Mirosław Polipowski[1,*], Piotr Więcek[2,3], Bogusław Więcek[3], Anna Pinar[1]

Analysis of the Effect of Channel Parameters between Filaments and Single Fabric Parameters on Air Permeability, Water Vapour Resistance and Thermal Resistance

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[1] **Textile Research Institute,**
ul. Brzezińska 5/15
92-103 Łódź, Poland
* E-mail: polipowski@iw.lodz.pl

[2] **Texo Systems,**
ul. Gorkiego 24/44
92-524 Łódź, Poland

[3] **Technical University of Lodz, Institute of Electronics**
Łódź, Poland

Abstract

The work presented is a continuation of research on the interthread channels of single fabric taking into account the parameters of fabric structure. The stereographic method of three-dimensional structure analysis of a single fabric, the method of 3D microscopy of fabric fragments in structural light and analysis of microscopic images of the 4th generation were introduced. Statistical analysis of the air permeability, water vapour resistance and thermal resistance indicators for flat textile products showed significant dependences of these flow rates on channel parameters as well as other fabric parameters. The correlation between the parameters measured and the flow indicators was determined. Very strong correlations of the air permeability indicator were found with the channel clearance area, warp count and approximate channel volume. A strong correlation with the thickness of fabrics was obtained for the water vapour resistance indicator. For heat resistance there was a strong correlation with the diameter of channel inlets. Strong correlations between fabric parameters and channel parameters were obtained for the channel clearance area and approximate channel volume, warp and channel ground area, weft count and fabric thickness, channel inlet diameter, and fabric thickness.

Key words: *Air permeability, water vapor flow, thermal resistance, ANOVA, inter-yarn channel parameters.*

Introduction

The complex spatial layout of the product structure in the form of a large number of channels of varying size and distribution in fibre and interthread systems makes it difficult to describe the transport of air, moisture and heat. A flat textile product, due to the nature of its destination, should fulfill a number of functions, the most important of which is to protect against adverse climatic conditions and to provide usable physiological comfort.

For most cases, according to prof. J. Szosland, the following describe the basic structure of fabric: the weave, weft and warp diameter or the linear masses of these threads, the density of the warp and weft, the thickness of the product or its surface mass [1-3]. The analysis of solids in fabric interthread channels indicates significant differences in such objects and is important not only for air permeability, water vapour and heat resistance but also for barriers against various types of electromagnetic radiation such as IR and UV and the textile filtration state [1, 2, 4-9].

There are considerable differences between the analytical descriptions of model and real fabric systems. When used, fabric undergoes stretching and shrinking, resulting in different shapes of spatial channels that significantly alter the actual usable conditions resulting from the fabric construction [1]. When considering flows, the type of yarn is important, i.e. the yarn making method, the raw material composition, the linear mass (yarn diameter), the linear mass irregularity, the twist and its distribution, and the hairiness. The theoretical model of a flat textile structure is based on the ideal model of circular yarn and homogeneous compact design. In practice, yarns, in particular made of staple fibres, are characterised by linear mass variations and the cross-section deviates significantly from the circular cross-section. In the field of virtual modelling of a flat textile product, a geometric model of yarn is often adopted, based on spatial scanning of long yarns [10]. The existence in the interthread channels of narrowings leads to, among others, changes in the velocity of the medium transported by the fabric [1-3, 6].

Recognition and identification of spatial objects that form interstitial channels in fabric is important not only for air, moisture and heat flow, but they can also be used in in-depth structural analysis, for example, in the fabrication of textile barriers for various types of adverse electromagnetic radiation, the textile filtration state, and imparting various properties to the fabric. [5-9].

Table 1. Basic characteristics of finished fabrics subjected to testing, technological parameters of single fabrics [20].

No.	Name of the fabric	Raw materials composition	Weave	Yarn linear density, tex	Yarn diameter, mm (± 0.01)	Surface mass of the product, g/m² (±6.0)	Thickness of the product G, mm (± 0.01)	Sett of warp/ weft (density), 1/dm (±8.0)	Warp/ weft Filling, %	Porosity 2D, %
1	Gustaw 6/150	CO72 PES28 warp weft	plain	18.0 18.0	0.165 0.165	100	**0.27**	385/260	117/79	14.1
2	Kornel 150K	CO100 warp weft	twill (course) 2/1 Z	18.0 18.0	0.168 0.168	120	**0.33**	500/260	130/67	0.8
3	Andromeda 150	CO65 PES35 warp weft	twill (course) 2/1 S	19.5 40,0	0.150 0.32	180	**0.39**	480/205	164/75	1.8
4	KM 1/150	CO100 warp weft	Angled twill 2/2 Y_{12}	22.2 38.8	0.190 0.290	160	**0.45**	340/190	113/66	19.9
5	91/2009	CO50 PES50 warp weft	plain	8,0x2 17,5/96f	0.158 0.162	125	**0.28**	425/280	132/87	17.7

Table 2. Summary of averages of parameters of fabrics and parameters of interfilament channels.

