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Porosity of the Flat Textiles

Danilo Jakšič¹ and Nikola Jakšič²

¹University of Ljubljana

²Turboinštitut
Slovenia

1. Introduction

Flat textiles play an important role in clothing and as component of composites. Besides of that, it would be difficult to imagine the processes of filtration without the flat textiles. They can be divided into three main groups: woven fabrics, knitted fabrics and non-woven textiles if their design is disregarded. The quality of the flat textiles can be defined by many parameters. In this chapter, we will focus on one of them - the porosity.

What is porosity? How could we define it? Way and where is it important? Usually we have more questions than answers. The porosity in flat textiles is defined as a void part of the textile's full volume. The full textile's volume is usually occupied by a mixture of three components: fibres, air and water. The part of the volume that is occupied by fibres is constant. On the contrary the portion of the volume that is occupied by water may vary considerably. For instance, there is no water in the absolutely dry flat textile, and in the absolutely wet condition, air is replaced by water. The water content in the textiles plays very important role in the clothing insulation due its effect on the clothes' thermal resistance. The coefficient of the thermal resistance of air is much larger than the coefficient of the fibres or water. Hence, it is extremely important to keep the clothing dry in a cold weather.

The coefficient of the thermal conductivity scales in the inverse manner with the coefficient of the thermal resistance and both are frequently used in the literature. The coefficient of the thermal conductivity is not solely influenced by the porosity in terms of its water content in the still weather, but also by the moving air - windy weather - that can penetrate the pores in the flat textiles.

The porosity can be defined by several parameters. The pore distribution is an important parameter and it is seldom well known. Even the average pore size is difficult to estimate. Yet, our aim was to describe the pore distribution by its attributes: average pore diameter, number of pores and distribution of pore diameters in a histogram form. The method that is capable of providing us with all these data is described in this chapter. The surface of the flat textile open to the flow of the fluid is of the interest as well. Additionally, the velocity of the fluid flow through the flat textile, driven by the pressure difference between textiles surfaces, is important when analysing the process of filtration or the properties of clothing. In the latter case the fluid is air.

Clothing has certainly a specific role in our life. It protects us against cold, wind, rain and sun radiation. Clothing must be suitable in the dry and wet, cold and hot weather and in the

windy weather. Only one set of clothing can't be enough for all these situations – we do not have the universal clothing. Instead, we use clothing composed in layers. Problem may arise as energy or heat is produced by our metabolism. Heat production depends on the intensity and sort of the activity. Sweating is the body response on its own temperature rise and it is wetting the clothes. The thermal resistance coefficient of the wet clothing is smaller than the dry one. The similar effect can be observed when wind velocity increases. The influence of the temperature, water and wind velocity on the thermal coefficient is shown in equation (1) for a flat surface (Jakšić, 2004).

$$R_s = \frac{d_c}{\lambda_0(1 + k_T \Delta T_c + k_w \Delta G_c) + bc_a \gamma_c V_a d_c} + \frac{0.0429}{0.4 + 2.0\sqrt{v}} \quad (1)$$

where R_s stands for the clothing's coefficient of thermal resistance, d_c for the thickness of the clothing, λ_0 for the coefficient of thermal conductivity of clothing in the standard environment, k_T for the coefficient of direction curve temperature - the thermal resistance of the clothing, ΔT_c for the difference of the clothing temperature regarding the temperature in the standard environment, k_w for the coefficient of direction curve for the content of water in clothing - the thermal resistance of the clothing, ΔG_c for the change of the water content in the clothing, b for the coefficient, which describes the tightness of the clothing (if the value is 1, the air flows through the surface of clothing layers and not through the holes in the clothing, c_a for the specific heat of the air, γ_c for the specific mass of the air, V_a for the volume of the air which penetrate through the clothing due to the velocity v of the air flow.

The use of flat textile in the composites and as the geo textiles, the diameters of pores are also very important. For example, in a composite structure the diameters of pores must allow resin a good connection between the layers of the flat textile. The pores must simply be large enough to allow resin penetration. On the other hand, the diameters of pores in woven fabrics used as geo textiles must be small enough to effectively filtrate earth particles. Pores in the woven fabrics are voids between threads of the warp and weft and the light can go directly through. This sort of material is not suitable for use in the masks destined for protection against viruses. Viruses are extremely small and we can't get pores in textiles to be smaller. Hence, non-woven fabrics are used for the masks design in spite of the fact that the pores are many times larger than the viruses. The walls of pores are defined by fibres, and not by threads, in the non-woven fabrics. Pores change direction many times from one surface of the non-woven fabrics to another. The probability for the aerosol flowing through such a pore to deposit fine solid or liquid particles including bacteria and viruses on the fibres is extremely high, even 100% for some limited time. The micro fibres, which diameter is about 1 to 2 micrometers, must be used for this purpose. The porosity of the non-woven fabrics is high enough to enable us to breathe normally. The protection against microbes and viruses are tested in the special laboratories. However, if we could measure the composition and the porosity of masks, the number of those tests would be reduced. It would be enough to estimate porosity only, but it is not so straightforward without a suitable method.

We have developed a method for the assessment of the parameters of the porosity in all flat textiles. The method is relatively simple and efficient at the same time. The apparatus for measuring the airflow through a flat textile sample due to the pressure difference is needed. The application software has been developed on a basis of the method's algorithm.

2. Methods for estimating the porosity of the flat textiles

There are several different methods available for the assessment of the parameters of porosity, such as: geometrical methods (Matteson & Orr, 1987), (Piekaar & Clarenburg, 1967) and (Dubrovski & Brezocnik, 2002), liquid intrusion methods (Dosmar et al., 1993), (Rucinski et al., 1986) and (Rebenfeld & Miller, 1995), liquid extrusion methods (Miller & Tyomkin, 1986a), (Miller & Tyomkin, 1986b) and (Rushton & Green, 1968), liquid through methods (Hssenboehler, 1984), etc. Some of them can only give truly very approximate values, which may not be accurate enough. On the other hand some of them are not capable of estimating all the relevant porosity parameters.

A lot of work has been done over the years to overcome the mentioned shortcomings. We have developed a method for estimation of the parameters defining the textile's porosity. The method is suitable for all types of flat textiles: woven fabrics, knitted fabrics and non-woven fabrics (Jakšić, 2007). We have named it J-method after the first letter of authors' surname.

Main feature that set J-method apart of the other methods is that J-method is also suitable for the non-woven fabrics.

3. Theoretical bases for J-method

A flat textile product gets wet and the fluid pushes the air out of the product - especially from voids, if the product is immersed into a fluid. These voids are formed out of pores between fibres in the non-woven fabrics, as well as out of pores between threads in the woven and knitted fabrics. The pores between the threads of the warp and weft in the woven fabrics, figure 10a, are the most interest from the practical point of view. The pores between the threads of the warp and weft are well defined in textile fabrics made of monofilament and of some multifilament yarns. The pores can be counted on a defined area in such cases. This is not the case with the fabrics made of wool yarn where some fibres jut out of the yarn and thus cover the pores. A pore is thus divided into several smaller pores. It is thus impossible to ascertain the exact number of pores in the non-woven fabrics.

The porosity parameters that are needed in most of the cases are: the pore size distribution, the average hydraulic pore diameter, the open area for fluid flow and the air volume velocity as a function of the air pressure. The method under consideration is able to provide mentioned parameters with sufficient accuracy.

The method is based on selectively squeezing the fluid in the pores out of the wet fabrics by air pressure and on the presumption that a pore is approximated with a cylinder. The selectivity is assured by the fact that the fluid is squeezed out of the pores with a certain hydraulic diameter providing that the precise value of the air pressure is applied. The air pressure is inversely proportional to the hydraulic diameter of the pores (see equation (3)). Latter is important, while the process of squeezing out the fluid contained in the pores of the wet fabrics is under examination. There is always a small amount of the fluid that remains at the edges of pores if such edges exist.

