

Porosity of Knitted Fabrics in the Aspect of Air Permeability – Discussion of Selected Assumptions

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¹Technical University of Liberec,
Department of Textile Evaluation,
Liberec, Czech Republic
*E-mail: marie.havlova@tul.cz

²Technical University of Liberec,
Department of Textile Technology,
Liberec, Czech Republic
E-mail: jana.spankova@tul.cz

Abstract

The main focus of this paper is to look into the relationship between the structure and air permeability of single jersey knitted fabric – especially verifying some basic assumptions. First, if it is possible to neglect the permeability of yarns themselves when we evaluate that of knits, and second, if yarn hairiness plays a significant role when we evaluate the relationship between air permeability and the porosity of knits. Theoretical calculations and experiments which were performed using an analysis of microscopic images of the structure of textile materials are used for the determination of inter-yarn and intra-yarn porosity. The paper aims to show that the characteristic dimension of inter-yarn pores is significantly higher than that of intra-yarn pores, and also that the values of inter-yarn porosity measured using image analysis methods with hairiness and after the removal of hairiness are statistically significantly different. The correlation coefficients for the porosity values measured and calculated are very high.

Key words: knitted fabric, yarn, porosity, air permeability, image analysis.

■ Introduction

Air permeability is one of the fundamental textile properties [1] and it is an important factor in the comfort of a fabric [1, 2]. Air permeability is generally understood as the ability of air-permeable fabric to transmit air under the given well specified conditions [3, 5], and this parameter depends on the structural parameters of the fabric, with porosity playing a crucial role among them [1]. Therefore a number of authors have researched the relationship between the structure and permeability of a textile fabric – woven or knitted [e.g. 1, 2, 4-8]. The property usually given by the description of the structure of the fabric is the porosity. The results of a number of earlier papers show that these two characteristics of textile material – air permeability and porosity – are strongly related to each other [e.g. 1-5]. The size of the pores in textile as well as their shape, arrangement and distribution are decisive characteristics of fabric in terms of air permeability. The pore dimension and distribution are functions of fabric geometry. All the models that lead to the determination of the porosity of fabric – woven or knitted – include some simplifying assumptions; yet they introduce some inaccuracies into the result. Therefore it is very difficult to find an optimal method that predicates the permeability of textile fabric best. There is also an assumption [9] that if the inter-yarn pores in woven fabric are large enough and the air has enough space for free passage, it will mostly flow just in that way. Based on this assumption, most

authors dealing with the air permeability of fabrics consider yarns as an impermeable body – usually a cylinder [e.g. 2, 7, 12]. Moreover if the fabric is made of yarn with staple fibres, protruding fibres forming the hairiness enter the path of flowing air. These fibres extend into the inter-yarn pores of the fabric. Many theoretical models describing the porosity of knitted fabric work with the diameter of yarn as one of its input parameters. Determining the yarn diameter itself is difficult, especially if the yarns are made from staple fibres and are characterised by a greater or lesser degree of hairiness. We can assume that in the evaluation of the permeability of knitted fabric, yarn hairiness is also important. In our paper, when evaluating the relationship between the permeability and porosity of knitted fabric, we primarily examined two questions:

1. Can the air permeability of yarns themselves be neglected?
2. Does yarn hairiness play a significant role?

Answers to these questions were searched for using theoretical calculations and experiments performed with the use of the analysis of microscopic images of the structure of textile materials.

■ Porosity of textile fabrics

Inter-yarn and intra-yarn porosity

Textile is a porous material. According to a number of authors [e.g. 10, 11], the porosity inside textile materials can be divided into:

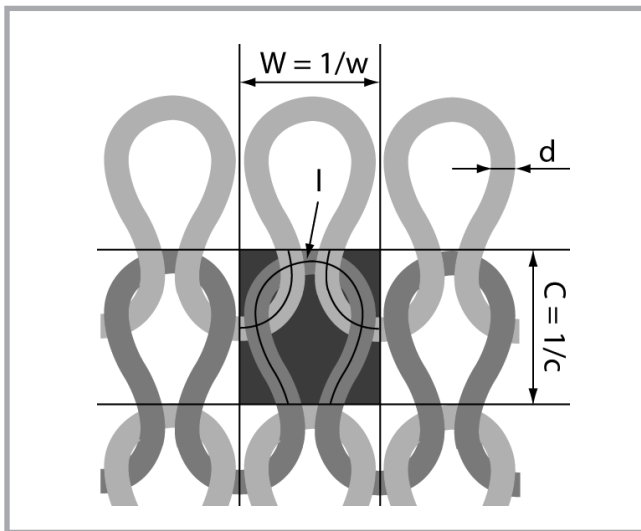


Figure 1. Scheme of unit cell of a plain knitted fabric.

