and to make greater use of their properties. It is also a prognostic for appropriate programming of voids in woven fabrics to optimise the flow of various media (air, moisture and under special conditions various types of electromagnetic radiation such as IR).

Key words: *strain state of fibre, fibre slippage, mutual displacement, compressive stress, axial stress, twist angle.*

State of the art in Poland and other countries

A significant influence of the spatial structure of a flat textile product on its applicability was emphasised by J. Szosland [1], among others. Previous studies on the structure of woven fabrics have shown the presence of channel spacings of various and complex shapes between threads (in a virtual 3D configuration). An analysis of solids formed in the channels between threads, according to prof. J. Szosland, proves big differences in such objects, and it is important not only for the air flow but also for examining and attaining a barrier effect against various types of electromagnetic radiation, such as IR and UV [2 - 6]. The methods developed so far enable to find and identify the channels in woven fabric in different virtual woven structural modules.

Among the analytical descriptions of model configurations and real woven fabrics, there are significant differences. While using woven fabric, it goes through stretching and shrinking phases, obtaining different shapes of spatial channels, which noticeably change the actual conditions of usage resulting from the predetermined structure of the woven fabric [2].

Research was also conducted on the influence of knitted products on their biophysical properties. Previous studies in this area were limited to the correlation between the structural parameters of knitted fabrics (density, thickness, filling coefficient) and biophysical properties. The relationship between the parameters characterising the spatial structure of a knitted fabric and biophysical properties was not determined, although they are the ones who determine the phenomenon of air and heat flow in the arrangement of channels and spacings between threads. In recent studies within this field the application of the digital image processing of a knitted fabric was taken into account. As a result of using computer registration and the processing of 2D images, the number and dimensional value of 2D porosity between threads and their arrangement in a knitted fabric were determined. In the studies on the structure of knitted fabrics discussed, the need for more research in the direction of three-dimensional image analysis to evaluate the spatial structure of knitted textiles was indicated [3].

Research was also performed on the porosity of textile products in a 2D system in the context of yarn properties and a significant impact of the yarn's properties, particularly its hairness, on the porosity of the products tested was stated. among others [15]. From the studies carried out in recent years there are some interesting works determining the influence of the structure of woven fabrics on its UV transmittance in virtual three dimensional configurations. The relationship of the configuration of the woven fabric structure (resulting from the spacings between threads) on the barrier effect coefficient UPF, characterising the value of UV transmittance, was found [4, 5].

Studies on the behaviour of selected standard and barrier woven fabrics against infrared radiation IR were also performed using transmission spectroscopy FTIR, taking into account the relevant parameters of these woven fabrics. As a result of the analysis performed, it was stated that there are many factors influencing the characteristic of curves for the reflection and transmission of IR radiation. The dominant parameter of the barrier effect of woven fabrics for IR was the structure of the woven fabric, dependent on the type of weave, sett of warp and weft, filling with warp and weft and the structure of both yarns.

The important parameters of woven fabrics were also the raw material composition, surface mass and thickness of the woven fabric. Research on the porosity of woven fabrics in a 2D arrangement was carried out on a measuring stand at IW (Textile Reserch Institute), equipped, among others, with a CCTV Panasonic digital camera, Textil3d application and Loo3D application [6].

The development of computer technology has brought huge development of image analysis methods, including 3D configurations, which enable to obtain in-depth information about different types of materials [8].

Computer methods of image analysis enable the automation and significant shortening of the research.

Computer analysis enables to avoid many incidental errors which occur in traditional measurement methods. The image in a digital format requires some perfections to improve its quality. Processing refers to the image both at the input of the algorithm processing the information, as well as at the output. The image after improvement and processing has the test characteristics marked, and next analysis of the sets already limited is carried out in order to apply the methods and algorithms for identification.

One of the modern research methods for image registration is the application of the infrared technique with the use of a thermal imaging camera, which processes the invisible infrared radiation coming from the object observed to the infrared image processing the intensity distribution of temperature radiation. Analysis of the results of thermographic tests is performed using algorithms which calculate differences in the time of temperature behaviour in the area of defects and beyond them. The methods of image processing in infrared thermography tests include the following steps:

- digitisation & compression of data,
- enhancement, restoration & reconstruction,
- matching, description & recognition [9].

