The Aerodynamic Method in Studies of Selected Nonwovens

Abstract
This article briefly presents a new research method which enables the estimation of the internal structure of textiles, and also verifies the possibility of structure differentiation by this method, with two filtration nonwovens taken as examples. The method consists in blowing an air stream through the sample, and measuring the pressure drops at different mass fluxes. The theoretical model is based on the principles of conservation of mass and momentum, the mass conservation law, as well as the Darcy and Hagen-Poiseuille laws, and assumes the division of the sample’s thickness into layers. The geometrical and aerodynamic factors are calculated for every layer on the basis of measuring the pressure and the mass flux in the layers. Next, the research results of the local structures are also analysed globally, and presented as general dependencies. The calculation results are shown as curves which exhaustively present the structure properties of the textile material. Comparative results are presented for one structure of random fibre distribution and very high irregularity, and the second structure of fibres very regularly distributed in the layers. A test stand for the aerodynamic research of textiles is also described.

Key words: aerodynamic test method, textiles, flat textile products, nonwoven, filters, criterial numbers.

Introduction
The wide range of applications for textile materials, their different requirements, and the complex geometrical structures of their internal space make it necessary to use new, interdisciplinary research methods in order to meet the needs of textile users [1-3]. Aerodynamic methods are increasingly frequently applied for determining the usability characteristics of a wide assortment of textile materials, such as woven & knitted fabrics and nonwovens [5,12]. The authors have developed a new aerodynamic method which is briefly described in the next section. A more detailed description is presented in [8,9,11,19]. On the basis of this method, a measuring test stand has been developed. The method enables the evaluation of textile products’ properties, and their axial & circumferential irregularity, as well as the determination of physical modelling factors, hitherto not used in the aerodynamic research of textile products. Such factors are the Reynolds and the Euler numbers (Re, and Eu), and the Darcy coefficient (K), as well as the geometrical parameters such as number of ducts (j), diameters of ducts (d_k), and the specific surface (f) of the sample. The studies can also be used for the comparative analysis of various textile materials and the evaluation of their suitability for different industrial applications. The instruments used so far (e.g. the Tilmet-10p, designed at the Technical University of Łódź, and the FF-12 available on the market) do not enable the determination of the mentioned-above factors. This article presents the results of the first comparative investigations carried out on two nonwovens with very differentiated internal structures and destined for filters, by using the new research method. The structures selected are characterised by the following features: the first by random fibre distribution and very high irregularity, and the second by fibres very regularly distributed in layers. The aim of the preliminary work was to determine the characteristic dependencies of both nonwovens, and to estimate to what degree their structural differentiation influences their aerodynamic properties as presented by the dependencies obtained.

Methodology of Experimental Studies
The research method consists in blowing an air stream through a textile sample of a porous structure; it can be applied to different flat textile materials. The

Figure 1. Multilayer duct model of the tested duct structure.
flow is described by the Darcy and Poiseuille-Hagen laws and by the principles of conservation of mass, momentum and energy [4,6,8]. The flow is considered as incompressible and isothermal.

The experimental stand (Figure 2), described in detail in [6-8], was equipped with the following devices: a measuring cassette (PKF) containing the sample, manometers (MB), a Roots blower (DR) with a controlled rotational speed n≤3000 rpm working on suction, flow meters for measuring the air mass flux up to =0.05 kg/s (a turbine flow meter measuring m₀ and an El-flow meter measuring m₁), control valves ZR1 and ZR2, and a cut-off valve ZO. The dust generator GP is an additional device used for studying the filtration properties of textile products with dust application.

Table 1. Material characteristics of filtering samples (PA - polyamide, PET - polyethylene terephthalate).

<table>
<thead>
<tr>
<th>Sample symbol</th>
<th>PR-I</th>
<th>PR-II</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type of raw material</td>
<td>PA</td>
<td>PET</td>
</tr>
<tr>
<td>Average thickness of fibres, μm</td>
<td>300</td>
<td>25</td>
</tr>
<tr>
<td>Apparent density, kg/m³</td>
<td>107.7</td>
<td>113.7</td>
</tr>
<tr>
<td>Porosity</td>
<td>0.90</td>
<td>0.92</td>
</tr>
</tbody>
</table>

The theoretical model of our investigation [9] assumes that the the sample thickness is divided into layers, as well as simultaneous measurements of the mass flux \( \dot{m} \) and the flow resistance \( \Delta p \) for each layer of thickness \( \Delta g \), and for the whole thickness \( g \) of the sample. Measurements are carried out at different volumes of the air stream. The method presented is based on a multilayer duct model shown in Figure 1 and described in detail in [8]. This model, especially designed for analysing filter properties, is characterised by an internal filtration zone of thickness \( g \), and the inlet and outlet convection zones.