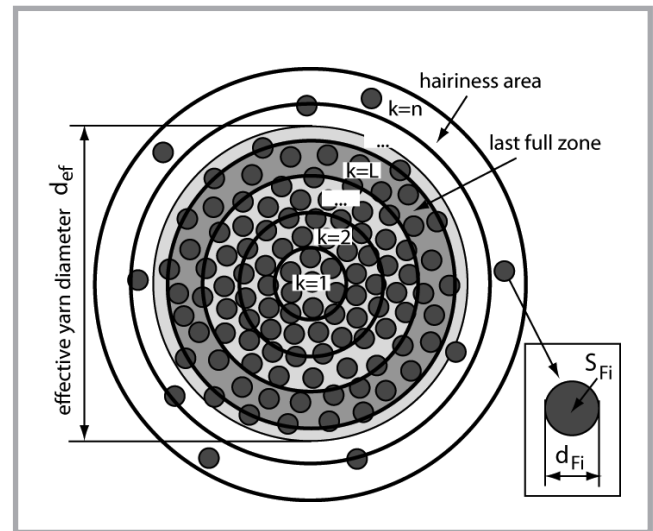


Figure 2. Scheme of yarn cross-section (zone $k = L$ is the last full zone in the effective yarn diameter).

- Inter-yarn porosity (also known as macro porosity) – including pores between the yarns from which the fabric is made (see **Figure 1**). When air flows through the fabric, most air flows in this way.
- Intra-yarn porosity (also known as micro porosity) – including pores inside the yarns, which are formed between the fibres (see **Figure 2**). When evaluating air permeability this kind of porosity is usually neglected.

The porosity inside yarns, however, is not constant throughout its cross-section. The tightness of the fibre arrangement in the yarn decreases towards its surface and continuously changes in the hairiness area. The yarn hairiness itself complicates the determination of the yarn diameter and inter-yarn porosity of fabric.

However, in their models, most authors [e.g. 2, 7, 12] considered yarn as an impermeable cylinder with diameter d [m].

Such a diameter of yarn can be calculated as:

$$d = \sqrt{\frac{4T}{10^{-6}\pi*\mu*\rho_F}} \quad (1)$$

where ρ_F [kg/m³] is the density of fibres, T , tex the count of yarn, and μ , – is the packing density of yarn [13]. In this case, a free yarn diameter is involved. However, the yarn cross-section is deformed at the interlacing points in the textile structure, therefore it is not circular, and also the packing density becomes higher. Under these conditions yarn diameter determination is very complicated and in the majority of cases the real diameter according to **Equation (1)** is used.

In addition to the yarn diameter, other basic geometrical parameters of knitted fabric usually considered are as follows (see **Figure 1**):

- loop length l , m,
- wale spacing W , m or the number of wales per metre w , 1/m, while $W = 1/w$,

- course spacing C , m or the number of courses per metre c , 1/m, while $C = 1/c$,
- fabric thickness t , m.

The loop length is a very important parameter of a knitted structure. In our paper the geometrical model by Dalidovic [14] is used for calculation of the loop length:

$$l = \frac{\pi}{2}W + \pi d + 2C \quad (2)$$

Theoretical calculation of porosity

Generally all spaces filled with air can be considered as pores in fabric. Then the porosity P , – can be expressed as a portion of air in the fabric. There exist three basic techniques for characterization of idealized fabric porosity [15]: density based porosity, area filling based porosity and volumetric filling based porosity. In our research, area filling based porosity was used for calculation of the inter-yarn porosity of knitted