Another method for image registration is the use of a digital camera and a number of applications and algorithms such as those for capturing, storing and analysing images. Digital processing of the images obtained includes their analysis and conversion using software. Each image processing leads to distortion, which should be included in certain limits defined and should clearly relate to the model of the woven fabric and interesting structural parameters of such an object.

A complex spatial configuration in the structure of the product in the form of large quantities of channels of different size and distribution in textile and between-thread arrangements makes it difficult to describe the transport of air, moisture and heat. Due to the nature of its application,a flat textile material must fulfill a number of functions, in which the most important are protection against adverse climatic conditions and assurance of physiological and hygienic comfort.

The need to extend studies on the structure of flat textile products in the field of image processing techniques in the 3D configuration has also been discussed in recent reports in worldwide literature [10 - 12]. Some authors rightly noticed that the internal structure of woven fabrics is the basis of information about their properties. Yarn parameters are indicated as very important i.e. its unevenness, the direction and amount of twist, as well as the arrangement of fibres. The parameters of the internal structure can be identified on the basis of a computer image of the woven fabric, and they influence, among others, the filterability, propagation of multidirectional internal stress and exhibit the ability of spatial formation under the influence of a load. Tests were carried out with the use of computer image analysis of these woven fabrics. A stand for measuring multidirectional stresses in the structure of the woven fabric was used in this research. Image analysis enables to identify the structural parameters of woven fabrics, including yarn spacing, as well as the size, shape and position of spacings between the threads. These studies allow us to evaluate the behaviour of the woven fabric structure under a spherical load in a multidirectional arrangement of the distribution of internal stress and enable to determine the size and shape of deformations [12].

Recognition and identification of spatial objects which form channels between threads in the woven fabric is important not only for the air flow and humidity transfer, but it can also be used for in-depth structural analysis such as the creation of a barrier effect with the use of woven products for various kinds of adverse electromagnetic radiation, or when determining different properties of woven fabric, including antibacterial properties.

A structural model of a flat textile product is based on the ideal model of yarn with a circular cross-section and homogeneous compact structure [1 - 3]. In fact, the yarn, in particular when made of staple fibres, is characterised by variability in linear density, while for textured yarns the cross section significantly differs from a circular cross-section. For this reason, in further stages of research on the virtual modelling of a flat textile product, a geometric model of yarn is adopted based on the spatial scanning of long sections of yarn.

The presence of the narrowings in a channel between threads leads to changes in the course of the velocity of the air stream, fluid transported through the woven fabric, or the electromagnetic radiation used. Different spatial shapes of the channels and the presence of narrowings cause a change in the conditions of flow of various media and in the capacity and effectiveness of their filtration, and significantly affect the properties of the woven fabric.

So far there have been no practical solutions.

Currently the Textile Research Institute (IW) in cooperation with Lodz University of Technology (TUL) is conducting research works on the application use of knowledge gained for evaluation of a woven fabric's structure in the 3D configuration taking into account the in-depth identification of the channels between threads, which is a new unique approach to the practical use of assessing a woven fabric's structure [13, 14].

Aim and scope of the research

The aim of this work was to develop a methodology for testing and non-invasively evaluating the structure of a woven fabric with the in-depth identification of channels between the threads in the woven fabric with a 3D configuration on the basis of a computer program for image processing and analysis.

The scope of the research included standard woven fabrics of low thickness - about 0.45 mm and surface mass reaching 180 g/m^2. A statistically significant relationship was assumed between certain tested parameters of the channel between threads in the woven fabric and the physical and mechanical properties determined.

The method developed enables to predict functional properties at the stage of designing and can help to optimise the functional properties of a flat textile product.

The research works in this field can be used to further broaden knowledge of the channels between threads and contribute to a more complete assessment of the structure of flat textile products.

Research methodology

It was assumed that a single channel in the structure of a woven fabric be considered as a vague spatial figure. Such a solid has a base of various shapes and dimensions, and is obtained as an image as a result of light passing through the channel (projection of the spacing). Because the image obtained is distorted by numerous fibres, a binarisation of the surface shape of the channel is provided. As the observations of the channels between threads show, the solid is inclined and forms a small angle to the vertical axis. At this point we can distinguish important parameters: the height of the solid and its length corresponding to the angle of inclination of the channel. The height of the solid can be measured using a well-dimensioned calibrator, whose dimensions (X, Y, Z) will be recorded, respectively, by a computer program before the test of the woven fabric (calibration). The measuring of the angle was developed at the input to the plane of the channel and registration of its angle of inclination to the position of the vertical axis was made. The measurements of the parameters obtained and statistically processed will be used at this stage to calculate the approximate volume of a single channel and all those visible in the image. However, in the stereo-visual configuration of the overview of the channel, it refers to two images (left and right) as seen from two separate cameras [14].

