Use of air permeability for determination of equivalent average pore diameter in woven fabrics

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Abstract. Scientific description of porosity/inner porous structure of textile fabrics is very complex mater and usually is made through description of so called porosity parameters. In general these are the size, number and distribution of pores in textile fabrics. Woven fabrics are the easiest case comparing them with knit and nonwovens fabrics since their structure is closer to any model representing textile fabrics. In spite many methods for determining porosity parameters no method is giving the full range of necessary results. The paper is dealing with introduction of newly developed method for determining equivalent average size of pores in woven fabrics. Equivalent average diameter of pores is defined as diameter of certain number of cylindrical pores that allow the same air permeability as real woven sample with the same number of pores (macro pores). It gives the real correlation with air permeability taking in account all characteristics of pores that participate in loose of energy i.e. the length of pores, their structure, their tortuosity and their bottle necks. The method combined with geometrical, porosity parameters determined by planar structure of woven fabrics can give connection between them and better understandings of porous structure in connection with its transmission properties.

1. Introduction
Air permeability is one of the important parameters of woven fabrics contributing to different practical application as clothing fabrics or technical fabrics (e.g. filtration, drying processes). It is the function of, so called, porosity parameters which are: the number, size and distribution of pores in the woven fabrics structure. Beside geometrical [1] and optical [2], there are several other methods for determining porosity parameters as are: mercury intrusion [3], liquid extrusion [4], fluid flow [5, 6, 7] methods. All of them are using some liquid material to be intruded in or extruded from previously saturated fabric [2, 3, 4]. From the connection between surface tension of used liquid and used pressure for its intrusion/extrusion is calculated the size and distribution of pores. As is obvious from the number of methods, no one is giving full range satisfactorily results. That because of measuring principle and measuring condition adapted for the primary measured parameter necessary for the purpose in use. Almost in all cases it is the size of pores but not always the same parameter of pores that could be the volume, the diameter or the throat of pores their minimal, maximal, average value and its distribution. The structure of pores in woven fabrics is complex and different which make them difficult to be described. For that reason many researches are treating them as cylinders with certain constant diameters and length equivalent to the fabric thickness. The definition of equivalent average pore diameter is such diameter of cylindrical pores structure with known number that allows the same air permeability as real woven fabric sample with the same number of pores. This is the basis of our approach to the problem which gives us the connection between equivalent average pore diameter and air permeability.
Equivalent pore diameter is a new introduced variable which takes into account not only diameter of pore but also all its internal structure like direction, walls of pores, throat, tortuosity. It can be obvious from the set of open woven fabrics in same warp and weft densities but in plain and 2/2 twill weave. Geometrically the size and consequently diameter of pores should be the same but in reality because the different type of pores the air permeability of fabrics in twill weave will be, depending on densities, up to 20% higher. Equivalent average pore diameter calculated from the air permeability measurements should show about 20 % bigger diameter.

2. Theoretical
As basis for development of model for determining average equivalent diameter of pores we used some facts of planar, geometrical presentation of one layer woven fabrics and some facts from fluid mechanics that describe the nature of flow through the fabrics.

2.1. Pores structure of woven fabrics
There are four types of pore in one-layer woven fabrics. Depending on weave one woven fabric can consists of only one (plain and twill 2/2), two types of pores (twill 1/2), three types of pores (twill 1/3) or sometimes even four types of pores [1]. The pores are rectangular shape and differ in dimensions, texture of pores walls, length and positioning of their bottle neck. Planar structure of pores presented in Figure 1b, does not take in account the third dimension of pores, but allow calculation of hydraulic diameter of pores that transfer the two dimensions (length and width) of rectangular pores to only one (diameter) of cylindrical shape according to equation (1).

\[ D_h = \frac{2 \times a \times b}{(a + b)} \]  

Where: a – the width and b – the length of rectangular pores

It simplifies presentation of pores and makes it closer to prediction of some permeability properties (air permeability). The biggest disadvantage of such defined hydraulic diameter of pores is that with the same constructional parameters in woven fabric construction ( fineness of yarns and densities) always gave the same resulting value no meter what kind of pore are in the woven structure.

![Figure 1](image-url) Four types of pores in woven fabrics showed three-dimensionally (a), in a planar way (b), and on the weaving paper (c) [1].