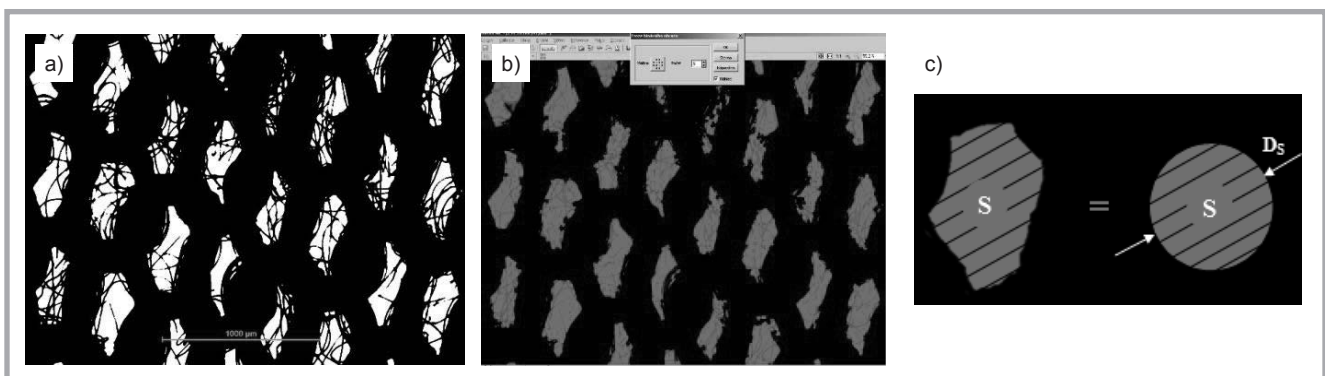


Figure 3. Image processing for image analysis: a) binary image – image after thresholding, b) binary image after thresholding, morphological dilation and erosion, c) equivalent pore diameter (inter-yarn porosity).

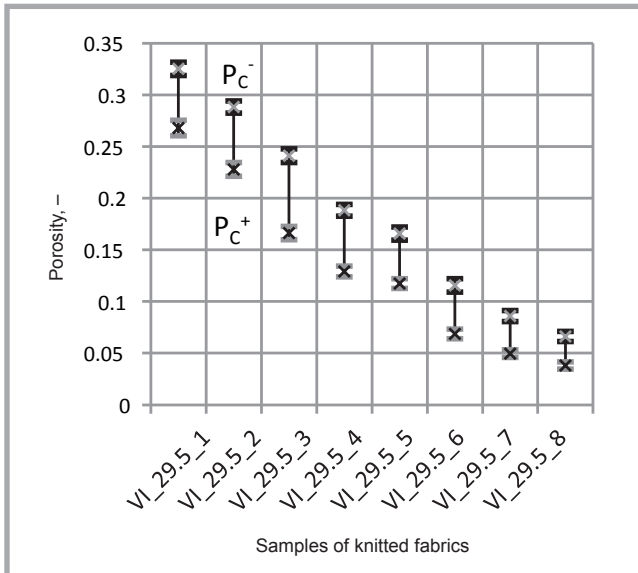


Figure 4. Data measured for knitted fabric porosity with and without hairiness (set VI_29.5 tex).

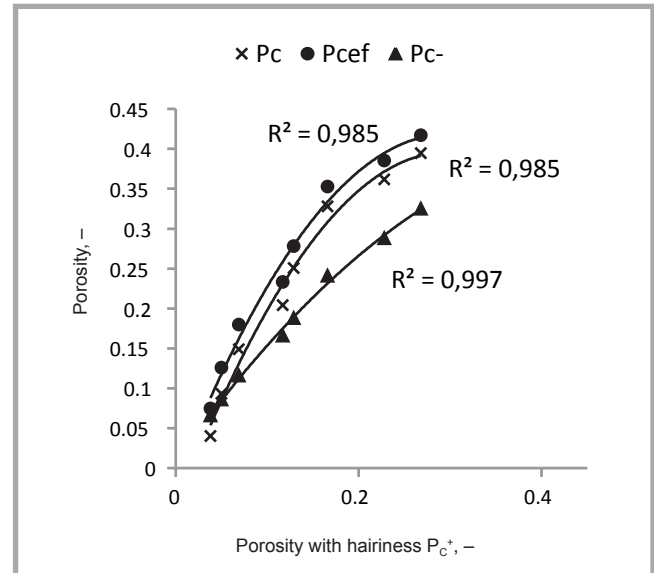


Figure 5. Relationship between calculated porosity and porosity measured with hairiness (set VI_29.5 tex).