Results of the measurements of the statistically significant number of channels between threads for a specific population (a series of woven fabric determined) enables to determine:

- the average number of channels
- the average surface area of the spacing
- values of brightness thresholds at the binarisation (level of brightness thresholds for binary images),
  - for parameters of the channels between threads: height of the channel, surface area of the spacing and the angle of channel deflection from the vertical position:
- minimum value
- maximum value
- average value
- standard deviaition
- variation coefficient
  - length of the channel determined on the basis of above-mentioned parameters of the channels between threads

Knowing the length of the channel, the surface area of the spacing and angle of channel deflection from the vertical position, it is possible to determine the approximate volume of a single channel and approximate volume of the channels for the whole series of woven fabrics statistically determined.

The research work was based on a computer program – Textile3D developed to test and identify the channels between threads in a woven fabric and on the development of a research method in this field, which enables to introduce a new tool for measurement and analysis of the structural parameters of a woven fabric and its evaluation. Algorithms of 3D analysis properly selected enable to significantly minimise the influence of these errors on the test results [13, 14].

This method of computer image analysis is used to clearly describe the woven fabric in regard to classical evaluation of the parameters of woven fabrics and to fully characterise a woven fabric. Measurement results of the parameters of the channels between threads determined enable to process them statistically, which accelerates evaluation of the results and enables to interpret the influence of the structure of the product on biophysical properties associated with the penetration of the medium through the product (e.g. air and water vapour, and even under additional conditions of some kinds of electromagnetic radiation) [2 - 6]. A detailed description of the whole methodology is given in [14].

Method for measuring the channel according to Textile 3D software

Before actual measurement of the channel of a given series of woven fabric in the left and right image, obtained from two separate cameras, it is necessary to calibrate according to the calibrator's dimensions in a flat and spatial configuration (x, y, z and X, Y, Z), with an accuracy of 20 μm, for a minimum of 6 points designated on the calibrator. After registration of the results of calibration, measurements of the channel are conducted after designation of a minimum of 3 points for each channel visible in the left and right image. For each image binarisation is performed by setting the threshold of brightness for the left and right images and then optionally closure is performed. The parameters of channels determined are calculated automatically. Results of the measurements were registered in a summary report. To obtain a statistically significant number of measurements, there were min. 10 measurements of channels carried out for each series of woven fabric (separately for the left and right images). This assumption allows to obtain min. 100 measurements of randomly selected channels for each series of woven fabric. The system and Texlite3D software, developed by TEXO Systems – Łódź, for a three-dimensional analysis of woven fabric was presented in [14].

Tests on the channels between threads in a 3D configuration for the selection of woven fabrics and analysis of results

Four finished standard woven fabrics (Gustav 6/150, Kornel 150K, Andromeda 150, KM 1/150) and two woven fabrics with a barrier effect against IR (91/2009, III 79/2009) were selected for tests. The selection criteria were visible or nearly visible spacings between the threads.

Microscopic images of these woven fabrics are shown in ***Figure 1***.

Microscopic images of woven fabrics selected for testing the channels between threads (***Table 1***) were made at TUL using a microscopic attachment - Irtron-μ for a size of the image (measurement area) of 1.2 × 0.9 m, with a lens and condenser of the type Cassegrain, with a range of magnification of 8 - 12×, and a CCD camera.