The pore cross-section is approximated by a circle of the diameter d . The parameter d is the hydraulic diameter of the pore. It is defined by equation (2) where f denotes the surface of the cross-section of the pore, o the circumference of the cross-section of the pore w , the width of the pore cross-section and l denotes the length of the pore cross-section.

$$d = \frac{4f}{o} = \frac{2wl}{w+l} \quad (2)$$

The pressure difference p_i between the opposite surfaces of the flat textile, equation (3) and (4), results in squeezing the fluid out of the pores, which diameter is equal or larger than d_i . The fluid is characterised by the surface stress α .

$$d_i \geq \frac{4\alpha}{p_i} \quad (3)$$

$$p_i = \rho g h_i ; d_i \geq \frac{4\alpha}{\rho g h_i} \quad (4)$$

The fluid is first squeezed out from pores, which have the largest hydraulic diameter. The flow of air will establish itself through these pores that are now empty. The volume flow rate of air through the flat textile can be described by equation (5)

$$V_i = A p_i^b = P a p_i^b = P v_i \quad (5)$$

where V_i stands for the air volume flow rate through the sample at the air pressure p_i , A for a regression coefficient when fitting equation (5) to the measured dry data, P for the open surface, v_i for the linear air flow velocity, a for the coefficient and b for the exponent. The parameters a and P are unknown and they have to be estimated as well. The solution of the problem is enabled by equation (6) by putting the velocity v_i in the relationship with the air pressure p_i . The value for the exponent b is bounded between 0.5 and 1.0. The air volume flow rate depends on the degree of porosity of the flat textile fabrics and the air pressure difference between the two surfaces of the fabrics. Larger porosity means larger air volume flow rate through the fabrics at the constant pressure. The last part of equation (6) holds in the ideal circumstances, when all of the energy dissipation mechanisms are neglected.

$$v_i = a_0 p_i^b = 1.28 p_i^{0.5} \quad (6)$$

Suppose that the fluid is squeezed out from the largest n_1 pores with hydraulic diameter of d_1 at the pressure difference p_1 . The volume flow rate of V_1 is thus established through empty pores, equation (7).

$$V_1 = \frac{\pi d_1^2}{4} n_1 v_1 = \frac{\pi}{4} a p_1^b n_1 d_1^2 \quad (7)$$

Additional n_2 pores will open at p_2 , $p_2 > p_1$, and the volume flow will rise to value V_2 , equation (8).

$$V_2 = \frac{\pi}{4} a p_2^b (n_1 d_1^2 + n_2 d_2^2) \quad (8)$$

The pressure value can be increased incrementally till all pores are opened. Hence at the i^{th} incremental step the volume flow rate is V_i , equation (9).

$$V_i = \frac{\pi}{4} a p_i^b \sum_{j=1}^i n_j d_j^2 \quad (9)$$

The selective squeezing out the fluid from pores as described in equations from (3) to (9) enables us to compute the number of pores at each interval defined by the incremental pressure growth. The number of pores of the first interval n_1 can be estimated as

$$n_1 = \frac{4V_1}{\pi a p_1^b d_1^2}, \quad (10)$$

for the second interval as

$$n_2 = \frac{4}{\pi d_2^2} \left[\frac{V_2}{a p_2^b} - \frac{\pi d_1^2}{4} n_1 \right], \quad (11)$$

and for the i^{th} interval as

$$n_i = \frac{4}{\pi d_i^2} \left[\frac{V_i}{a p_i^b} - \frac{\pi}{4} \sum_{j=1}^{i-1} d_j^2 n_j \right]. \quad (12)$$

It is clear from the equation (9) that

$$\frac{\pi}{4} \sum_{j=1}^{i-1} d_j^2 n_j = \frac{V_{i-1}}{a p_{i-1}^b} \quad (13)$$

and hence, equation (12), which defines the number of pores in the i^{th} interval, can be rewritten as

$$n_i = \frac{4}{\pi a d_i^2} \left[\frac{V_i}{p_i^b} - \frac{V_{i-1}}{p_{i-1}^b} \right] \quad (14)$$

and by taking into account equation (3), the final form of the equation for the number of pores in the i^{th} interval can be derived as

$$n_i = \frac{p_i^2}{4\pi a \alpha^2} \left[\frac{V_i}{p_i^b} - \frac{V_{i-1}}{p_{i-1}^b} \right] \quad (15)$$

The air volume velocity through the wet sample depends on the air pressure and on the open surface of the sample. As the pressure increases, the open surface increases as well due to the squeezing the fluid out of pores with smaller hydraulic diameter. Hence, the rise of the air volume flow rate is consequence of the open surface and the pressure growth. As a consequence the sequential pore opening of the wet sample is achieved by increasing the air pressure gradually when testing. When the pressure is increased then the open surface and the linear velocity of the airflow is also increased. This enables us to calculate the portion of air volume flowing through the empty pores and to calculate the number of pores in i^{th} pore's diameter interval by starting from the first interval with the pores with the largest hydraulic diameter, equation (7), where p_1 and V_1 stand for the air pressure and the volume flow rate respectively when the first air bubble is spotted during the testing of the wet sample.

The presumption of the equal regime of the airflow through the wet sample's open area and the dry one at the same pressure is taken into account. Small values of the Reynolds number,

$Re < 50$, in the extreme causes (maximal hydraulic diameter of pore), support that presumption. The airflow is either laminar through open pores in the wet sample and through all pores in the dry sample, or the type of the airflow is the same. This is the criterion for using the exponent b , which is estimated when equation (5) is fitted to the measured dry data, in the process of determining the pore distribution from the measured wet data.

The method's algorithm can be presented in step-by-step scheme:

1. The measurements of the air volume velocity flowing through a dry sample as a function of the air pressure at several distinct air pressures produce the "dry data".
2. The measurements of the air volume velocity flowing through a wet sample as a function of the air pressure at several distinct air pressures produce the "wet data".
3. The weighted power approximation is fitted to the dry data, and thus the exponent b is estimated, see equation (5).
4. The approximating cubic splines are fitted to the wet data thus smoothing it.
5. The porosity parameters are computed with the help of b , estimated in the step 3, and with the help of smoothed wet data together with equations (2) - (4) and (6) - (15).
6. The procedure is repeated at step 3 on the portion of measurements (at the pressure interval) where pores were identified in the first algorithm sweep.

When the dry and wet data are measured (steps 1 and 2) the numerical data processing can start. A computer application was built for that purpose to enable one to interactively carry out the porosity parameters numerical computation. A user interaction with the application is needed at steps 3 and 4 when choosing weights to the approximations used to fit the dry and wet data and at the step 5 where a user chooses between two procedures for computing porosity parameters and defines the length of the base interval of the pore diameter distribution (histogram). At step 6 the algorithm is repeated from the step 3 on. The exponent b is computed on the portion of the dry data measurements (pressure interval) where pores were identified in the first algorithm sweep. The upper limit is the pressure, which squeezes the fluid from the smallest hydraulic pore detected by the first algorithm sweep.

Two different procedures are foreseen depending on the type of the flat textile under consideration. The first procedure is suitable for the flat textiles where the number of pores between threads of the warp and weft is known e.g. very thick monofilament woven fabric (sample d). The second procedure is used in other cases e.g. cotton fabric woven out of cotton yarn (sample a).

The corresponding coefficient a_j are also determined by equation (16)

$$a_j = 1.28 \frac{n_{cj}}{n_t} = \frac{1.28}{a^*} ; a^* = \frac{n_t}{n_{cj}} \quad (16)$$

where n_t stands for the true number of pores, n_{cj} for the computed number of pores and a_j for the corrected a in equation (11). The values of theoretical limits, for exponent b ($b_0 = 0.5$) and coefficient a ($a_0 = 1.28$), that are used in the second procedure are shown in the last part of equation (6).