Fabric/Indicators and parameters	Gustaw 6/150	Kornel 150K	Andromeda 150	KM 1/150	91/2009
Air permeability R, mm/s	642.3	179.4	80.1	802.9	313.2
Water vapour resistance R_{et}, m²Pa/W	2.13	2.90	3.09	2.79	2.25
Thermal resistance R_{ct}, m² K/W	0.0026	0.0016	0.0028	0.0012	0.0035
Diameter of input into channel, mm	0.245	0.311	0.328	0.489	0.206
Fabric thickness, mm	0.27	0.33	0.39	0.45	0.28
Density of warp, 1/dm	385	500	480	340	425
Density of weft, 1/dm	260	260	205	190	280
Spacing (clearance) surface area, μm²	20 800	6 937	2 838	2 5560	10 770
Angle of channel inclination, °	24.77	36.51	27.28	22.21	19.30
Approximate volume of channel V_p, mm³	0.0062	0.0028	0.0012	0.0124	0.0032

Flow studies among flat textile products have been the subject of numerous analyses, studies and publications. Recent research confirms the experience gained so far and the application of new test methods to the requirements of modern products [11-17]. For example, the impact of the distance construction of a shoe insert and its thickness on the value of air permeability and heat conductivity was determined. Soft layer inserts are recommended for increased foot padding. The basis of the study was the analysis of a 3D image of the layered structure of inserts. Polyester matrix inserts with good cushioning, air permeability and heat conductivity were made for the tests. The middle layer consisted of polyester monofilament yarns, which determined the thickness of the material, and the two outer surfaces of the knitwear were made of polyester yarn, which gave the closed and open structure of the liner. The comfort of the distance knitwear was tested by measuring the air and water vapour permeability and thermal properties depending on the porosity of the product. One-way analysis of variance was used to evaluate the thickness of the knit and its surface structure. Experimental results indicate that the distance between the two outer layers of the insert and the pore dimension in the product determine the properties of air permeability, water vapour and thermal conductivity. Higher porosity knitwear shows high air and water vapour permeability. Depending on the thickness and structure of the locknit fabric, differences in air and water vapour permeability were obtained. It was found that the thickness of knitted fabric of hexagonal structure showed optimum air and water vapour permeability and lower thermal conductivity [15]. In another work [16] it was found that the transport of water vapour through textile structures is complex and associated with many factors such as the porosity of the fabric structure (size and distribution of pores), product thickness, fibre properties and yarn.

Based on the mechanisms of water vapour permeability of porous textile materials, the coefficient of water vapour permeability was developed. A prognostic model was developed that describes the transport of water vapour through the fabric using critical parameters. Statistical analyses were conducted to examine the relationship between the above, as well as fabric parameters and the water vapor permeability index. These analyses showed that the fabric thickness, plurality, warp and weft, pore diameter and fibre type influenced the flow of water vapour through the fabric. The correlation coefficient for a separate set of final model parameters was 0.97. Under the experimental conditions described, the impact of yarn spinning and fibre packing was negligible and significant at 5% [16]. In clothing design, comfort is an important parameter. Numerous factors influencing the thermal performance of garments were identified: Thermal insulation, moisture and water transfer through clothing and heat exchange. The thermal comfort characteristics of two different specially designed left and right weave knit fabrics were investigated. The properties of knitwear in terms of air permeability, water vapour and thermal resistance were tested. In addition to assessing the impact of yarn and knitwear, the effect of dyeing knitwear on flow properties was studied. It was found that the values of the air permeability and thermal resistance index were lower after the dyeing process and that the thermal conductivity index value increased. The structure of fabric of the pique type made of polyester yarns has a higher air permeability index and higher moisture absorption at lower temperatures [17].

Due to the lack of comprehensive application methods for the examination of the structure of flat textiles, a research experiment was carried out on the application of non-invasive methods of examining the structure of a single fabric, not yet used in the textile industry. For identification of interthread channels, the parameters of the channel were defined and the relationships between the basic parameters of the fabric and the parameters of the interthread channel were determined. The influence of the values of channel parameters and actual fabric parameters on those of air permeability, water vapor resistance and heat resistance [18-21] was investigated.

Research material

The purpose of the study was to analyze the influence of the size and distribution of interthread channels and the parameters of single fabric on the values of air permeability, water vapour resistance and thermal resistance of fabrics and to establish mutual statistical correlations.

The physical-mechanical parameters of the fabrics selected and the parameters of the interthread channels were used for the purpose of the research. The scope of the study included single polyester-cotton fabrics made of yarns with different proportions of polyester fibres and cotton. The woven fabrics differed in composition, type of weave, surface weight, thickness, density of warp and weft (***Table 1***), the size of the interthread channel volume, the channel clearance area and angle of channel inclination (angle of channel spatial orientation) – ***Tables 1*** and ***2***.