Characteristics of the woven fabrics according to the standard parameters and value of their indicators are presented in ***Table 1***. These woven fabrics, finished in a standard manner - subjected to chemical treatment of selected processes: mercerisation, peroxide bleaching (chemical or optical whiteness), dyeing and sanforisation, differ in their purpose of application, the composition of raw materials, weave, sett of warp and weft, filling of warp and weft, and the porosity in a 2D configuration. The woven fabrics were designed for shirts (surface mass of 100 - 125 g/m^2) and clothing (surface mass of 160 - 180 g/m^2). The composition of the woven fabrics includes 100% cotton and

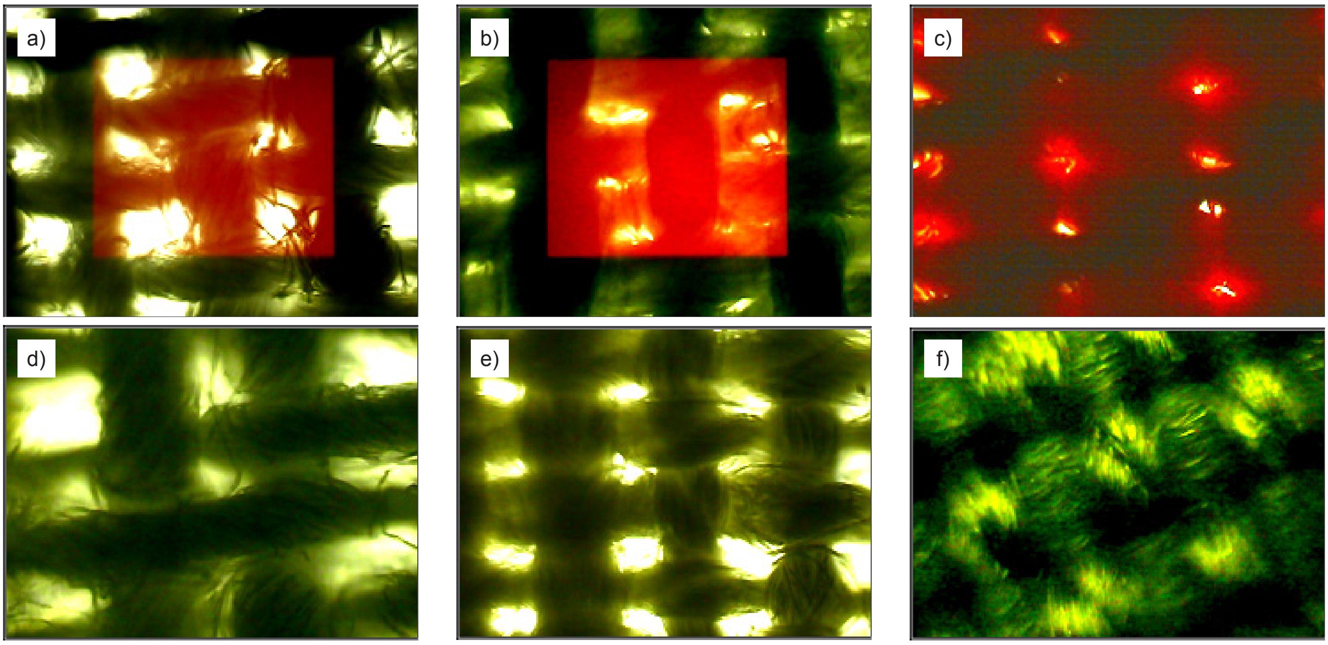

Figure 1. Microscopic images of woven fabrics selected; a) woven fabric Gustaw 6_150 PES28CO72, b) woven fabric Kornel 150k CO100, c) woven fabric Andromeda 150 CO65PES35, d) woven fabric KM 1/150 CO100, e) woven fabric 91/2009, f) woven fabric III 79/2009.

*Table 1. Characteristics of selected woven fabrics ready for use in the research; *) The tests on the thickness of woven fabrics were conducted at IW using a digital thickness gauge – MO34A, made by Atlas, with a load of 1000 Pa and foot surface of 20 cm². **) Tests were conducted at IW on measuring stand for computer analysis of 2D images, equipped with, among others, a camera - CCTV Panasonic, Textil3D application and Loo3D application.*

Series No.	Name of product	Raw materials composition	Yarn density, tex/ yarn diameter, mm	Weave	Surface mass of woven fabric, g/m²	Thickness of woven fabric* G, mm	Sett of warp/ weft, 1/dm	Filling of warp/ weft, %	Porosity 2D **), %
1	Gustaw 6/150	CO72 PES28	18.00 / 0.165	plain	100	0.27	385 / 260	117 / 79	14.1
2	Kornel 150K	CO100	18.00 / 0.170	twill 2/1 Z	120	0.33	500 / 260	130 / 67	0.8
3	Andromeda 150	CO65 PES35	25.00 / 0.200	twill 2/1 S	180	0.39	480 / 205	164 / 75	1.8
4	KM 1/150	CO100	25.00 / 0.200	twill 2/2 Y_{12}	160	0.45	340 / 190	113 / 66	19.9
5	91/2009	CO50 PES50	16.90 / 0.160	plain	125	0.28	425 / 280	132 / 87	17.7
6	III 79/2009	CO30PES70	8.74 / 0.120	trans-verse rep wave 1/1	115	0.28	425 / 520	111 / 97	9.5

blends of cotton with polyester fibres of different shares.