fabrics. This two-dimensional interpretation of porosity P_C , – is derived from the pure geometry of yarn projection (see Figure 1):

$$P_C = 1 - \frac{\text{projected area of yarn in the unit cell}}{\text{projected area of the unit cell}} = 1 - \frac{S_l}{S_T} = 1 - \frac{d \cdot l - 4 \cdot d^2}{C \cdot W} \quad (3)$$

where S_l [m²] is the area of projection of the yarn in one unit cell of the knitted structure (see Figure 1), $d \cdot l$ the area of projection of the yarn which must be decreased by overlapping area $4 \cdot d^2$ and S_T [m²] is the total area of projection of this unit cell, given by $C \cdot W$. This method of calculation of the porosity best fits the experimental method of image analysis, which is also used in our paper.

The three general formulations of the porosity of textile materials (density based, area based and volume based) mentioned above for knitted fabrics are also useful for calculation of the porosity within yarn. In our research the intra-yarn porosity was determined experimentally by the image analysis of cross sections of the yarns. Principally, in this case, it is the interpretation of the area based porosity (see Figure 2). The porosity of the yarn P_Y , – can be calculated as:

$$P_Y = 1 - \mu = 1 - \frac{\Sigma S_{Fi}}{S_Y} \quad (4)$$

where μ , – is the packing density of the yarn, ΣS_{Fi} , m² the cumulative area of all sections of fibres in yarn, and S_Y , m² is the total area of the yarn cross section.

The equivalent fibre diameter d_F , m can be calculated as:

$$d_F = \sqrt{\frac{4T_F}{10^{-6} \cdot \pi \cdot \rho_F}} \quad (5)$$

where T_F , tex is the fineness of fibres and ρ_F , kg/m³ is the density of fibres.

Neckář [16] concerns himself with intra-yarn porosity and he derives a relation for the equivalent diameter for intra-yarn pores d_p , m which is based on several simplified assumptions, one being that pores are the same in the yarn (the so called average pore):

$$d_p = \frac{1+q_p}{1+q} \cdot \frac{1-\mu}{\mu} \cdot d_F \quad (6)$$

where q_p , – is the shape factor of the pores, q , – the shape factor of the fibres, μ the packing density of the yarn, and d_F is the equivalent diameter of the fibres calculated according to Equation (5). The problem is that we do not know the shape factor of the pores, therefore convention $q_p = 0$ is implemented. Pores with a shape factor equal to zero correspond to a system of cylinder tubes of compact mass, with their volume and surface being the same as those of the pores in the real yarn structure. Then the equivalent diameter of the conventional pore d_p^* according to Neckář [16] is:

$$d_p^* = \frac{1}{1+q} \cdot \frac{1-\mu}{\mu} \cdot d_F \quad (7)$$

Experimental determination of porosity using image analysis

The principle of this method is based on taking pictures with the use of a CCD

camera. Through connecting the camera to a microscope, a microscopic image of a textile material can be obtained. Using specific software (for example, Nis Elements from Laboratory Imaging) enables the image to be processed and analysed based on mathematical morphology.

First, for the measurement of inter-yarn porosity, the picture in grey-scale is converted to a binary image (Figure 3.a), which is the key operation because it says where the threshold point is, meaning where pores and yarns begin. In our research the subjective threshold method was used. The porosity is determined as a ratio between the number of pixels belonging to pores and the total number of pixels in the image.

The binary image was further processed using morphological operations, the aim of which was to eliminate the hairiness of the yarn, which decreases the porosity of the structure measured. In our paper both types of porosities are determined, namely with hairiness P_C^+ , – and without hairiness P_C^- , –. The pores are highlighted in red colour. The hairiness was removed by the following morphological operations:

1. Morphological dilation – dilation, putting together the points of two sets using vectorial summation. The objects in the picture are extended by one layer till the exclusion of the background after dilation. The pores are more solid.
2. Morphological erosion – dilation, putting together the points of two sets using

ing vectorial subtraction. The erosion was processed with the same structural elements as the dilation, meaning that the small objects were removed, but without changing the size of the pores (**Figure 3.b**).