The lack of the third dimension properties of pores does not allow direct accurate connection between hydraulic diameter of pores and air permeability. There is need for other variable to be included in equation for more precise prediction of air permeability. In previous work we used for that, beside number of pores on square area the total porosity of woven fabric as compensation for missing data of third dimensions. The three variables were chosen because they can be determined easily from the
primary constructional parameters and physical properties of woven fabrics: theoretical diameter of yarns, the density of yarns and thickness and mass per square meter from which the total porosity is calculated. Linear combination of all three variables covers large amount of accurate prediction of air permeability of woven fabrics (2), (3).

\[ Q = f(\text{d}_h, n, \varepsilon) \]  

\[ Q = k_1 \times \text{d}_h \pm k_2 \times n \pm k_3 \times \varepsilon \]  

Where: \( \text{D}_h \) – hydraulic diameter of pores; \( n \) – number of pores in square area, \( \varepsilon \) – the total porosity of woven fabric and \( k_1, k_2 \) and \( k_3 \) – coefficients.

2.2. Theory of fluids flow

There are two types of flow in fluid mechanics theory - laminar and turbulent. Laminar flow is linear function of pressure drop and turbulent power function of pressure drop with exponent lower than 1.

The nature of flow in circular tubes is defined by so called Reynolds number. For Laminar flow Reynolds number must be lower or equal to 2200.

\[ R_e = v + d/\theta \leq 2200 \]  

where: \( v \) is the fluid velocity (m/s), \( d \) is the diameter of tube (m) and \( \theta \) dynamic coefficient of viscosity (m\(^2\)/s).

Exact solution of fluids flow through circular tubes in the range of laminar flow is giving Hagen-Poiseuille equation

\[ Q = \pi \times d^4 \times n \times \Delta p / 128 \times \mu \times l = A \times \Delta p \]  

Where: \( Q \) – volume flow rate (cm\(^3\)/s, cm\(^2\)), \( d \) – diameter of pores (cm), \( n \) – number of pores, \( \mu \) – kinematic coefficient of viscosity (Pas) in our case 1,8369 * 10\(^{-5}\), \( l \) – thickness of fabric/length of pores (cm) and \( \Delta p \) – pressure drop (Pa).

2.3. Development of idea for determining average equivalent pore diameter in woven fabrics

From the equation (5) is evident that if someone succeed to keep the flow through woven fabric in the range of laminar flow using very low pressure, from the very few measured pars of fluid flow - pressure can identify the coefficient A and from its value when number of pores \( n \) is known can calculate equivalent average diameter of pores according to equation (6).

\[ d_e = (128 \times A \times \mu \times l / \pi \times n)^{1/4} \]  

3. Experimental

3.1. Materials and Methods

To check theory we provided measurements on the set of referential samples. The samples were chosen among real cotton fabrics in certain domain of warp and weft densities in three basic weaves plain, twill 2/2 and twill 1/3. The weaves were chosen intentionally since plain and twill 2/2 weaves have only one type of pores and twill 1/3 have in its structure 3 types of pores. On the other hand the weaves differ in floating length which participate to their thickness and consequently to three dimensionality of pores. This is evident from Table 1 where all relevant parameters of investigated woven fabrics are given.
Table 1. Constructional characteristics of referential samples.

|    | Densities (D_w/D_f) | Measured densities (D_w/D_f) | Fineness Tex_w,f | Weave | Thickness cm | Mass g/m² |
|----|---------------------|-----------------------------|------------------|-------|--------------|-----------|
|    | Ends,picks/cm       | Ends,picks/cm               |                  |       |              |           |
| 1  | 22/15               | 21/15                       | Plain            | 0,439 | 143,91       |
| 2  | 22/20               | 21/20                       |                 | 0,438 | 166,59       |
| 3  | 29/15               | 28/15                       |                 | 0,468 | 180,41       |
| 4  | 29/20               | 28.5/20                     |                 | 0,514 | 209,50       |
| 5  | 22/15               | 22/15                       | 17 x 2           | Twill | 0,508        | 141,78    |
| 6  | 22/20               | 21/20                       | 2/2              | 0,504 | 160,66       |
| 7  | 29/15               | 29.5/15                     |                 | 0,604 | 173,34       |
| 8  | 29/20               | 29.5/20                     |                 | 0,568 | 197,48       |
| 9  | 22/15               | 21/15                       | Twill            | 0,565 | 141,36       |
| 10 | 22/20               | 21.5/20                     | 1/3              | 0,558 | 162,24       |
| 11 | 29/15               | 29/15                       |                 | 0,596 | 176,61       |
| 12 | 29/20               | 29/20                       |                 | 0,586 | 198,11       |