Table 2 summarises the measurement results of parameters of the channels between threads for selected woven fabrics according to the report of the Textile3d program.

Table 3 presents characteristics of the channels between threads for selected woven fabrics and the basic relationships determined resulting from the parameters of the channels.

For the calculations, a new coefficient of surface spacings of the woven fabric (ksi) was introduced:

$$\xi = \Delta P_p / \Delta P_c \times 100\% \qquad (1)$$

where, ΔP_p - summary surface area of the channel spacings for a series of woven fabric, ΔP_c - total surface area for a series of woven fabric.

Figures 2 - 7 present two out of the six woven fabrics tested (***Table 1***), with the graphs showing:

- histograms of distribution of the angles' orientation in the channels between threads at the input to the channel (***Figures 2***, ***5***)
- histograms of the distribution of surface areas of spacings in the channels between threads (***Figures 3***, ***6***),
- correlation of the surface areas of spacings with an orientation of angles in the channel (***Figures 4***, ***7***).

In total, there were 624 measurements conducted on the channels between threads for three channel parameters determined and for 6 different series of woven fabrics.

The average surface area of spacings for the 3D configuration (***Table 3***) is comparable to the porosity parameter for the 2D configuration (***Table 2***), while the method for determining the surface area of the spacing for the 3D configuration is more precise. Analysis of the results obtained was conducted from measurements for the same woven fabrics within the range of the height of the channel in a 3D configuration (***Table 2***) and from those of measurements of the woven fabric thickness obtained by a traditional method

*__Table 2.__ Measurement results of the channels between threads for selected channel parameters of the woven fabrics chosen according to the method developed; *) L - measurment results from the left image (camera 1), P - measurement results from right images (camera 2).*

Parameters and its factors		Gustaw 6/150	Kornel 150K	Andromeda 150	KM 1/150	91/2009	III 79/2009
Parameters of channel and its factors	Average number of channels	149	113	55	62	127	118
	Average surface area of spacing, %	7.05	1.36	0.65	15.30	10.62	5.55
	Brightness treshold L*)	209	188	208	178	187	193
	P	251	179	218	141	162	192
Length of channel Z, μm	Average value	82.21	190.6	190.2	1063	663.7	557.1
	Median	88.43	133.1	181.9	1074	609.5	580.6
	Standard deviation	84.65	221.9	94.21	87.45	165.5	95.31
	Coefficient of variation, %	103.0	116.4	49.5	8.2	24.9	17.0
Surface area of spacing P_p, μm²	Minimum value	3603	310,1	503,4	3060	2607	1383
	Maximum value	58500	36270	11580	79750	19770	12820
	Average value	20800	6937	2838	25560	10770	5066
	Median	20100	5353	2225	24590	10510	5023
	Standard deviation	9502	5441	2137	14090	3457	2267
	Coefficient of variation, %	0.457	0.784	0.753	0.551	0.321	0.447
Angle of channel deviation from vertical position α, °	Minimum value	5.694	10.82	1.717	2.984	1.690	0.567
	Maximum value	72.97	74.97	55.30	72.76	44.41	72.47
	Average value	24.77	36.51	27.28	22.21	19,30	24.49
	Median	22.34	35.66	27.40	19.38	18.43	23.10
	Standard deviation	13.19	16.170	13.97	14.92	9.200	14.15
	Coefficient of variation, %	0.532	0.443	0.512	0.672	0.477	0.578

*__Table 3.__ Characteristics of the channels between threads for woven fabrics used in the tests; *) The test on the thickness of woven fabrics was conducted at IW using a digital thickness gauge – MO34A, made by Atlas, load 1000 Pa, foot surface of 20 cm2. **) Tests were conducted at IW on a measuring stand for computer analysis of 2D images, equipped with, among others, a camera - CCTV Panasonic, Textil3d application and Loo3D application. ***) Calculation of the channel length D was based on the trigonometric function: ΔD = G / cosΔα, where: G- thickness of woven fabric, Δα –angle of channel deviation from the vertical position resulting from the measurement. ****) Approximate average volume of the channel ΔVp = ΔPp × ΔD, where Pp was taken from __Table 2__ as an average value of the surface area of the spacing.*