Afterwards the porosity can be measured as the proportion of the open area of the textile material as well as the geometric characteristics of the individual inter-yarn pore (e.g. equivalent diameter (**Figure 3.c**), area of the pore, perimeter, and shape factor, etc.).

Measurement of the intra-yarn porosity was carried out according to the internal standard TUL No. 22-103-01/01, mainly characterised by Neckar's theory [17]. In the image of the yarn cross-section (**Figure 2**), a system of $k = 1, 2, 3,$ and $\dots n$ circle zone of constant width are created, with the centre on the axis of the yarn. Using the image analysis, the cumulated area of all cross-sections of fibres S_{Fk} [m²] in each zone and the zone area S_{Ck} [m²] are measured. The ratio of these values represents the radial packing density μ_k [-] in this zone [18]:

$$\mu_k = \frac{S_{Fk}}{S_{Ck}} \quad (8)$$

The above-mentioned internal standard TUL No. 22-103-01/01 states that the effective yarn diameter d_{ef} corresponds to a decrease in the radial packing density to the value $\mu_k = 0.15$, and then the effective packing density μ_{ef} of the yarn is the portion of the cumulated area of all cross-sections of fibres S_{Fef} in the circle of the effective yarn diameter and area of this circle S_{Cef} :

$$\mu_{ef} = \frac{S_{Fef}}{S_{Cef}} \quad (9)$$

The value of the effective packing density μ_{ef} is considered as a representative for each yarn and can be used for the calculation of yarn porosity P_Y according to **Equation (4)** or equivalent yarn diameter d according to **Equation (1)**.

Methods and experiment

Knitted fabrics of single jersey structure were used for the experiment. These were manufactured on a small-diameter circular knitting machine – *Rius-Protex* (Spain) from polyester and viscose ring-spun yarns, which have always been of two linear densities – 20 tex and 29.5 tex. Samples of the fabrics with different densities were knitted from each yarn

Table 1. Parameters of knitted fabrics.

Material	T, tex	C, mm	W, mm	t, mm	$W_p, \text{g/m}^2$	l, mm	$D_s, \mu\text{m}$	$P_c^+, -$	$P_c^-, -$	$AP, \text{mm/s}$	$r, -$	$r_L, -$	
Polyester	20	0.88	1.05	0.430	85	3.9	433	0.323	0.361	3138	228	47	
		0.79	0.88	0.458	100	3.5	351	0.250	0.284	2500	185	38	
		0.69	0.75	0.486	119	3.1	220	0.136	0.178	1784	116	24	
		0.65	0.73	0.515	133	3.0	187	0.128	0.163	1354	98	20	
	29,5	1.00	0.98	0.543	120	4.1	354	0.194	0.244	1929	136	27	
		0.76	0.88	0.557	147	3.5	251	0.138	0.170	1084	97	19	
		0.68	0.85	0.561	172	3.3	168	0.084	0.112	726.0	65	13	
		0.63	0.83	0.580	185	3.2	136	0.048	0.080	564.5	52	10	
		0.61	0.82	0.583	187	3.1	112	0.038	0.064	525.0	43	8.4	
Viscose	20	0.93	1.05	0.435	84	4.0	451	0.281	0.345	2318	116	17	
		0.80	0.92	0.453	99	3.5	358	0.226	0.283	1759	92	14	
		0.74	0.89	0.462	105	3.4	312	0.192	0.250	1554	80	12	
		0.67	0.83	0.470	117	3.1	224	0.128	0.186	1100	57	8.6	
			0.58	0.72	0.475	134	2.8	169	0.095	0.143	873.0	43	6.5
	29.5	0.97	1.24	0.469	108	4.5	494	0.268	0.325	1980	159	22	
		0.92	1.17	0.481	115	4.3	435	0.228	0.288	1630	140	19	
		0.87	1.11	0.487	126	4.1	372	0.166	0.241	1392	120	16	
		0.80	0.96	0.520	138	3.7	290	0.129	0.188	983.0	94	13	
		0.76	0.89	0.535	149	3.5	254	0.117	0.166	941.4	82	11	
		0.68	0.86	0.549	165	3.3	183	0.069	0.116	626.3	59	7.9	
		0.63	0.81	0.567	181	3.2	139	0.050	0.086	512.3	45	6.0	
			0.56	0.81	0.578	201	3.0	110	0.038	0.066	400.3	35	4.8

Table 2. Parameters of yarns.