The experimental stand (Figure 2), described in detail in [9,10], was equipped

![Figure 2. Experimental test stand; p, T, w - pressure, temperature and humidity (all controlled) of the incoming air; \( \dot{m}_0 \) - air mass flux, GP - dust generator; PKF - measuring cassette with sample; MB - manometers at particular individual layers; P - pressure (vacuum) meter; T - thermometer; \( m_f \) - turbine flow meter; \( m_{EL} \) - El-flow meter; ZO - cut off valve; ZR1, ZR2 - control valves; DR - Roots blower.

The results of experiments and calculations are presented in diagrams. The tests can be used for the comparative analysis of different textiles, and for evaluating their usefulness for specific industrial applications; filtration may be one good example of this. In this paper, the results of local measurements are presented, as are generalised dependencies of the studied parameters.

### Theoretical Bases

In each layer \( i \) there are \( j \) ducts of diameters \( d_{ki} \), described by the following geometrical relations:

\[
j = \frac{D}{\Delta k} \frac{\eta \, \Delta m}{\pi \, \rho \, D^2 \, \varepsilon \, \Delta p}
\]

The mathematical definitions of the number \( j \) and density \( \bar{j} \) of ducts, as well as of the criterial numbers, are described in detail in [6-8].

On the basis of measurements of \( \dot{m} \) and \( \Delta p \), and the Hagen-Poiseuille law [1,6] for a single duct, the duct diameter \( d_k \) can be calculated as follows:

\[
d_k = \sqrt{\frac{128 \eta \, \Delta m}{\pi \, \rho \, D^2 \, \varepsilon \, \Delta p}}
\]

The permeability coefficient \( K \) of the layer is determined from the Darcy law [1,4]:

\[
K = \frac{\dot{m} \eta \Delta m}{A \rho (\Delta p + \rho \, g \, \Delta z)}
\]

where the gravitational acceleration \( g_0 \approx 9.81 \text{ m/s}^2 \).

The Reynolds and Euler numbers [7-11] are calculated from the following equations:

\[
Re_k = \frac{4 \, \dot{m}}{\pi \, \eta \, \bar{j} \, d_k} \quad \text{Re} = \frac{c_e \, D \, \rho}{\eta}
\]

\[
Eu = -\frac{\Delta p}{\rho \, \varepsilon \, \Delta z}
\]

### Results of Experimental Studies

The experimental studies were carried out for two types of textile nonwoven samples (PR-I and PR-II), destined for filtering material, both in the shape of a cylinder with height \( g = 38 \text{ mm} \) and diameter \( D = 80 \text{ mm} \). PR-I was a structure made from fibres with a random arrangement of fibres and very large structural irregularity, whereas PR-II consisted of non-woven layers with fibres with a very high level of arrangement of parallel-positioned fibres (Table 1). The PR-I nonwovens were manufactured by hand from curled fibres (Table 1).
polyamide monofilaments glued with foamed butadiene-styrene latex. The final product consisted of latex in the amount of 10% dry mass. In this way a product was achieved with a random arrangement of fibres and high structural irregularity, but with a near point-like structure of the joints. On the other hand, the PR-II nonwovens were manufactured by carding (twice) with longitudinal fibre arrangement. Next, the fleece obtained was joined by needling. Such a technology enabled a very regular structure of parallel positioned fibres to be obtained. The samples destined for tests consisted of four nonwoven layers prepared as mentioned above.

The results of the experiments, as the average values of four measurements of the samples tested, are presented in Figures 3-9 for different values of mass flux ($m$). Figure 3 shows an example of the basic measurement results for both non-woven samples, the values $\Delta p_i$ as a function of the distance from the inlet $z$ for four selected values of mass fluxes. In Figure 3, the measuring points obtained are presented, as well as the approximated dependencies, which are marked by dotted lines. The existence of an intersection point $H$ (which indicates an equal pressure drop at a given distance from the inlet) of the measurement curves for both samples, which changes in dependence of the mass flux, suggests different manufacturing technologies of the samples tested. The results of calculations of the diameter $d_k$ according to equation (2), the number of ducts $j$ according to equation (1), and the Darcy coefficient $K$ (3) inside the studied samples, are shown in Figures 4, 5 and 6 respectively. The local characteristic curves show further specific effects related to the method of samples’ manufacture and their internal geometry. Further diagrams (Figures 7-9) describe the ‘global’ properties of both samples. The Reynolds number $Re_k$ is a value calculated in relation to the arithmetic average of the duct diameters of the whole sample, whereas $Re_0$ is the Reynolds number at the inlet of the pipe of diameter $D$ serving as the measuring cassette. Figure 7 shows the interrelation between these two Reynolds numbers for both nonwovens, whereas Figures 8 and 9 show the dependencies of $Re_k$ and the Euler number respectively, both on the mass flux. Independently of the experimental curves determined by the calculations based on the measuring points, the proposed approximation dependencies are drawn for all the above-discussed quantities, presented by dotted lines in Figures 7-9.