No.	Name of woven fabric	Woven fabric thickness *) G, μm	Porosity 2D**), %	Coefficient of spacings of woven fabric surface ξ $\Delta P_p/\Delta P_c \times 100$, %	Average height of channel ΔZ, μm	Average angle of channel deviation from the vertical position Δα, °	Average surface area of channel spacing ΔP_p, μm²	Average length of channel ***) ΔD, μm	Approximate average volume of channel ****) ΔV_p, μm³
1	2	3	4	4	5	6	7	8	9
1	Gustaw 6/150	270	14.10	7.05	82.21	**24.77**	**20800**	**297.358**	**0.0062**
2	Kornel 150K	330	0.80	1.36	190.6	**36.51**	**6937**	**410.574**	**0.0028**
3	Andromeda 150	390	1.80	0.65	190.2	**27.28**	**2838**	**438.805**	**0.0012**
4	KM 1/150	450	19.90	15.30	1063.3	**22.21**	**25560**	**486.064**	**0.0124**
5	91/2009	280	17.70	10.62	663.7	**19.30**	**10770**	**296.673**	**0.0032**
6	III 79/2009	280	9.50	5.55	557.1	**24.49**	**5066**	**307.681**	**0.0016**

(***Table 1***). There was no correlation between the height of the channel and the thickness of the woven fabric.

For calculation of the approximate length and volume of the channel, the value of thickness for each woven fabric was assumed. (***Table 3***).

The analysis of the standard deviation and coefficient of variation for selected parameters of the channel between threads: surface area of the spacing and angle of deviation of the channel from the vertical position proves the high dispersion of the results. In all cases, there was no correlation between the average surface area of the channel and the angle of inclination of the channel (***Figures 4 - 7***).

For the cases tested for the same woven fabrics, the values of the surface areas of spacings in the channels differed significantly. This channel property is confirmed by the microscopic images analysed. The angle of deviation of the channel from the vertical axis was less diverse. Comparing the values of this angle for all the woven fabrics, a median of inclination of the channel was obtained within the range of 19.30° - 36.51°.

It was stated that the values of the channels' length calculated are proportional to the thickness of the woven fabric, as well as greater than this thickness. The approximate value of the volume of the channel in the woven fabrics tested is greatly influenced by the value of the spacing area in the channel, and to a lesser extent by the channel length. It was stated that the ratio of the total surface area of the spacings in the channels to the total surface area in the image was the highest for woven fabric KM 1/150 (15.3%) and the lowest for woven fabric Andromeda 150 (0.65%). The values of the surface area of spacings in the channels and channel length obtained proportionally convert into an approximate average volume of the channel in the woven fabrics tested (0.0012 - 0.124 μm³).

Test procedure No. 98

Test procedure No. 98 "Determination of parameters of textile products using three-dimensional image analysis in the Textile 3D system" was developed for the Laboratory of Testing Textile Raw

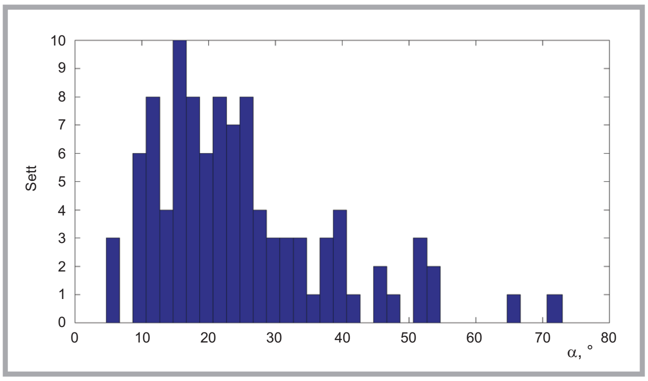

Figure 2. Histogram of distribution of the angles' orientation in the channels for Gustaw 6/150 woven fabric.