Research methodology

Research methodology was based on:
1. Examination of physical-mechanical parameters of single fabrics and their analysis, resulting from previous works [20].
2. Examination of fabric interthread channels with the use of the stereographic method, 3D microscopy in structural light and analysis of microscopic images, resulting from previous works [18-21].
3. Measurement of air permeability, water vapour resistance and thermal resistance indicators for single fabric with analysis of first-rank statistical indicators.
4. Statistical analysis of flow indicators for fabrics with known characteristics (parameters) and parameters of interthread channels.

Table 3. *Summary of test results of fabric's air permeability indicator R and values of first-rank statistical parameters.*

Ordinal No.	Products statistical parameters	Gustaw 6/150 CO72 PES28	Kornel 150K CO100	Andromeda 150 CO65 PES35	KM 1/150 CO100	91/2009 CO50 PES50
1	Air permeability indicator R, mm/s	591	175	74.2	812	317
2		618	181	78.9	841	325
3		657	172	76.5	810	320
4		658	178	79.4	809	301
5		664	187	79.4	796	303
6		648	185	81.3	794	–
7		631	180	83.0	789	–
8		636	181	84.2	765	–
9		659	178	82.2	804	–
10		661	177	81.7	809	–
	Minimum value	591.0	172.0	74.2	765.0	301.0
	Maximum value	664.0	187.0	84.2	841.0	325.0
	Average	642.3	179.4	80.1	802.9	313.2
	Median	652.5	179.0	80.4	806.5	317.0
	Range	73	15	10	76	24
	Standard deviation	23.533	4.452	3.052	19.485	10.640
	Coefficient of variation, %	3.7	2.5	3.8	2.4	3.4
	Skewness	1.304	1.780	-0.689	-0.024	-0.299
	Kurtosis	1.228	-0.036	0.070	2.063	-2.663
	Variance, %	553.80	19.82	9.31	379.70	113.20

Table 4. *Summary of test results of the water vapor resistance indicator R_{et}, water vapor permeability W_d, and values of the first-rank statistical parameters.*

Ordinal No.	Products statistical parameters	Gustaw 6/150 CO72 PES28	Kornel 150K CO100	Andromeda 150 CO65 PES35	KM 1/150 CO100	91/2009 CO50 PES50
1	Indicator of water vapor resistance R_{et}, m²Pa/W	2.01	2.90	2.93	2.78	2.31
2		2.22	2.86	2.96	2.78	2.19
3		2.17	2.96	3.07	2,83	2.26
4		2.13	2.92	3,20	2.74	2.23
5		2.13	2.88	3,27	2.84	2.25
	Minimum value	2.01	2.86	2.93	2.74	2.19
	Maximum value	2.22	2.96	3.27	2.84	2.31
	Average	2.13 ±0.06	2.90 ±0.04	3.09 ±0.14	2.79 ±0.04	2.25 ±0.06
	Median	2.13	2.9	3.07	2.78	2.25
	Range	0.21	0,1	0.34	0.1	0.12
	Standard deviation.	0.078	0.038	0.148	0.041	0.044
	Standard error	0.035	0.017	0.066	0.018	0.020
	Coefficient of variation, %	3.64	1.33	4.79	1.47	1.95
	Skewness	-0.963	0.590	0.247	-0.115	0.194
	Kurtosis	1.781	-0.022	-2.336	-1.473	0.890
	Variance, %	0.006	0.001	0.022	0.002	0,002
	Water vapor permeability W_d, g/m²Pa *h	0.699	0.513	0.482	0.532	0.662

Table 5. Summary of test results of the thermal resistance of fabric R_{ct} and values of first-rank statistical parameters.

Ordinal No.	Fabric/ Statistical indicators	Gustaw 6/150 CO72 PES28	Kornel 150K CO100	Andromeda 150 CO72 PES28	KM 1/150 CO100	91/2009 CO50 PES50
1	Indicator of thermal resistance R_{ct}, m^2 K/W	0.0024506	0.0020210	0.001300	0.00090	0.00350
2		0.0020279	0.0013563	0.002711	0.00070	0.00500
3		0.0030929	0.0016636	0.002569	0.00200	0.00420
4		0.0030929	0.0010747	0.003624	0.00100	0.00350
5		0.0027110	0.0022370	0.001771	0.00050	0.00340
	Minimum value	0.00203	0.00107	0.0013	0.0010	0.0034
	Maximum value	0.00309	0.00224	0.0036	0.0020	0.0050
	Average	0.0026 ±0.0004	0.0016 ±0.0004	0.0028 ±0.0018	0.0012 ±0.0004	0.0035 ±0.0006
	Median	0.003	0.002	0.003	0.001	0.003
	Range	0.001	0.001	0.003	0.001	0.001
	Standard deviation	0.001	0.001	0.001	0.001	0.001
	Standard error	0	0	0.001	0	0
	Coefficient of variation, %	21.066	34.233	46.566	37.268	16.109
	Skewness	-0.609	-0.609	-0.541	2.236	0.609
	Kurtosis	-3.333	-3.333	-1.488	5,000	-3.333-
	Variation, %	10^{-6}	10^{-6}	10^{-6}	10^{-6}	10^{-6}