The first procedure is totally valid for the monofilament woven fabrics, which have the same or similar density of the warp and weft and have threads of the yarn of the similar size (yarn count) and quality. It can be used for monofilament and multifilament fabrics, which have similar density of the warp and weft and if the coefficient a_0 , equation (6), is smaller than 1.28 (theoretical maximum). A single pore between threads of the warp and the weft can be

counted for several hydraulic pores if pores are of rectangular shape (sample b) due to the differences in the densities of the threads of the warp and the weft or due to differences in fineness of the yarn and possibly due to the binding. The value of the coefficient a_0 is greater than theoretical maximum and the computation of the porosity, is continued by using the second procedure.

As a rule, the second procedure should be used if the number of pores is unknown or a_0 is larger than 1.28 or the type of fabrics unsuitable for the first procedure is used. The number of pores in intervals are computed first by using equations (10) and (15) and using maximal value of the coefficient a ($a_1 = 1.28$). The computed number of pores is minimal and so is the corresponding estimated open surface. If the computed coefficient a_0 is larger than 1.28 then the true value of the coefficient a , is computed as quotient between a_1^* and a_0' . Whole procedure is repeated with newly computed a . For example $a_1' = 1.28$; $a_0' = 8$; $a_0'/1.28 = 6.25$; $a_1/6.25 = 0.2048 = a$; $a_1^*/a_0' = 0.2048 = a$; $a_0 = 1.28$.

4. Experiment

Four different samples were used for the method's testing, which practically encompasses all the fabric types that the method is suitable for. The basic design parameters of the woven fabrics are presented in table 1. They are made of monofilament, multifilament and cotton yarn. The measured average pore's hydraulic diameters of the textiles are in the interval of 18 up to 200 micrometers. The wide assortment of textiles is thus covered.

| Sample | Description | Interval of measurement [μm] | Numbers of pores per cm^2 | Warp/weft, threads per cm |
|--------|--------------------------------------|---|------------------------------------|---------------------------|
| (a) | Cotton woven fabric | 160 - 20 | 452 | 22/21 |
| (b) | Thick monofilament fabric | 80 - 10 | 2200 | 55/40 |
| (c) | Multifilament woven fabric | 270 - 140 | 960 | 32/30 |
| (d) | Very thick monofilament woven fabric | 24 - 12 | 32400 | 180/180 |

Table 1. Samples used in the testing of J-method

The results of the textile's porosity tests are presented in table 2 and in figures 1 - 8. The first procedure is used for all four samples. The second procedure was used for porosity parameters estimation of samples (a) and (b) due to large value of the parameter a_0 .

We worked under two presumptions:

- The regime of the airflow through the dry and the wet sample is the same at same pressure difference regardless of the size of the open area of the wet sample.
- The number of the hydraulic pores is not the same as number of pores between threads of the warp and weft if the ratio of the rectangular sides, which represents real pore's cross-section, is at least 3:1.

The first presumption applies that the airflow regime through all pore's should be the same regardless of their diameter. This is certainly true for sample (d) due to the fact that the 90% of all pores are in the interval between 18 and 20 micrometers. If the regression parameters of the air flow through dry samples are obtained on the measurement's interval of pressures where pores actually exist then the values of the pore's average diameter obtained by the microscope and the scanning-electron microscope are in good agreement with those obtained with the method presented here indicates justification of the presumption of the same regime of the air flow through dry and wet sample at the same pressure difference. This holds for all tested samples due to low Reynolds number. Reynolds numbers have values 12 and 39 for flow through sample (d) and sample (c) respectively, if we take into account the average hydraulic diameters of 18.78 μm for sample (d) and 199 μm for sample (c). Hence, the flow through all samples is laminar and the exponent b , which is estimated by equation (5), can be used in equations (7) - (11).

The nomenclature in table 2 - b stands for the exponent in equation (5), h [μm] for the width of the interval of the pore distribution, m for the number of the distribution intervals, n_t for the true number of pores between the threads of the warp and the weft per cm^2 , n for the computed number of hydraulic pores between the threads of the warp and the weft per cm^2 , when the true number of pores (or number of hydraulic pores) is unknown (second procedure), d for the average hydraulic diameter of pores, d_t for the optically measured average hydraulic pore diameter - for samples (b), (c) and (d); the pores are ill-defined in sample (a), P [%] for the average open hydraulic flow area, P_t [%] for the average open flow hydraulic area computed on the bases of the optical experiment, a_0 for the coefficient a , equation (5), at presumption that exponent b has minimal value ($b = 0.5$).

| Porosity test procedure | Parameter | Samples | | | |
|--|-------------------------|---------|--------|--------|--------|
| | | (a) | (b) | (c) | (d) |
| Porosity parameters when the number of pores is known (first procedure) | b | 0.5794 | 0.6647 | 0.8329 | 0.7174 |
| | h [μm] | 14 | 10 | 13 | 2 |
| | m | 10 | 7 | 10 | 7 |
| | n_t | 452* | 2200 | 960 | 32400 |
| | d [μm] | 45.04 | 31.37 | 200.45 | 18.84 |
| | d_t [μm] | 53 | 30 | 199 | 18.78 |
| | P [%] | 0.98 | 2.07 | 31.32 | 9.06 |
| | P_t [%] | 1.00** | 3.43 | 29.84 | 8.98 |
| | a_0 | 9.4074 | 2.3872 | 0.28 | 0.8791 |
| Porosity parameters when the number of pores is unknown (second procedure) | d [μm] | 45.00 | 31.35 | | |
| | P [%] | 6.96 | 3.87 | | |
| | n | 3314 | 4115 | | |
| | a_0 | 1.28 | 1.28 | | |

Table 2. Parameters of porosity estimated with J-method for all four samples. * - the number corresponds to the product of the warp and weft. ** - corresponds to the 452 measured pores - between the threads of warp and weft only one typical pore was measured in each void between the threads of warp and weft.