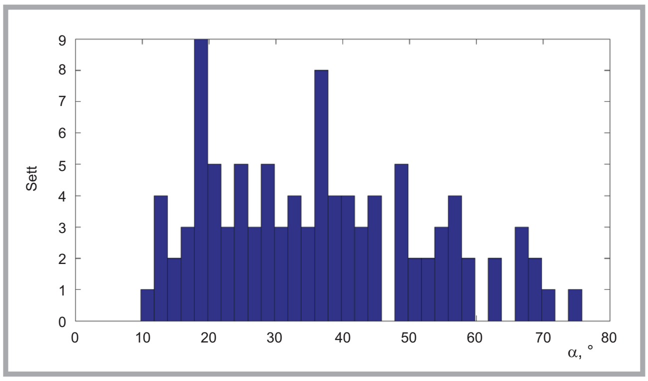

Figure 5. Histogram of the distribution of the angles' orientation in the channels for Kornel 150K woven fabric.

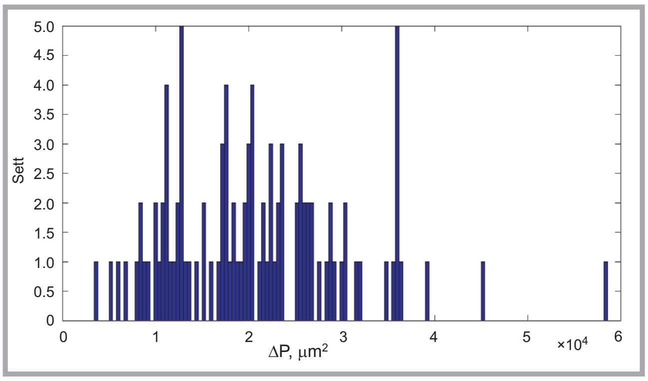

Figure 3. Histogram of the distribution of surface areas of channel spacings for Gustaw 6/150 woven fabric.

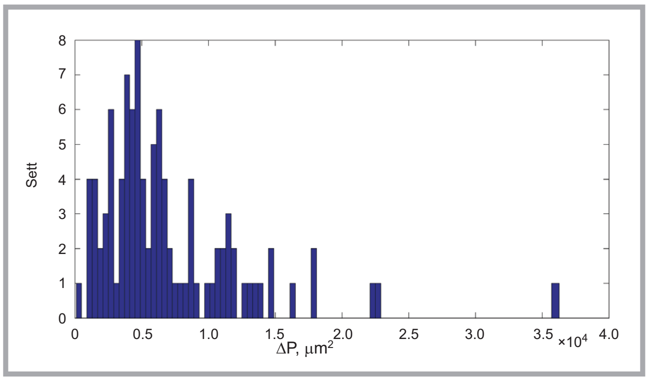

Figure 6. Histogram of the distribution of surface areas of channel spacings for Kornel 150K woven fabric.

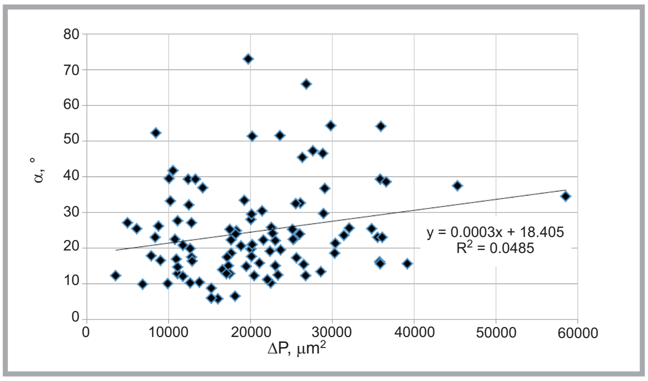

Figure 4. Correlation of the surface area of spacings and orientation of angles in the channels for Gustaw 6/150 woven fabric.

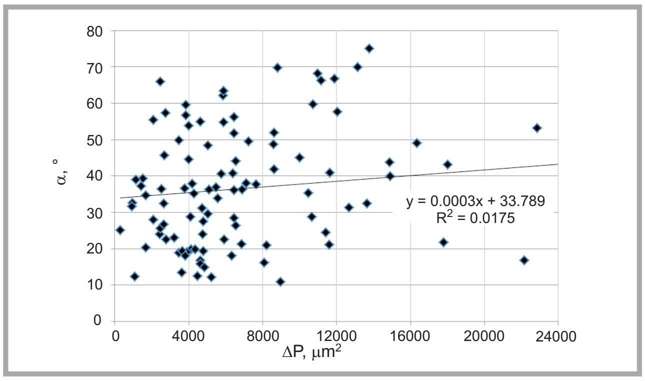

Figure 7. Correlation of the surface area of spacings and orientation of angles in the channels for Kornel 150K woven fabric.