Examination of air permeability, water vapour resistance and thermal resistance indicators of fabric

Flow tests for fabrics were conducted at the Accredited Laboratory of Testing Raw Materials and Fabrics, IW, the results of which are presented in ***Tables 3, 4*** and ***5***. Measurement uncertainty was determined according to document [23] and constitutes an expanded uncertainty, with 95% confidence and coverage factor k = 2 [24]. The population of measurement tests for fabric and the parameters of the interthread channels presented differ (significantly lower) from the population of the measurement tests according to previously conducted research [19-21]. The randomly selected numbers of measurement parameters were adequate to those of flow indicator measurements, i.e. from 5 to 10 partial measurements for each parameter and each fabric sample (***Tables 3-5***).

Examination of air permeability indicator of fabric

Examination of the air permeability indicator R (mm/s) in fabric (***Table 1***) was performed according to Standard [22]. Climatic conditions of measurement: temperature $T_a = (21.0 \pm 0.1)$°C, relative humidity of the air R.H.(65.0 ± 3.0)%, pressure drop 100 Pa, surface area of test sample 20 cm^2, and number of measurements 5-10 for each sample. A collective summary of measurement results of fabric air permeability with the value of the first-rank statistical indicators is presented in ***Table 3***.

The dominant factor influencing the value of the air permeability indicator was the size of the channel clearance surface area and approximate channel volume. For example, in the case of Andromeda fabric having a compact structure with a few, small volume channels between threads, the median of the air permeability indicator amounted to R = 80.4 [mm/s]. However, for KM fabric with a significant volume of channels between threads and loose spaces in the interthread channels in yarn (in microscopic images), the median of the indicator discussed amounted to R = 806.5 [mm/s] and was approx. 10 times higher in comparison with Andromeda fabric. The median value and average value of the air permeability indicator for particular fabrics were at the approximated level and standard deviation constituted the level of measurement uncertainty of the values analyzed. Statistical value distributions of the fabric's air permeability were directly proportional to the volume of interthread channels [20].

Examination of water vapour resistance of fabric

The appointed fabrics (***Table 1***) underwent examination of water vapor resistance R_{et} (m^2Pa/W); measurements were made according to Standard [25]. The climatic conditions of measurement were as follows: temperature $T_a = (21.0 \pm 0.1)$°C, relative humidity of the air R.H.(65.0 ± 3.0)%, average velocity of air flow 1.0 m/s, and number of measurements n = 5 for one sample. A collective summary of measurement results of the fabric's water vapour resistance and water vapor permeability W_d (g/m^2Pa *h) with the value of the first-rank statistical indicators are presented in ***Table 4***. Water vapour permeability resulted from calculations according to the measurement conditions in relation to water vapour resistance. The stream of heat of vaporisation may consist of diffusion and drift. Water vapor resistance is a characteristic value for textile materials specifying "the latent" stream of heat of vaporisation flowing throughout the given surface with the effect of maintaining a constant difference of water vapour pressure [25]. During the measurement of water vapor resistance, the molecules of water vapour penetrate the structure of the fabric and full it, due to the effect of the raw material type and character of the structure. The fabric consists of cotton yarn and polyester yarn with various proportions of cotton. In the research presented, cotton shows high moisture absorption whereas polyester yarns have hydrophobic properties. The properties of yarns significantly influence the test results of the fabric's water vapour resistance.

The volume of the cotton component proportion in the fabric and its structure proved to be a dominant factor influencing the value of the water vapour resistance indicator.

For Kornel and KM fabrics (100% cotton proportion), values of the water vapor resistance indicator were higher and at the approximated level (***Table 3***). Standard deviation was at a lower level and measurement uncertainty of the water vapour resistance value was low.

Values of the air permeability indicator refer more to the size of the channel clearance area and approximate volume of the channel (***Table 3***).