Material	$\rho_{F_i}, \text{kg/m}^3$	$d_{F_i}, \mu\text{m}$	$q, -$	T, tex	$\mu_{ef}, -$	$d_{ef}, \mu\text{m}$	$d_p^*, \mu\text{m}$	$\mu_L, -$	$d_{PL}^*, \mu\text{m}$	$d, \mu\text{m}$	$P_Y, -$
Polyester	1390	11.7	1	20	0.752	156.2	1.9	0.389	9.2	163.2	0.248
				29.5	0.693	194.0	2.6	0.306	13.3	190.3	0.307
Viscose	1480	11.0	0.6	20	0.636	156.6	3.9	0.210	25.9	154.9	0.364
				29.5	0.689	188.2	3.1	0.230	23.0	195.8	0.311

(see **Table 2**). Fiber fineness was PL – 1.5 dtex and VI – 1.4 dtex.

Parameters of knitted fabric

The air permeability AP [mm/s] of the samples was measured according to the method specified by Standard ČSN EN ISO 9237 using a Textest FX 3300 air permeability tester (Switzerland). The measurements were performed with a constant pressure difference of 50 Pa and 20 cm² test area. Furthermore the number of courses per mm and wales per mm was measured according to Standard EN 14971, the thickness of the fabrics according to Standard EN ISO 5084, and the weight of the fabrics according to Standard EN 12127. The loop length l was calculated according to **Equation (2)**, with the yarn diameter value d calculated according to **Equation (1)** in this case. Using image analysis, the surface porosity of knitted fabric with hairiness P_c^+ and without hairiness P_c^- was measured. Then the equivalent pore diameter D_s [μm] was also measured (see **Figure 3.c**). The parameters of the knitted fabrics are summarised in **Table 1**.

Parameters of yarn

A methodical process of creating the cross sections of yarns was carried out according to the internal standard TUL No. 46-108-01/01, which includes two different methods of how to prepare the samples; we used the soft section method that is also described in [19]. In the experiment 20 cuts from each yarn were processed. The effective packing density value μ_{ef} was determined experimentally using the methods described above. The yarn diameter d was calculated according to **Equation (1)** and the diameter d_{ef} was measured using image analysis. The porosity of yarns P_Y was calculated according to **Equation (4)**, the equivalent fibre diameter d_f according to **Equation (5)**, and the equivalent diameter of the intra-yarn pore d_p^* according to **Equation (7)**. The parameters of yarns are introduced in **Table 2**.

Results and discussion

The equivalent pore diameter D_s (see **Table 1**) is a characteristic dimension of inter-yarn pores. The equivalent intra-yarn

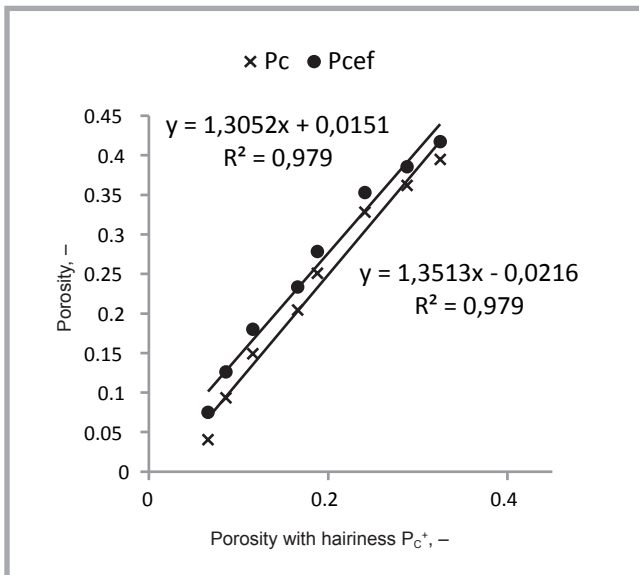


Figure 6. Relationship between calculated porosity and porosity measured without hairiness (data of VI 29.5 tex).