**Summary**

All the dependencies presented in this article are clearly different for both kinds of nonwovens, related to their qualitative and quantitative property differences. The following facts should be emphasised:

- The curves, which directly characterised the measurements (presented in Figure 3), have different inclinations to the $z$-axis, and for the different nonwovens they intersect in a point ($H$) of an abscissa increasing with the increase in mass flux.
- The local characteristic curves of duct diameters, density of ducts, and Darcy coefficients, presented in Figures 4, 5, and 6, have distinctive local maxima for the PR-I nonwovens, whereas the curves for the PR-II nonwovens are relatively flat.
Figure 4. Local characteristic curves of duct diameters vs. distance from inlet surface $d_k=f(z)$ at different air mass fluxes $\dot{m}$ in the pipe of the measuring cassette for both kinds of nonwovens PR-I and PR-II.

Figure 5. Local characteristic curves of the density of ducts vs. distance from inlet surface $j=f(z)$ at different air mass fluxes $\dot{m}$ in the pipe of the measuring cassette, for both kinds of nonwovens PR-I and PR-II.

Figure 6. Local characteristic curves of Darcy coefficient vs. distance from inlet surface $K=f(z)$ at different general characteristic curves of Reynolds number in the pipe of the measuring cassette, for both kinds of nonwovens PR-I and PR-II.

Figure 7. General characteristic curves of Reynolds number in pipe vs. Reynolds number in the ducts $Re_{0}=f(Re_k)$, for both kinds of nonwovens PR-I and PR-II (the points calculated for different air mass fluxes); the dotted lines indicate the proposed approximated dependencies.

Figure 8. General characteristic curves of Reynolds number in the ducts vs. air mass fluxes $\dot{m}$ in the pipe $Re_{0}=f(Re_k)$, for both kinds of nonwovens PR-I and PR-II; the dotted lines indicate the proposed approximated dependencies.

Figure 9. General characteristic curves of Euler number $Eu=f(Re_k)$, for both kinds of nonwovens PR-I and PR-II; the dotted lines indicate the proposed approximated dependencies.
Corrections

The general dependencies, which are related to the criterial numbers, differ for both the nonwovens by their inclination to the abscissa axis, as is clearly visible in Figures 7-9.

Conclusions

The proposed approximated dependencies shown in Figures 6-9 enable the determination of differences related to selected parameters of various textile samples tested.

Analysing textile materials by the aerodynamic method proposed by the authors enables the differentiation of their internal structure which depends on the manufacturing technology and raw materials used. This suits this method for the modern analysis and comparison of textile materials, e.g. by considering their usage characteristics.

The different character of the local factors in the function of the distance from the inlet surface \((z)\), which depends on the air mass flux, and the high non-linear character of the global curves (also as a function of the air mass flux) indicate that investigating the aerodynamic features at one selected air mass flux may be insufficient for estimating the textile products’ properties of usage. This statement is valid especially for textile products destined for specific applications. Unfortunately, such a procedure is prescribed for the air permeability measurements of textile products by standard PN-EN ISO 9237 [13].

Obtaining a total description of the properties of the textile material tested as a function of all the factors presented in this work, the geometrical factors (Figures 4 and 5), as well as the criterial factors (Figures 6-9), requires that the tests be conducted in a broad range of air mass flow. Only a method like that described in this article allows the complete aerodynamic characteristic of the textile barrier to be obtained.

Acknowledgement

The investigations presented in this article were carried out within the scope of the supervised research project entitled ‘Modelling of Characteristic States of Gaseous Dust Filtration in Nonwovens’, sponsored by the Ministry of Science, Polish Committee of Scientific Research, No. 3 TO8 020 27E.

References


Received 07.04.2004   Reviewed 18.07.2004