Examination of thermal resistance of fabric

The appointed fabrics (***Table 1***) underwent examination of thermal resistance R_{ct} (m^2 K/W) in accordance with Standard [25]. Climatic conditions of the measurement were as follows: temperature $T_a = (21.0 \pm 0.1)$°C, relative humidity

Table 6. Summary of the correlation of fabric parameters and interfilament channel parameters. ***Note:*** *Indications, units of indicators and parameters in **Table 6** correspond to the description set in **Table 2**.*

	Air permeability	Water vapor resistance	Thermal resistance	Diameter of input	Fabric thickness	Density of warp	Density of weft	Spacing surface	Angle of channel inclination	Approx. volume
Air permeability	1									
Water vapor resistance	0.4457063	1								
Thermal resistance	0.4189485	-0.4740546	1							
Diameter of input	0.4555681	0.5884267	-0.8278537	1						
Fabric thickness	0.1996796	0.7495526	-0,6451971	0.9412784	1					
Density of warp	-0.9591130	0.4681889	0.2285978	-0.4135862	-0.2273923	1				
Density of weft	-0.2483276	-0.6684294	0.5330347	-0.8813131	-0.9440829	0.2930357	1			
Spacing surface	0.9991827	-0.4602267	-0.4244324	0.4408344	0.1775650	-0.9512853	-0.2180119	1		
Angle of channel inclination	0.4903510	0.5419805	-0.4473628	0.0437107	0.0149163	0.7077519	0.06063831	-0.4751848	1	
Approx. volume	0.9386929	-0.1445531	-0.6254684	0.7134742	0.4946665	-0.8976303	-0.47323156	0.9354156	-0.3900135	1

of the air R.H.(65.0 ± 3.0)%, and number of measurements n = 5 for one sample. A collective summary of measurement results of the fabric's thermal resistance with the value of first-rank statistical indicators are presented in ***Table 5***. During the measurement, the dry thermal stream may consist of one or more components: thermal convection (carryover), thermal conduction and thermal radiation. Thermal resistance is a characteristic value for textile materials, determining the flow of dry thermal stream through a given surface, as a result of maintenance of the constant difference in temperature [25]. Measurements of thermal resistance were carried out without air exchange. The type of raw material and structure of fabric influence the test results. In the results presented, the raw material composition of cotton yarn and polyester yarn with different proportions of cotton in the fabric is essential.

The increase in the accuracy of thermal resistance indicator measurements (the number of decimal places R_{ct}) was used to construct correlation graphs in a precise manner. The dominant factor influencing the volume of the thermal resistance indicator, similar to water vapor resistance, was the proportion of the cotton compound in the fabric and the structure of the fabric. Standard deviation was at a low level, and the measurement uncertainty of values of the thermal resistance indicator analysed was reduced.

Statistical analysis of findings

Evaluation of measurement results was based on one-factor analysis of variance (statistic F), which in this case is the statistical test, to compare the averages of many populations. In one-factor analysis

*Table 7. Summary of results of one-factor analysis of variation of air permeability (reference to **Table 5**).*

Groups	Lot size	Sum	Average	Variation		
Gustaw 6/150	10	6423	642.30	553.7889		
Kornel 150K	10	1794	179.40	19.82222		
Andromeda 150	10	800.8	80.08	9.312889		
KM 1/150	10	8029	802.90	379.6556		
91/2009	5	1566	313.20	113.20		
ANALYSIS OF VARIATION						
Variation source	**SS**	**df**	**MS**	**F**	**Value – p**	**$F_{tab.}$, α = 0.05**
Among groups	3749835	4	937458,7	4113.458	0	2.605975
Within groups	9116.016	40	227.9004			
Total	3758951	44				

*Table 8. Summary of results of one-factor analysis of variation of water vapour resistance (reference to **Table 5**).*

Groups	Lot size	Sum	Average	Variation		
Gustaw 6/150	5	10.66	2.132	0.00602		
Kornel 150K	5	14.52	2.904	0.00148		
Andromeda 150	5	15.43	3.086	0.02183		
KM 1/150	5	13.97	2.794	0.00168		
91/2009	5	11.24	2.248	0.00192		
ANALYSIS OF VARIATION						
Variation source	**SS**	**df**	**MS**	**F**	**Value – p**	**$F_{tab.}$, α = 0.05**
Among groups	3.518984	4	0.879746	133.5782	0	2.866081
Within groups	0.13172	20	0.006586			
Total	3.650704	24				

*Table 9. Summary of results of one-factor analysis of variation of thermal resistance (reference to **Table 5**).*

Groups	Lot size	Sum	Average	Variation		
Gustaw 6/150	5	0.013375	0.002675	0		
Kornel 150K	5	0.008353	0.001671	0		
Andromeda 150	5	0.011975	0.002395	0		
KM 1/150	5	0.00510	0.001020	0		
91/2009	5	0.01960	0.003920	0		
ANALYSIS OF VARIATION						
Variation source	**SS**	**df**	**MS**	**F**	**Value -p**	**$F_{tab.}$, α = 0.05**
Among groups	0	4	0	14.70878	0	2.866081
Within groups	0	20	0			
Total	0	24				

Table 10. *Summary of results of one-factor analysis of variation of channel spacing surface area (reference to* ***Table 5****).*