Table 1 is giving the relevant characteristics of referential samples. Methods used for determining measured characteristics were standard methods for evaluation physical characteristics of woven fabrics as are thickness, mass per unit area, warp and weft densities of woven fabrics and fineness of warp and weft/filling yarns. For measurements of air permeability through samples was used air permeability tester AIRTRONIC 4567 – Mesdan supplier. Tests were made on the area of 100 cm² under different very low pressure drops – up to 25 Pa.

4. Results and discussion

4.1. Results of measurements

Results of measurements are given in Figures 2. They present the linear part of curves pressure drop versus air flow with linear equations that include inclination angle and coefficient of regression. From the coefficient of regression is obvious that the measurements follow linearity in this part of curves. Using equation (6) and from the curves determine coefficient A in the linear part of curves and thickness of fabrics as a pores length we calculated equivalent pore diameters for every investigated sample. We also calculated hydraulic diameter of pores using same data and theoretically determined yarns diameter. The results of calculations are given in Table 2.

Table 2. Calculated average equivalent diameter (eq. 6) and hydraulic diameter of pores according to densities and weaves.

| Densities | Equivalent diameter of pores d_e (µm) | Hydraulic diameter of pores d_h (µm) |
|-----------|--------------------------------------|-------------------------------------|
|           | plain Twill 2/2 Twill 1/3 plain Twill 2/2 Twill 1/3 |
| 22/15     | 205,851 246,1053 265,3497   274,25   274,25   255,67 |
| 22/20     | 185,5703 198,133 204,4385   215,41   209,6    215,41 |
| 29/15     | 173,9767 191,5005 190,0493   151,24   134,93   126,88 |
| 29/20     | 126,8625 144,3573 138,4029   125,21   118,94   110,94 |
Figure 2: The regression curves of samples in plain weave (a), twill 2/2 weave (b) and twill 1/3 weave (c) with coefficient A and regression coefficient $R^2$.

4.2. Discussion

Because of differences between declared and real densities of referential samples the number of pores and also the hydraulic diameter of pores among weaves differ even should be equal if were used declared values of densities. In both cases, within calculating equivalent diameter of pores and hydraulic diameter of pores were used real, measured values. From table 2 is obvious that both, average equivalent diameter and hydraulic diameter of pores in plain weave are the smallest comparing them to twill weaves. Expectably all values of diameter of pores decrease with increasing of number of pores. We expected always the bigger value of average equivalent diameter but surprisingly were only partly right. It was valid only for the samples with higher densities of yarn in their construction (29/15 and 29/20). In samples with lower densities of yarns in their construction, in all cases we had bigger hydraulic diameter than equivalent diameter of pores (Figure 3). The explanation for that phenomenon lays in fact that in samples with higher densities yarns have limited possibility to deform in plain direction. Because of that the thickness and three dimensionality of pore is getting bigger which reflect in higher equivalent diameter of pores comparing to hydraulic diameter. In more open, low densities samples the yarns has
more possibility to deform in plain direction, diminish the thickness and make the equivalent diameter smaller than hydraulic diameter.

![Figure 3](image-url)

**Figure 3**: Comparison of identified equivalent \( d_e \) in hydraulic diameter \( d_h \) of pores in investigated samples

5. Conclusions
In the paper was presented a method for determination of newly introduced parameter of porosity – average equivalent diameter of pores. It explains the internal structure of pores in woven fabric better than geometrical hydraulic diameter since its determination comes from real measurements of air permeability. That way is taking in account all possible deformations of yarns in the fabric structure caused by yarns, weave and its particularity as well as weaving conditions. For justifying the reality of the equivalent diameter of pores we used hydraulic diameter of pores. The comparison showed that values are of same range. Based on equivalent diameter of pores, can be calculated more accurate value of open area for flow. The good thing is that such way of determination of porosity parameters is very fast and, cheap and at the same time accurate. The accuracy and additional description of woven fabric internal structure can be confirmed with geometrical, planar methods or optical methods. All of them are fast, non-destructive methods suitable to combine the results, which give the real picture of porous structure of woven fabrics and connect it with different kind of permeability.

6. References

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