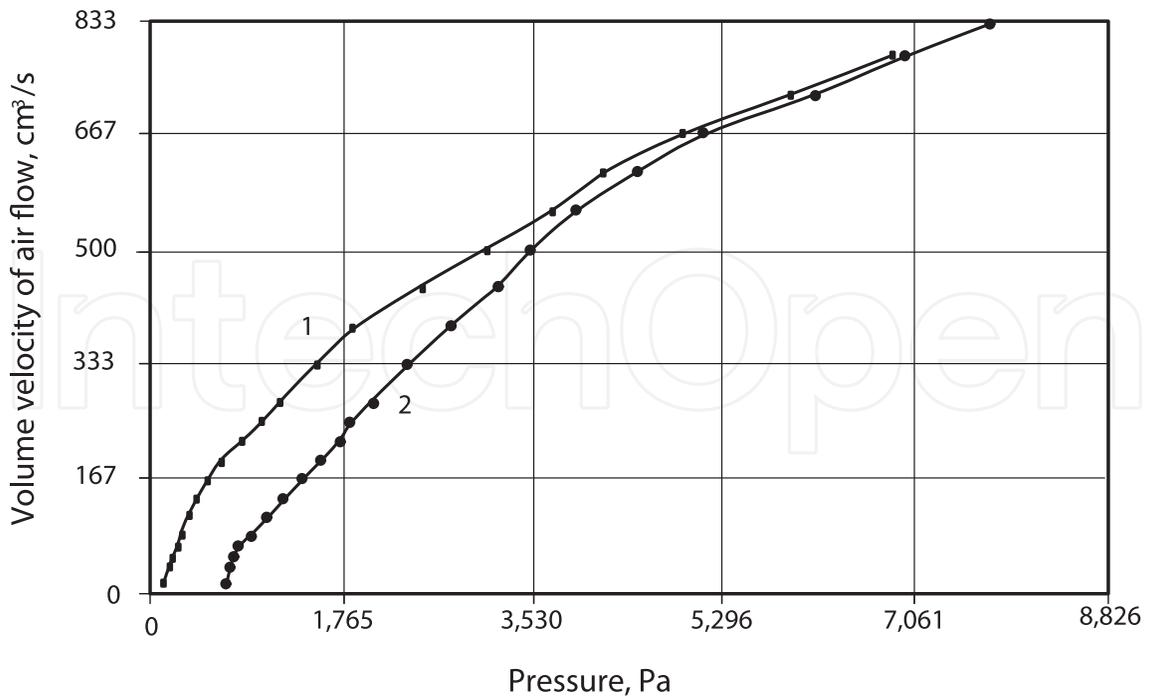


Fig. 1. Diagram of the volume velocity flow through open area of the sample (a) as a function of the pressure difference; 1 - velocity of the air through the dry sample; 2 - velocity of the air flow through the wet sample

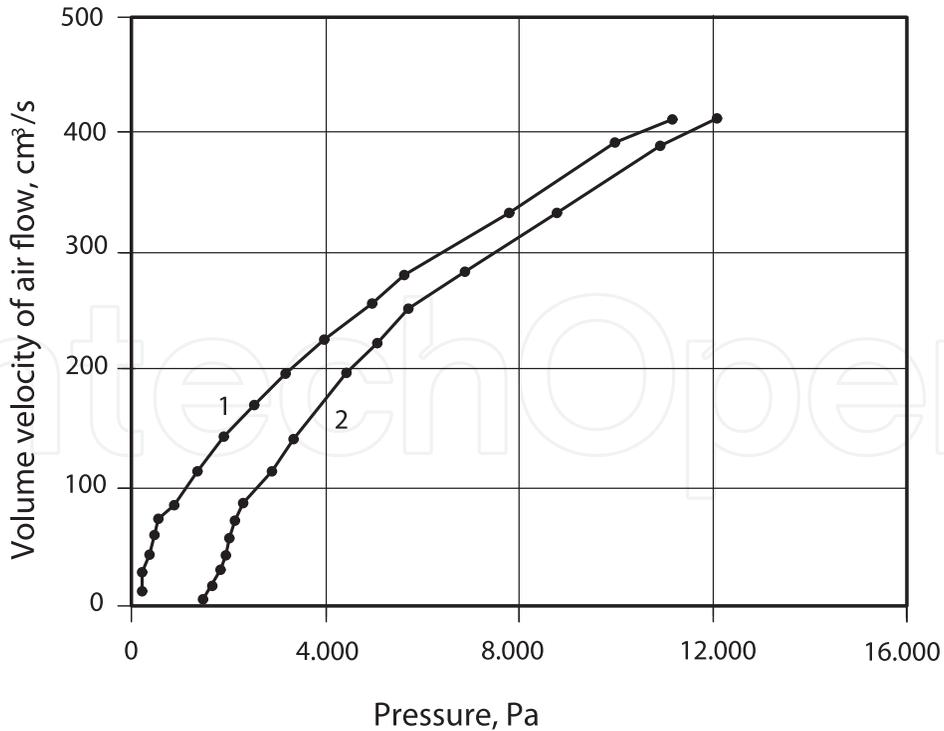


Fig. 2. Diagram of the volume velocity flow through open area of the sample (b) as a function of the pressure difference; 1 - velocity of flow air through the dry sample; 2 - velocity of the air flow through the wet sample

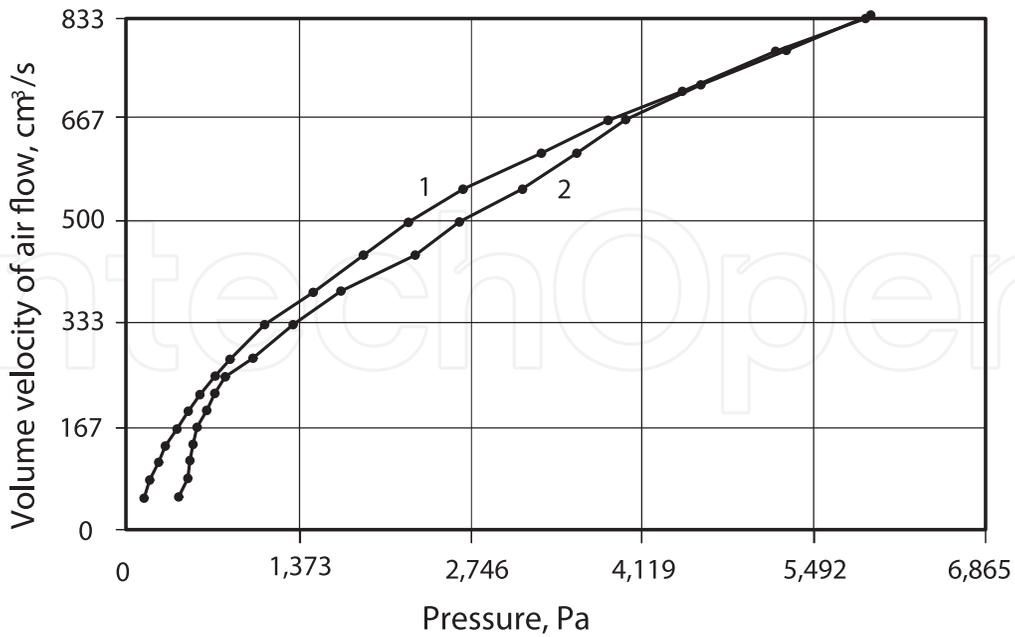


Fig. 3. Diagram of the volume velocity flow through open area of the sample (c) as a function of the pressure difference; 1 - velocity of the air flow through the dry sample; 2 - velocity of the air flow through the wet sample

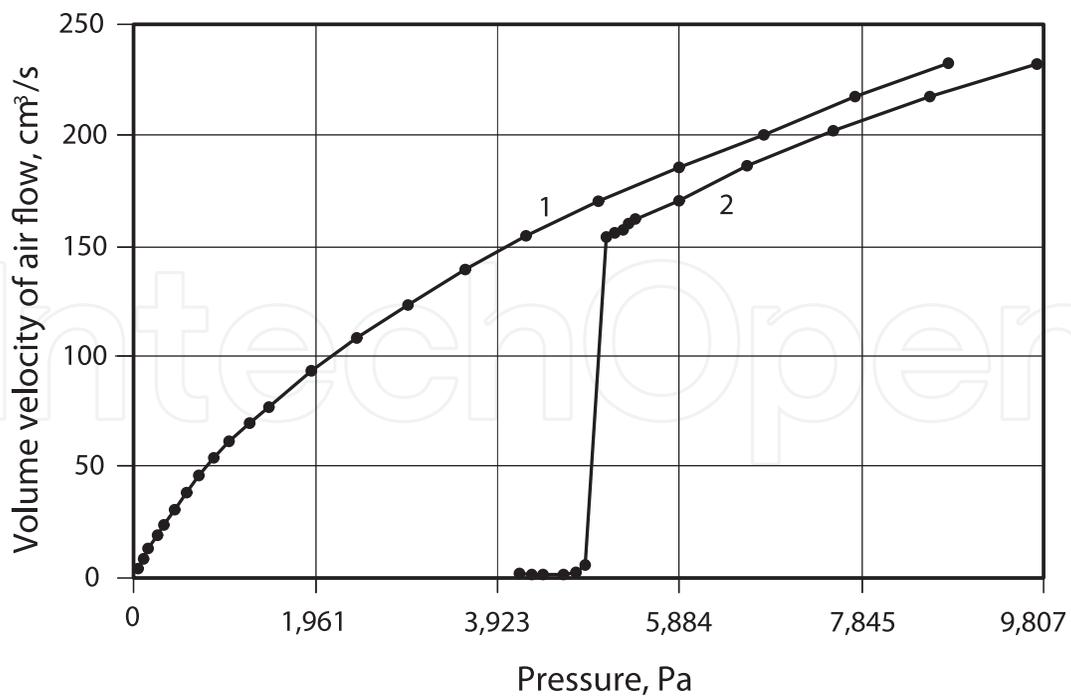


Fig. 4. Diagram of the volume velocity flow through open area of the sample (d) as a function of the pressure difference; 1 - velocity of the air flow through the dry sample; 2 - velocity of the air flow through the wet sample