Groups	Lot size	Sum	Average	Variation		
Gustaw 6/150	10	201363.10	20136.314	78576972		
Kornel 150K	10	31219.52	3121.952	3997806		
Andromeda 150	10	25416.30	2541.630	3142529		
KM 1/150	10	313722.60	31372.263	0		
91/2009	10	96387.58	9638.758	9505343		
ANALYSIS OF VARIATION						
Variation source	**SS**	**df**	**MS**	**F**	**Value -p**	**F_{tab}, α = 0.05**
Among groups	0	4	0	9.399889	0	2.578739
Within groups	0	45	0			
Total	0	49				

Table 11. *Summary of results of one-factor analysis of variation in the angle of channel inclination (reference to* ***Table 5****).*

Groups	Lot size	Sum	Average	Variation		
Gustaw 6/150	10	184.928	18.493	23.33962		
Kornel 150K	10	388.496	38.850	252.0488		
Andromeda 150	10	259.638	25.964	243.9764		
KM 1/150	10	267.011	26.701	369.7981		
91/2009	10	247.396	24.740	44.98308		
ANALYSIS OF VARIATION						
Variation source	**SS**	**df**	**MS**	**F**	**Value -p**	**F_{tab}, α=0.05**
Among groups	2190.451	4	547.6128	2.931088	0.030871	2.578739
Within groups	8407.314	45	186.8292			
Total	10597.77	49				

of variance, only one factor is available; in this case it is the arithmetical mean value of the flow indicator or the value of the fabric parameter or interthread channel parameter. It was also tested if the single factor has an impact on the dependent variable measured. Moreover it was found that this factor (dependent variable) takes, in these case, the form of the type of fabric. One-factor analysis of variance is treated as the "extension" of the t-Student test, which has application only in testing the differences between the two groups. The analysis of one-factor variance in the ANOVA method does not have such limitations and is used to compare more than two groups. The analysis of calculated variation is the ratio between the groups tested and the average variance observed within groups. This analysis is a statistical method which makes it possible to split the variability observed (variance) into separate parts. The variance for each factor evaluated as well as the error variance were analysed.

The averages of parameters of the evaluated fabrics and parameters of interthread channels are matched in ***Tables 1*** and ***2***, while interdependencies of their correlations are compared in ***Table 6***.

For one-factor analysis of variation, the following hypotheses were considered: zero hypothesis H_0 (all averages are equal to, H_0: $\mu_1 = \mu_2 = \mu_3 = \ldots \mu_k$) and alternative hypothesis H_1 (there is at least one pair of averages which differs H_1: $\mu_i \neq \mu_j$, i, j = 1, 2, …k, i≠j), where the "k" symbol means the number of groups of measurement result values of the given parameter – the number of fabrics examined. The value of statistic F-Snedecor was calculated (the so called empirical factor $F_{tab.}$), the critical value from the F-Snedecora distribution for a significance level indicated (α = 0,05), and the number of degrees of freedom determined (df_1 = k-1 and df_2 = N-k), where "N" is the number of all measurements of the given parameter (for each groups). If $F \geq F_{tab}$ – then the zero hypothesis is rejected, which forms a basis to state that there is at least one pair of averages that differs. Therefore the experimental factor has a statistical influence on the feature. In the case presented, the values of flow indicators depend on the type of fabric (fabric parameters and interthread channel parameters). Otherwise there are no grounds to reject H_0.

For the ***Tables 7-11*** the following symbols with explanations were entered:

SS_1 – sum of square deviations among groups, ***Equation (1)***,

SS_2 – sum of square deviations within groups, ***Equation (2)***,

$$SS_1 = \frac{\left(\sum_{i=1}^{N_1} x_{i,1}\right)^2}{N_1} + \frac{\left(\sum_{i=1}^{N_2} x_{i,2}\right)^2}{N_2} + \cdots$$

$$\cdots + \frac{\left(\sum_{i=1}^{N_k} x_{i,k}\right)^2}{N_k} - \frac{\left(\sum_{m=1}^{k} \sum_{i=1}^{N_k} x_{i,m}\right)^2}{N} \quad (1)$$

$$SS_2 = \sum_{m=1}^{k} \sum_{i=1}^{N_k} x^2{}_{i,m} - \frac{\left(\sum_{i=1}^{N_1} x_{i,1}\right)^2}{N_1} -$$

$$- \frac{\left(\sum_{i=1}^{N_2} x_{i,2}\right)^2}{N_2} - \cdots - \frac{\left(\sum_{i=1}^{N_k} x_{i,k}\right)^2}{N_k} \quad (2)$$

df – number of degrees of freedom, df_1 – number of groups, i.e. 5-1 = 4, df_2 – number of populations – number of groups, for example 45 – 5 = 40.

MS – average values of square deviations

$$MS_1 = SS_1/df_1 \ i \ MS_2 = SS_2/df_2 \quad (3)$$

Empirical value of statistic F-Snedecor amounts $F = MS_1/MS_2$. Symbol "p" means the empirical level of significance level.