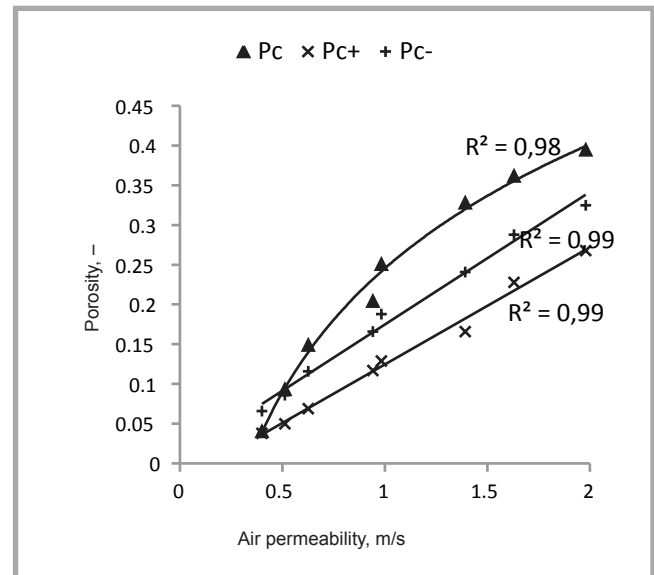


Figure 7. Relationship between porosity and air permeability (data of VI 29.5 tex).

pore diameter d_p^* (see **Table 2**) is a characteristic dimension of intra-yarn pores. Then, based on ratio r (see **Table 1**):

$$r = \frac{D_S}{d_p^*} \quad (10)$$

it is possible to determine that the characteristic dimension of each inter-yarn pore D_S is greater (min 35 and max 228 times) than that of the intra-yarn pores d_p^* . However, as mentioned above, the packing density of yarn is not constant throughout its cross section, decreasing towards the surface. In our experiment, values of the radial packing density μ_k were measured. Therefore the value of the packing density μ_L corresponding to the last full zone, which is included in the effective yarn diameter, can be used in **Equation (7)**, and the equivalent diameter of the intra-yarn pore near the surface of the yarn d_{pL}^* may be determined as (see **Table 2**):

$$d_{pL}^* = \frac{1}{1+q} * \frac{1-\mu_L}{\mu_L} * d_F \quad (11)$$

In this case, based on ratio r_L (see **Table 1**):

$$r_L = \frac{D_S}{d_{pL}^*} \quad (12)$$

it is possible to determine that the characteristic dimension of the inter-yarn

pores D_S is also greater than that of the intra-yarn pores d_{pL}^* , but ranging from 4.8 to 47 times. Thus D_S values for very dense knitted fabrics are orders of magnitude comparable with the values of d_{pL}^* . However, most of the pores within the yarn are deformed due to a twist and do not pass through the yarn. Moreover in the case of very dense knitted fabrics in particular, yarn compression occurs near the binding points. Assuming that air flows through the path of least resistance, and with respect to the size of individual intra-yarn and inter-yarn pores, it will flow through the inter-yarn pores.

Figure 4 shows the data measured for inter-yarn porosity with hairiness P_C^+ and after removing yarn hairiness P_C^- . For example, data for knitted fabrics made from viscose yarn 29.5 tex are shown here.

In the graph the boundaries of confidence intervals are plotted, from which it is evident that differences in the values P_C^+ and P_C^- measured are statistically significant, and in the case of knits with lower porosity the difference is relatively more significant. A statistical test of the conformity of two selections was also applied to all data. In all cases, a statistically significant difference between average values

was confirmed, namely at the level of significance 0.05. The variances of the two measurements were identical in most cases, except for the very dense samples of fabrics. For the very dense samples of fabrics (P_C^+ less than 0.070) statistically significant differences between variance values were confirmed, for which the statistical analysis software QC Expert was used.

Table 3 shows correlation coefficients for porosity values obtained in different ways. It is evident that all correlation coefficients have very high values, indicating a high degree of linear dependence.