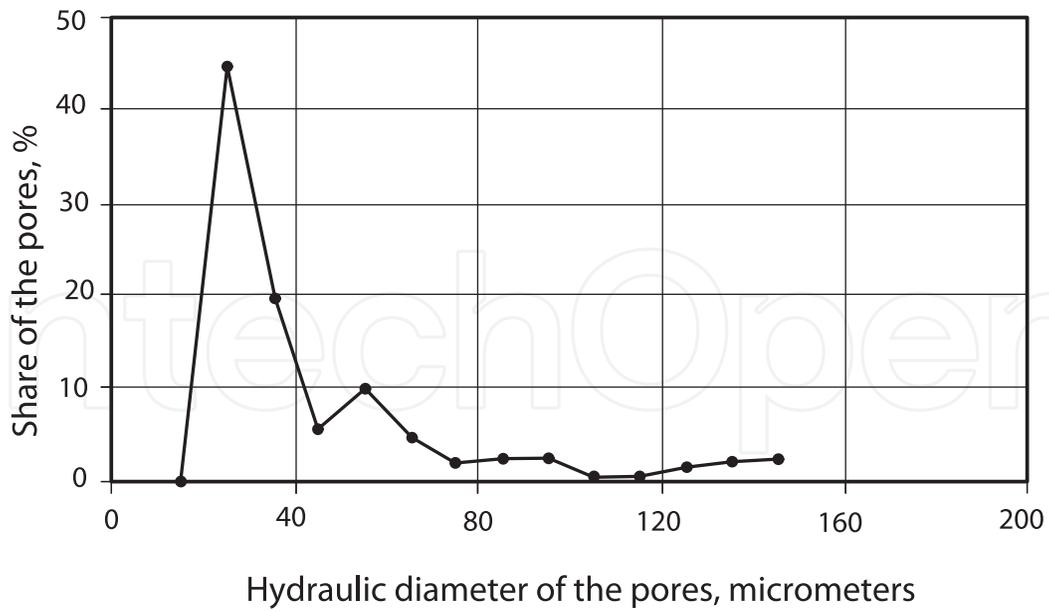


Fig. 5. Diagram of pore’s distribution in sample (a)

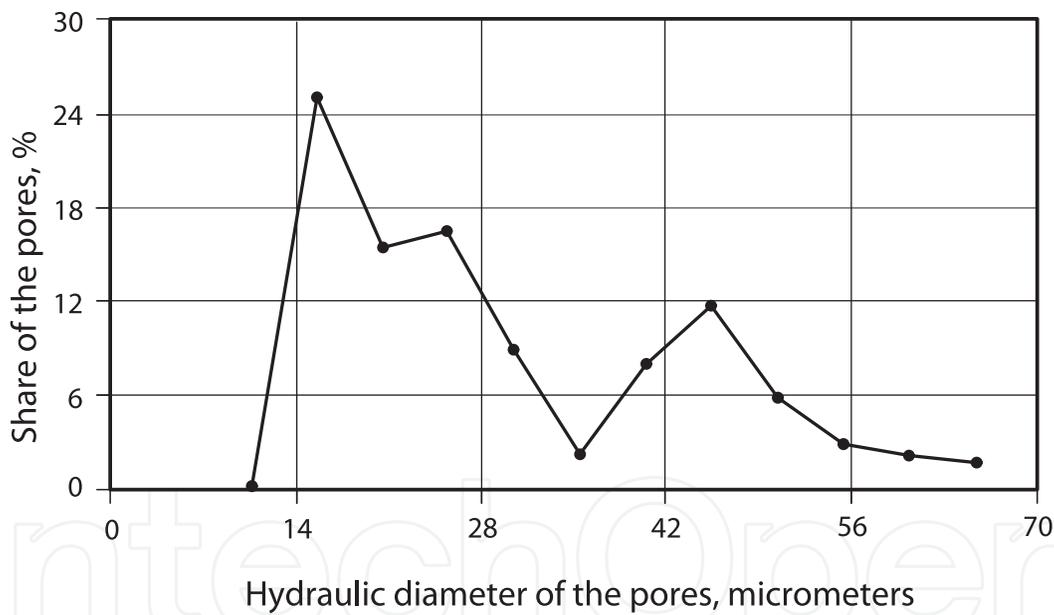


Fig. 6. Diagram of pore’s distribution in sample (b)

| Statistic parameters | w [μm] | l [μm] | d_t [μm] | $P_{real} = w * l$ [μm^2] | P_{hydr} [μm^2] | l/d_t |
|----------------------|-----------------------|-----------------------|-------------------------|--|--------------------------------|---------|
| Mean | 20.13 | 66.06 | 30.00 | 1364.67 | 786.29 | 2.50 |
| Standard deviation | 7.77 | 13.75 | 10.19 | 664.13 | 461.38 | 1.19 |
| Minimum | 4.76 | 23.81 | 8.82 | 287.12 | 61.07 | 1.04 |
| Maximum | 34.92 | 87.3 | 46.91 | 2519.68 | 1727.43 | 6.86 |
| Total | | | | 68233.43 | 39314.56 | |

Table 3. Results of the scanning-electron microscope pore’s shape and open area measured on 50 pores of the sample (b)

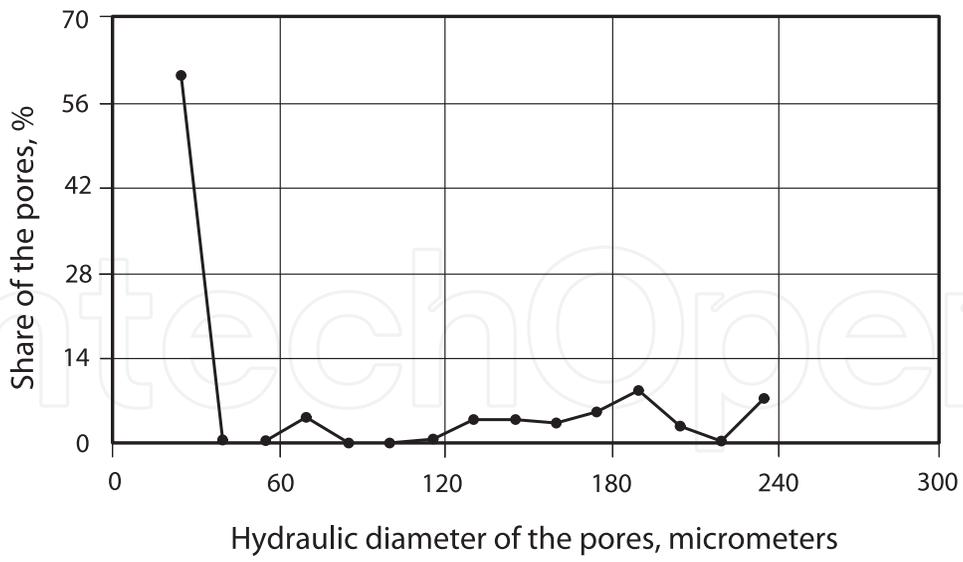


Fig. 7. Diagram of pore's distribution in sample (c)