For the cases presented, $F > F_{tab.}$ (***Tables 7-11***), the values of parameters measured (air permeability indicator, resistance of water vapor flow indicator, thermal resistance indicator, spacing surface area indicator, angle of channel inclination indicator) for the fabric differ significantly from each other at a the significance level of 0.05. For most parameters (air permeability indicator, resistance of water vapor flow indicator, thermal resistance indicator, spacing surface area indicator) these differences are significant for a value of the significance level lower than 0.05.

Research results discussion

The graphs (***Figures 1-5, Table 6***) show the significant correlations of the influence of parameter values of interthread channels and fabric parameters on the air permeability, water vapor resistance and thermal resistance, resulting from previous calculations (***Table 6***). The figures show very strong correlations of air permeability with the spacing surface area of channels (|R| = 0.999) – graph 1, the approximate volume of channel (|R| = 0.939) – graph 2, and the warp density (R = -0.959) – graph 3. It was stated that there is a lack of correlation of air permeability with fabric thickness (|R| = 0.199) in the limited range of fabric thickness evaluated 0.27-0.45 mm.

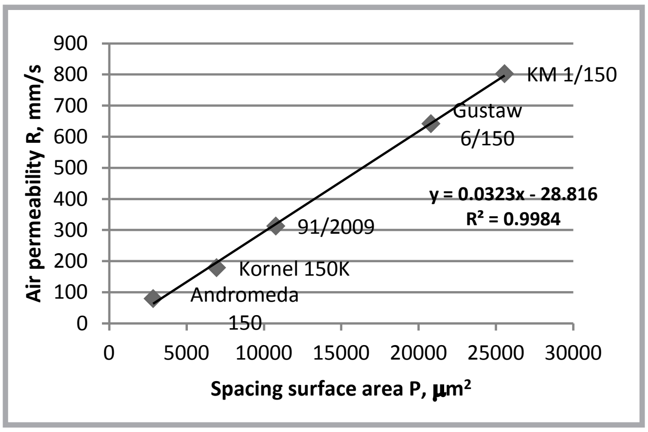

Figure 1. Linear correlation indicator of air permeability and channel spacing surface area for fabrics examined.

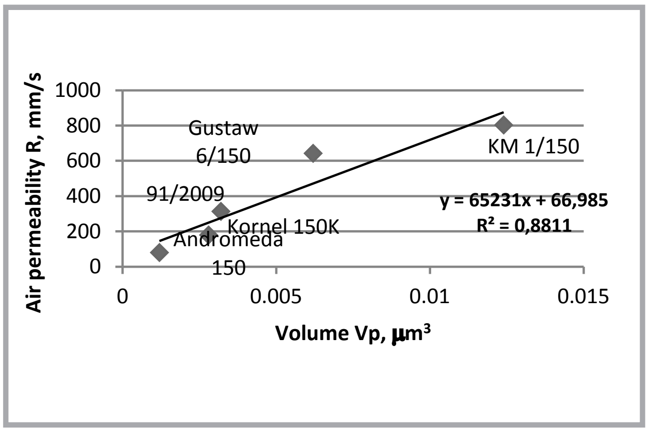

Figure. 2. Linear correlation indicator of air permeability and approximate volume of the channel for the fabrics examined

A strong correlation with fabric thickness was obtained for water vapor resistance (R = -0.749) – ***Figure 4***. Others correlations between the parameters evaluated and indicators achieved a medium level. No correlation (R = -0.145) was found for water vapor resistance with the approximate volume of interthread channels.

From the analysis of the thermal resistance indicator, a strong correlation with the diameter of interthread channel inlets (R = -0.828) – ***Figure 5*** was noted.

The correlations between fabric parameters and interthread channel parameters are as follows: A very strong correlation was obtained for the channel spacing (clearance) surface area and approximate volume of the channel (R = -0.935), as well as for the density of warp and the channel spacing surface area (R = -0.951), for the density of weft and fabric thickness (R = -0.944) and also for the diameter of channel inlets and fabric thickness (R = -0.941). No correlation was found for the fabric thickness and channel spacing surface area (R = -0.178) nor for the fabric thickness and angle of channel inclination (R = -0.015). The analyses of flow indicators tested within mutual relations showed a medium level of correlation (|R| > 0,400).