Materials and Fabrics, IW, where a modernised research stand was installed with Texlite3D software for the three-dimensional analysis of woven fabrics.

Summary of the research and direction of further studies

1. The following parameters of the channels between threads were determined using a method developed for testing the channels:
   - height of the channel Z in μm
   - surface area of the spacing P in μm2
   - angle of channel deviation from the vertical position α in °

For a single channel and for the entire image of the woven fabric viewed, the approximate volume was calculated on the basis of the surface area of the channel's spacing and the angle of channel deviation from the vertical position, according to which the channel length was determined.

A factor for the spacings of the woven fabric surface ξ (ksi) was introduced according to ***Equation 1***, which determines the relation of the surface area of the channel spacings and the total surface area of the woven fabric considering the channels between threads in the 3D configuration.

2. For the woven fabrics tested the following relationships were found:
   - the average surface area of the spacings for the 3D configuration is comparable to the porosity parameter for the 2D configuration, while the method of determining the surface area of the spacing is more accurate for the 3D configuration,
   - the values of standard deviation and coefficient of variation for se-

lected parameters of the channels between threads: surface area of the spacing and angle of channel deviation from the vertical position prove the high dispersion of the measurement results,
- for all cases tested, there was no correlation between the size of the surface area of the channel and the angle of channel inclination,
- significantly different values of the surface area of channel spacings were obtained for the same woven fabrics. This property is confirmed by the microscopic images analysed,
- the median value of the angle of channel inclination for the woven fabrics tested ranged 19.30°-36.51°,
- the length of the channels were always greater than the thickness of the woven fabric due to the inclination of the channel,
- the approximate value of the volume of the channel depends more on that of the surface area of the spacing and, to a lesser extent, on the length of the channel; it refers to woven fabrics of a small value of thickness, within the range of 0.27 - 0.45 mm.

3. An analysis of the results of the measurements of the channels enables to refer to the differences between various woven fabrics and a greater utilisation of their properties. It is also a statement of the possibility of an appropriate programming of the voids in a woven fabric in order to limit the flow of air, moisture, and various types of electromagnetic radiation such as IR.
4. Textile3D software developed a method for testing the channels between threads for woven fabrics, and procedure No. 98 was used to study the structure and identify the channels between threads in a woven fabric in preliminary testing thereof.

   In consequence of the study conducted, there is a need to extend the research works towards the development of the channel's model for stereo-visual penetration of the channel in order to obtain a precise geometry of spatial figures of these channels.

Conclusions

1. A new tool for measuring and analysing the structural parameters of fabric and its evaluation was introduced. This will broaden the scope of research on flat textile products and will also automate and significantly shorten research in the field.
2. The testing method proposed and characteristics of the channels between threads enable to compare woven fabrics with a low value of thickness and surface mass and also to predict the parameters of woven fabrics which affect their properties in a manner not previously used.
3. The approximate average volume of the channel calculated can be used in various comparative studies of standard woven fabrics designed for shirts and apparel products, differing in their purpose, the composition of raw materials, weave, sett of warp and weft, warp and weft filling, surface mass and thickness.
4. Analysis of spatial solids in channels between the threads of flat textile products can be of great help for better application of the structural characteristics of woven fabric, for example when considering the flow of air, moisture and for obtaining a sufficient level of the barrier effect of woven fabrics against various types of electromagnetic radiation such as IR. However in this case, additional careful analysis should be performed, as taking into consideration IR radiations, different phenomena occur, depending on many factors. It may also contribute to an increase in the applicable properties of woven fabrics designed for clothes for athletes and people staying in extreme weather conditions or extreme work environment.
5. A continuation of the research on the channels between threads is anticipated in order to optimise the measurement method of the channels to extent the research of other flat textile products and to create a model of the channel between threads, as well as order to improve the accuracy of determination, and to make the measurements fully automatized, which could be used in further applicable studies. Experimental verification of the concepts proposed is expected to be conducted in the future.

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