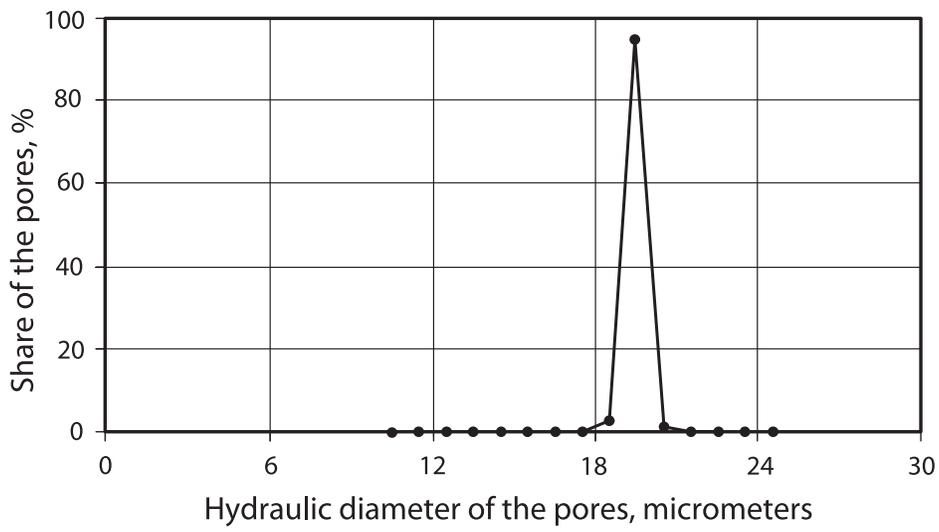
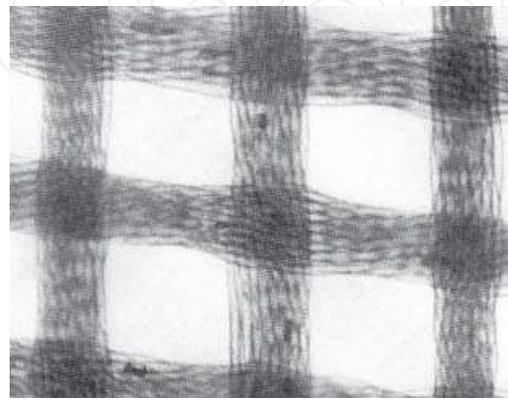


Fig. 8. Diagram of pore's distribution in sample (d)



Sample (a)



Sample (c)

Fig. 9. The photos of tested samples (a) and (c)

When dealing with the sample (b), the average ratio l/w , equation (2), in table 3 is $66.06/20.13 = 3.23$, see also figures 9 - 11. Hence, the criterion of having more than one hydraulic pore in a pore between threads of the warp and weft, figure 12, is thus met. The maximum value of the ratio between the value of the longer rectangular side l and the hydraulic diameter belonging the same pore is 6.84.

This results in almost doubling in number of hydraulic pores - from the 50 pores measured by the scanning-electron microscope with magnification of 630, a detail can be seen in figure 11b, to estimated 99 hydraulic pores. The real number of hydraulic pores is thus 4356, if the results in table 3 are extrapolated to the test area of 1 cm^2 , which is in good agreement, with 4112 hydraulic pores estimated by the J-method by using the second procedure, see table 2, sample (b). The difference in number of hydraulic pores is only 4.5 %. The true open area of pores extrapolated from results in table 3 to the test area of 1 cm^2 is 3.01 % and the true hydraulic open area 3.34 %. The estimated open area obtained by the method is 3.87 %, table 2, or 12.83 % more than true hydraulic open area, and 28.57 % more than true open area.