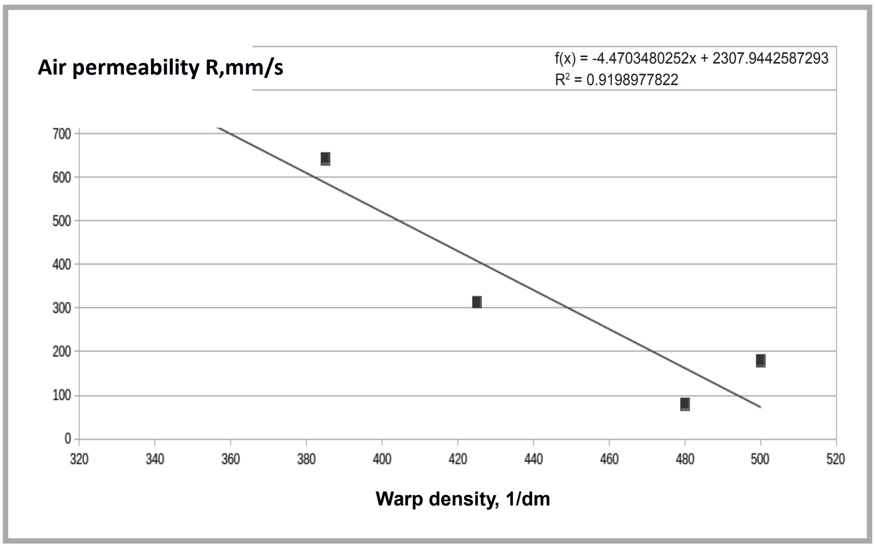

Figure 3. Linear correlation indicator of air permeability and warp density for fabrics examined [4].

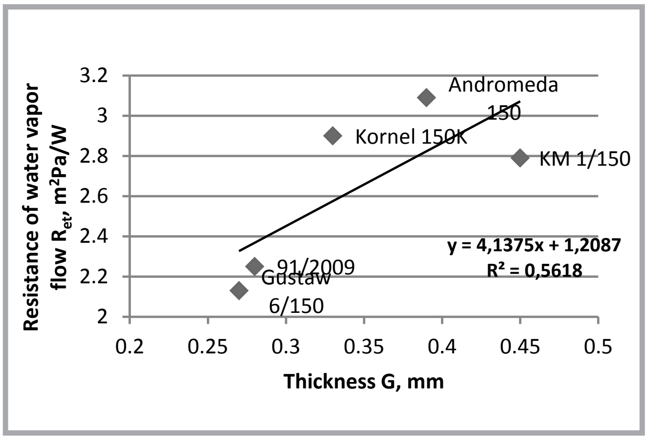

Figure 4. Linear correlation indicator of water vapour resistance and thickness for fabrics examined.

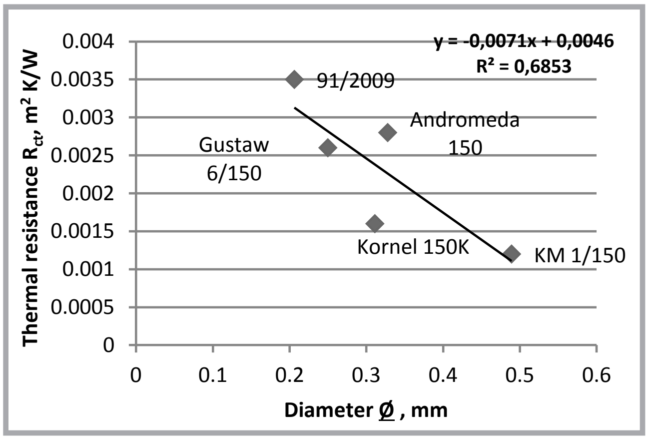

Figure 5. Linear correlation indicator of thermal resistance and diameter of channel inlets for fabrics examined.

Conslusions

- Due to the lack of comprehensive application methods for the examination of the structure of flat textiles, the research experiment was carried out with the application of non-invasive methods of examining the structure of a single fabric not yet used in the textile industry.
- For identification of interthread channels, the parameters of the channel were defined and the relationships between the basic parameters of the fabric and the parameters of the interthread channel were determined. The influence of the values of channel parameters and actual fabric parameters on the values of air permeability, water vapor resistance and heat resistance was investigated.
- The statistical analysis of the air permeability, water vapor resistance and thermal resistance indicators showed significant dependences of these flow rates on the interthread channel parameters as well as on other fabric parameters. The correlation between the parameters measured and the flow indicators was determined. Very strong correlations of the air permeability indicator were found with the channel clearance area, as well as of the density of warp (count) and the approximate channel volume. A strong correlation with the thickness of the fabrics was obtained for the water vapor resistance indicator. For heat resistance there was a strong correlation with the diameter of channel inlets. Strong correlations between the fabric parameters and channel parameters were obtained for the channel clearance surface area and approximate channel volume, the density of warp and channel clearance surface area, the density of weft and fabric thickness, and for the channel inlet diameter and fabric thickness.
- Strong mutual relations were proved for air permeability, water vapor resistance and thermal resistance, not only with the channel parameters and fabric parameters determined, but attention was also paid to the important role of yarn raw material compounds in the single fabric. The flow indexes examined showed a medium correlation level in mutual relations.
- Recognition and identification of spatial objects that form interstitial channels in fabric is important not only for air, moisture and heat flow, but they can be used in in-depth structural analysis, for example in the fabrication of textile barriers for various types of adverse electromagnetic radiation, the textile filtration state, and for imparting various properties to fabric.

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