However, the graph in **Figure 5** shows the relationship between the porosity calculated according to **Equation (3)**: first P_C^- in **Equation (3)** the diameter d calculated according to **Equation (1)** was used, second P_{Cef} – in **Equation (3)** the diameter d_{ef} (see **Table 2**) determined experimentally was used, and the porosity measured with maintained hairiness P_C^+ . While this graph shows that the data dependency of the second-degree polynomial fits better than the linear relationship, the graph in **Figure 6** shows the relationship between the porosity calculated and that measured after the removal of hairiness using the image analysis software P_C^- . In this case, the data rather correspond to a linear relationship. The values of porosities P_C and P_{Cef} are very close because the values of yarn diameter d and d_{ef} are also very close (see **Table 2**). However, they both

Table 3. Correlation coefficients for porosity values obtained in different ways (all data).

Type of porosity	P_C^-	P_{Cef}	$P_C^+, -$	$P_C^-, -$
$P_C^+, -$	0.953	0.964	1	0.991
$P_C^-, -$	0.976	0.988	0.991	1

correspond to the yarn diameter in a free state. **Figure 6** shows that the porosities P_C and P_{cef} calculated have a slightly steeper trend against the values of the porosity measured P_C^- .

Figure 7 shows the relationship between the porosity (calculated P_C and measured P_C^+ , P_C^-) and air permeability. It is evident that the values of P_C^- shift up towards those of P_C^+ . The corresponding regression lines are mutually displaced and very gradually converge towards lower values, which corresponds to the not entirely linear dependence between P_C^- and P_C^+ (see **Figure 5**). Further, **Figure 7** shows that the dependence between the porosity calculated P_C and air permeability is not linear, which may be due to the simplifying assumptions that enter into the theoretical calculations, one being the constancy of the yarn cross-section. In fact, the cross-section of the yarn changes as a result of interlacing. Furthermore it is very important that the relationship between wale spacing W and course spacing C is not actually linear. The length in a loop is changed by the sinking depth, which means that in the first phase we change the course spacing; the wale spacing in the machine is the same because the gauge of the machine is the same. Removing the knitted fabric from the machine is followed by relaxation which is dependent on several conditions (elasticity of the yarn, friction at interlacing points, density of the knitted fabric etc.). Obviously the length of the loop is the same, but W and C change nonlinearly.

Conclusions

Air permeability is a very important property of textile materials and is closely related to the porosity. A number of authors have researched the relationship between the porosity and air permeability of textile materials. The models proposed always include some simplifying assumptions, and our contribution is focused on some of these. The porosity of single jersey knitted fabrics and that of the yarns used were evaluated theoretically and experimentally. For the experiment a set of 22 single jersey knits was used.

- It was found that the characteristic dimension of inter-yarn pores is approximately 35-228 times greater than that of intra-yarn pores. Assuming that air flows through the path of

least resistance, air will primarily flow through the inter-yarn pores in knitted fabrics. Therefore, in the case of our set of fabrics, the porosity of the yarns themselves may be neglected in terms of air flow through the knitting. Thus the assumption that the yarn is taken as an impermeable cylinder with diameter d , which has often been used by other authors [e.g. 2, 7, 12], can also be used for our set of knitted fabrics.

- Only in the case of highly dense fabrics is it possible to consider that part of the air may pass through the surface layers of the yarn, because for such knitted fabrics the characteristic dimension of intra-yarn pores is quite comparable with that of inter-yarn pores. However, also in these cases the air permeability of the yarns themselves may be neglected. It can be assumed that due to yarn twisting and the compression of the yarn near the binding points, air will flow primarily through the inter-yarn pores. This is in accordance with the original assumption of passage of air through the inter-yarn pores of fabric [9].
- The surface porosity of jersey knitted fabrics was measured using image analysis methods – first, while maintaining the hairiness P_C^+ and also after its removal P_C^- . The correlation coefficient for this data is 0.991, but the values of P_C^- are significantly higher than those of P_C^+ . The significance of the difference in the two values is relatively greater for fabrics with higher density. The hairiness of yarns, therefore, plays an important role in assessing the porosity of knitted fabrics, which is also consistent with our previous findings [3]. However, the removal of hairiness is very important if we want to measure the geometrical characteristics of individual inter-yarn pores – diameter, area, perimeter, etc.

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