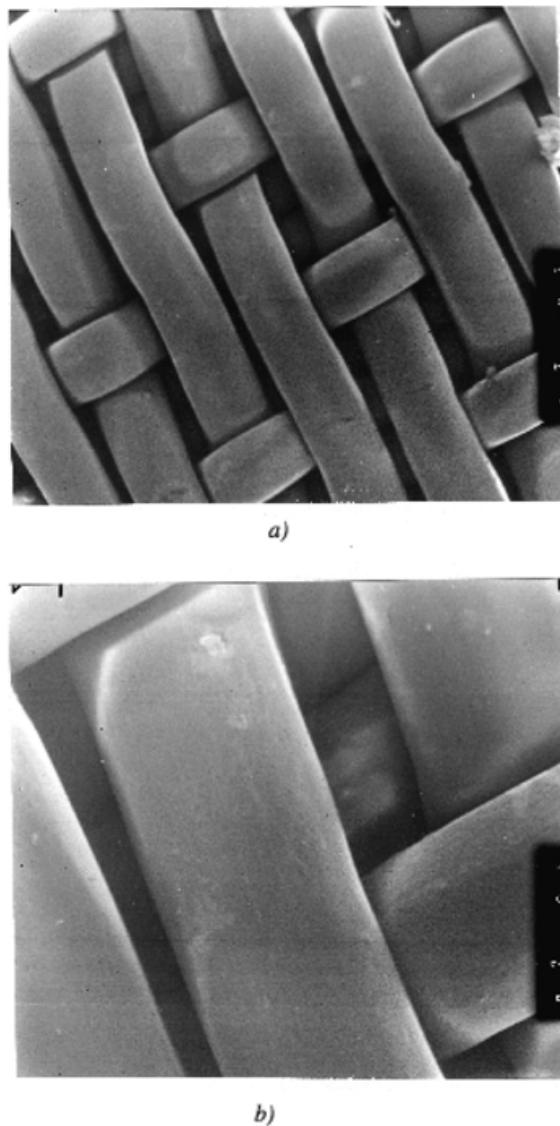


Fig. 10. Sample (b): a) magnification 63x, b) magnification 190x

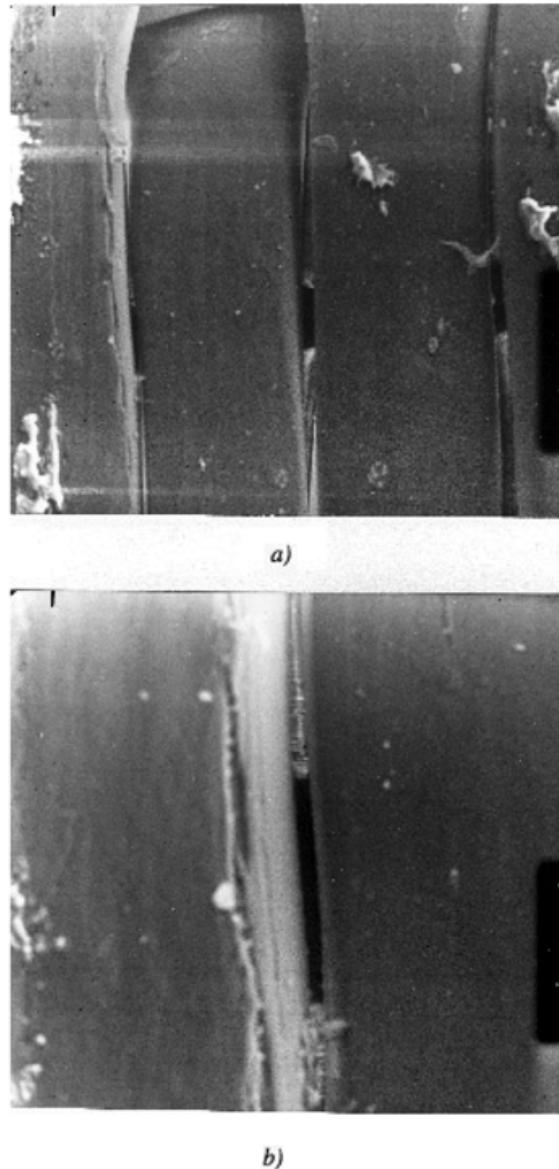


Fig. 11. Sample (b): a) magnification 190x, b) magnification 630x

The fibres that jut out of the yarn enmesh the pores between the threads of the warp and weft and thus dividing them into smaller pores with no regular geometrical shape if the textile is made of spinning yarn e.g. cotton woven fabric such as sample (a). The values of the porosity parameters of the cotton fabric obtained by the first procedure are shown in table 2. The most distinctive pore in voids between the threads of the warp and weft is taken into account when inspecting the fabric with a microscope and thus obtaining the number of pores of 452 and the average pore's hydraulic diameter of 53 micrometers. The lower value of the pore's hydraulic diameters set to 20 micrometers when computing the porosity parameters in this case. The value of a_0 , is high as well as the value of a_1 ($a_1 = 1.7416$), see equation (6). Both values are higher than theoretical maximum at $b = 0.5$. The number of pores is inversely proportional to the value of the coefficient a , equation (5), and the maximal value of the coefficient a , is 1.28. Hence, the porosity parameters of the samples (a) and also (b) are computed with the second procedure.

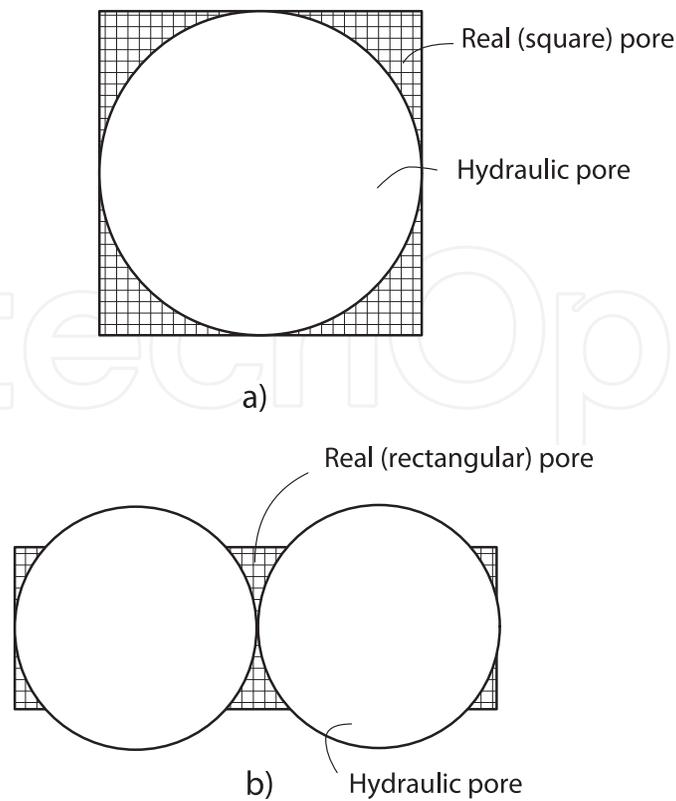


Fig. 12. Influence of the form of pores on the number of hydraulic pores in one pore between threads of the weft and warp in the woven fabric: a) square real pore, b) rectangular real pore

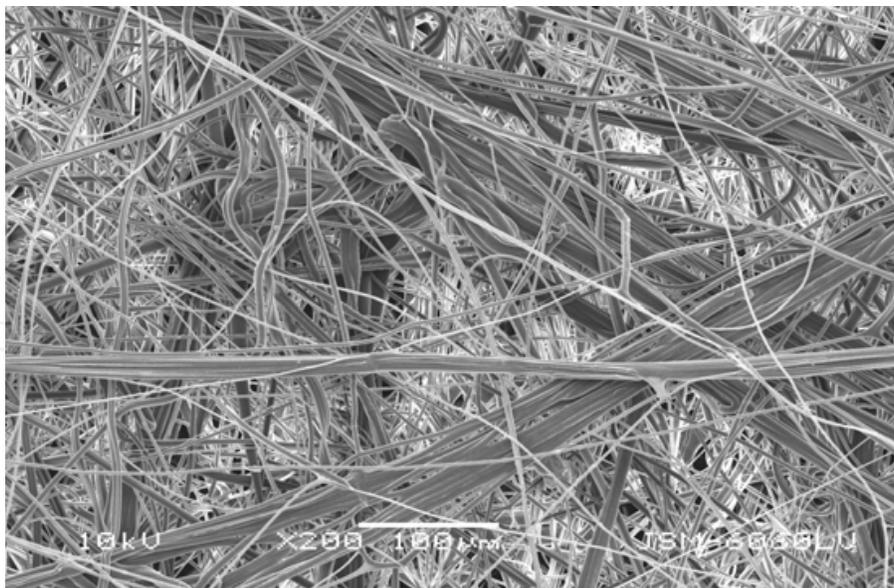


Fig. 13. The inner non-woven layer in the medical mask

The non-woven flat fabrics are extremely difficult to characterise in terms of porosity due to their irregular structure. The structure makes them better, more effective filtration media in comparison to the woven fabrics. Hence, the challenge is to estimate their porosity parameters. The experimental results presented in table 1, especially sample (b), proved that the porosity of the non-woven flat textiles can be estimated by J-method.

We have applied J-method in order to characterise the porosity of a medical mask. The mask fabric, figure 13, is composed of three layers. The data of layers is presented in table 4. The outer layer and the layer suite on the face of subject are composed from fibres which diameter is $18\ \mu\text{m}$. The inner layer is composed from microfibers which diameter is $2\ \mu\text{m}$. In this layer the fibres are arranged in 37 layers.

The walls of pores are defining by fibres. In contrast to a woven fabric, where pores are straight from one surface to the opposite one and where the length of pores is equal to thickness of the fabric, the pores in the non-woven fabric changes its direction and are thus much longer than the fabric's thickness. It is this property that makes them an excellent filtration media and at the same time, very difficult to characterise. Even though the viruses are much smaller than the hydraulic diameter of pores, the configuration of pores allows for 100% filtration efficiency.

The schematic airflow through the medical mask is shown in figure 14. The air flows through pores in a complex pattern. It is fairly difficult to developing a real theory of filtration due to that fact.

The number of the pores on $1\ \text{cm}^2$ is estimated as 63970, the maximal diameter of pores is $30.19\ \mu\text{m}$ and the open area (free for air flow) is 8.42%.

The results for porosity parameters estimated by J-method are presented in table 5 and the pore distribution in table 6. The coefficient a (regression equation (5) - flow air through dry sample) is 0.0890 and the exponent b (regression equation (5) - flow air through dry sample) is 0.7521. The mean hydraulic diameter of pores is estimated to the value of $12.46\ \mu\text{m}$, table 5. The nomenclature of table 5 is as following: d_{max} stands for the average pore diameter of the first interval (the largest pores), d_{min} stands for the average pore diameter of the last interval (the smallest pores), d_p stands for the average pore diameter of the sample and P stands for the average open hydraulic flow area.

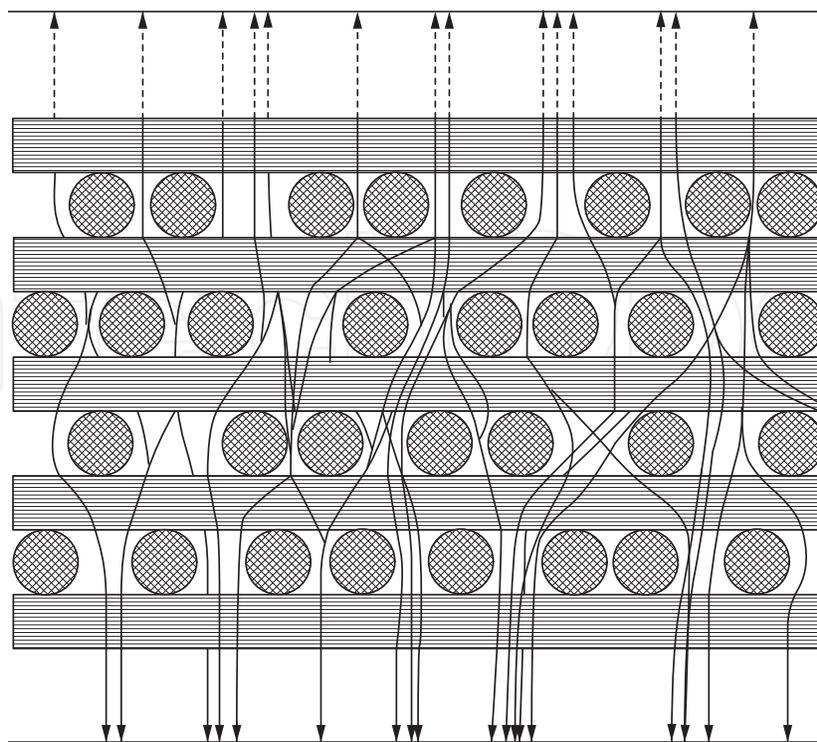


Fig. 14. Stream of air through the non-woven mask due to the respiration

| Non-woven layer | Mass [g/m ²] | Thickness [μm] | Numbers of the fibres layers | Thickness of the fibres [μm] | Active surface (not blocked whit resin) [%] | All surface of non-woven [cm ²] |
|---------------------------|--------------------------|----------------|------------------------------|------------------------------|---|---|
| Outer | 17.6 | 92 | 5 | 18 | 87 | 160 |
| Inner | 20.4 | 74 | 37 | 2 | 100 | 160 |
| Outer on the subject face | 19.1 | 120 | 7 | 18 | 75 | 160 |

Table 4. Comparison of chosen physical parameters of the fibres from different layers, that the mask is made of.

| Parameters of porosity | Outer non - woven layer | Inner non - woven layer | Outer on the subject face | Mask (all three non-woven layers) |
|---------------------------------|-------------------------|-------------------------|---------------------------|-----------------------------------|
| The biggest pore [μm] | 305 | 38 | 211 | 30 |
| dmax [μm] | 275 | 28 | 195 | 28 |
| dmin [μm] | 15 | 8 | 15 | 8 |
| dp [μm] | 83.2 | 12.46 | 76.3 | 12.61 |
| <i>b</i> | 0.6183 | 0.7313 | 0.6143 | 0.7521 |
| <i>a</i> | 0.249 | 0.0889 | 0.2925 | 0.089 |
| <i>P</i> [%] | 27.71 | 8.43 | 25.32 | 8.42 |
| Width of the classes [μm] | 13 | 2 | 18 | 2 |
| Number of the classes | 13 | 10 | 10 | 10 |
| Number of pores/cm ² | 3745 | 64016 | 4506 | 63970 |

Table 5. Parameters of porosity for all three non-woven layers of mask; the surface of samples: 1 cm²; liquid in the pores: n-butanol

| Meas. num. | Limits of the gradual classes [μm] | Hydraulic diameter of pores [μm] | Pressure [kPa] | Volumes flow [cm ³ /s] | Number of pores | Portion of pores [%] |
|------------|------------------------------------|----------------------------------|----------------|-----------------------------------|-----------------|----------------------|
| 1 | 26-28 | 27 | 0.360 | 0.924 | 136 | 0.36 |
| 2 | 24-26 | 25 | 0.389 | 2.115 | 184 | 0.19 |
| 3 | 22-24 | 23 | 0.423 | 4.412 | 388 | 0.57 |
| 4 | 20-22 | 21 | 0.463 | 9.833 | 1029 | 1.61 |
| 5 | 18-20 | 19 | 0.512 | 21.504 | 2488 | 3.97 |
| 6 | 16-18 | 17 | 0.572 | 41.916 | 4859 | 7.75 |
| 7 | 14-16 | 15 | 0.649 | 74.346 | 8770 | 13.82 |
| 8 | 12-14 | 13 | 0.748 | 113.669 | 11324 | 17.70 |
| 9 | 10-12 | 11 | 0.884 | 157.730 | 10611 | 16.59 |
| 10 | 8-10 | 9 | 1.081 | 219.088 | 24281 | 37.96 |

Table 6. Parameters of porosity for mask (for all three non-woven layers)

5. Conclusions

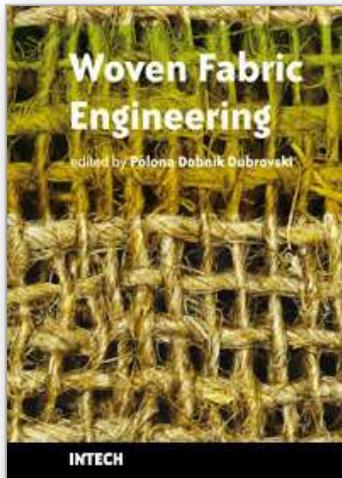
J-method of porosity assessment of the flat textiles is presented here. It enables us to compute maximal and average hydraulic diameter of pores and relative distribution of pore's diameters regardless of the type of the flat textile by using both procedures. It is also possible to compute distribution of pore's diameters and true value of the hydraulic open surface if the number of pores is known and first procedure is used. If the number of pores is unknown the second procedure should be used. In that case the distribution of pore diameters and true value of the hydraulic open surface are determined approximately but well enough to meet most requirements.

The results are in good agreement with those obtained by the microscope and scanning electron microscope. Considering the results obtained when testing woven fabric we have concluded that the method could be used to determine the porosity parameters of knitted fabrics and thinner non-woven fabrics.

Method is suitable for assessment parameters of porosity in textiles filters, if the average hydraulic diameters are in interval 5 to 200 μm (Jakšić, 2007).

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Woven Fabric Engineering

Edited by Polona Dobnik Dubrovski

ISBN 978-953-307-194-7

Hard cover, 414 pages

Publisher Sciyo

Published online 18, August, 2010

Published in print edition August, 2010

The main goal in preparing this book was to publish contemporary concepts, new discoveries and innovative ideas in the field of woven fabric engineering, predominantly for the technical applications, as well as in the field of production engineering and to stress some problems connected with the use of woven fabrics in composites. The advantage of the book *Woven Fabric Engineering* is its open access fully searchable by anyone anywhere, and in this way it provides the forum for dissemination and exchange of the latest scientific information on theoretical as well as applied areas of knowledge in the field of woven fabric engineering. It is strongly recommended for all those who are connected with woven fabrics, for industrial engineers, researchers and graduate students.

How to reference

In order to correctly reference this scholarly work, feel free to copy and paste the following:

Danilo Jaksic and Nikola Jaksic (2010). Porosity of the Flat Textiles, *Woven Fabric Engineering*, Polona Dobnik Dubrovski (Ed.), ISBN: 978-953-307-194-7, InTech, Available from: <http://www.intechopen.com/books/woven-fabric-engineering/porosity-of-the-flat-textiles>

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University Campus STeP Ri
Slavka Krautzeka 83/A
51000 Rijeka, Croatia
Phone: +385 (51) 770 447
Fax: +385 (51) 686 166
www.intechopen.com

InTech China

Unit 405, Office Block, Hotel Equatorial Shanghai
No.65, Yan An Road (West), Shanghai, 200040, China
中国上海市延安西路65号上海国际贵都大饭店办公楼405单元
Phone: +86-21-62489820
Fax: +86-21-62489821

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