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Device for Measurement of Static and Dynamic Air Permeability and Deformation Changes in Textile Materials

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Abstract
This article investigates the measuring of the air permeability of textiles. A new instrument designed to measure the air permeability of textiles is described in the article. The instrument differs from the standard devices mainly due to the components added, which enable the dynamic measurement of air permeability and give the possibility to investigate the structure of the textile tested during the process of measurement. Individual user settings are described and examples are given of how to process the data obtained. The device is operated by a control program. Contrary to the manual devices, the error introduced by the operating personnel is minimised in terms of setting up the measurement and reading the data measured. The device is controlled by a computer and the data obtained is stored in an electronic form for further processing.

Key words: *air permeability, device, static measurements, dynamic measurements, textile material.*

Air permeability measurement of textiles

Air permeability is generally understood as the transmission of air through a material. Air passes through the textile through inter-yarn and inter-fibre spaces (pores). Air permeability depends on the amount and size of pores, which enable air to pass through the textile. Permeability is defined as the speed of the air flow passing perpendicular to the textile sample at a defined pressure difference on the opposite sides of the textile, as well as in terms of the time and testing area. The measurement is normalised by standards, for example Czech standard ČSN EN ISO 9237 [1], which is identical to EN ISO 9237:1995 [2], the British standard [3], or German standard [4] etc.

Air permeability is an important utility characteristic of a textile material. The permeability of textiles used in clothing influences thermal regulation of the human body and comfort during wearing and also plays a role regarding health issues. This property is also important in technical textiles – in some cases such as airbags or parachutes low air permeability is desirable, and in filtration textiles the permeability needs to go hand-in-hand with the type of usage.

Air permeability is measured by creating a pressure difference between the opposite sides of the textile material investigated. In consequence of the pressure difference applied, there is an effort to minimise this difference, and therefore air passes through the open spaces in the textile. To create the pressure difference, a suction-pump is used, which sucks air, thus creating a lower pressure under the textile. Another possibility is to use an air-pump, which creates a higher pressure under the textile, and thus the air passes through the textile.

A general layout of the device is depicted in ***Figure 1***. This device is based on a suction-pump sucking air through the textile fastened in the fastening clamp. Depending on the air permeability of the textile, a pressure difference is created and is measured by the differential pressure sensor. The amount of air is measured by the flow meter and is regulated by the valve. [5]

Static and dynamic air permeability

We acknowledge the static and dynamic air permeability measurement.

In the static case, textile materials are evaluated at a constant pressure difference. In this case the amount of air which passes through the textile in the fastening clamp is measured when the pressure difference stabilises. During the experiment, air passes in one direction only. The above-mentioned standards [1 - 4] are based on this static version of air permeability measurement and are used for common assessment of textiles.

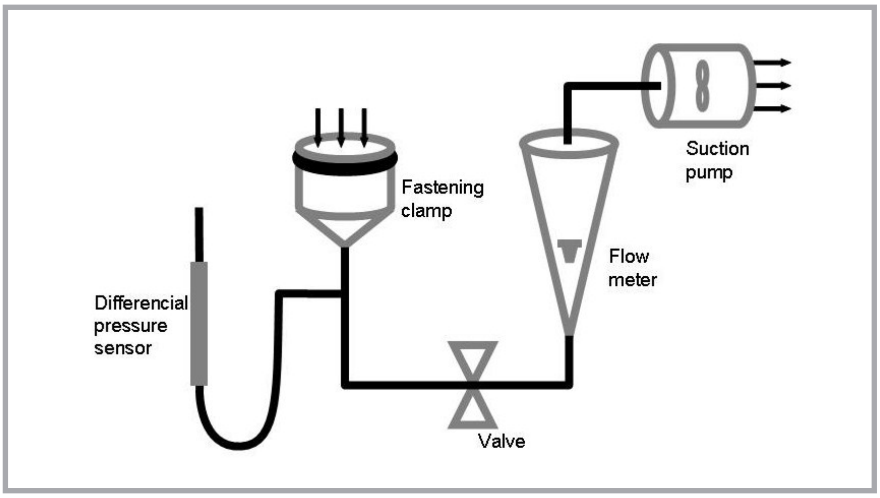

Figure 1. *General diagram of the device for air permeability measurement (with a suction-pump) [5].*

Contrary to static measurement of the textile air permeability, the dynamic solution also takes into account the changes in pressure difference affecting the textile. These changes are common when textiles are used in real life, and thus it is appropriate to asses textiles also according to the dynamic air permeability. An example of a practical case here are the properties of airbags and parachutes, or sports clothing.

Dynamic air permeability assessment was investigated by Gniotek and Tokarski [6] in their work. To measure dynamic air permeability, the authors use a device which has an air-tight piston moving in a cylinder attached in the position of the fastening clamp. Displacement of the piston changes the pressure difference dynamically. The device is described in their work [7]. Based on static and dynamic measurement, they determine the index of dynamic air permeability, which can be used when comparing the properties of textiles from the point of view of behaviour under static and dynamic stress. Tokarska in her work [8] modernises the dynamic air permeability index, which characterises the textile in terms of the yarn layout within the structure.

The dynamic air permeability was also investigated by Xiao et al. in their work [9], in which they describe an experimental study of the dynamical air permeability of textiles. In the work, a device is used and described, designed by Bandara et al. [10], which enables to measure the air permeability at high pressures, using a pressure regulator and tank to pressurise the air.

Behaviour of textiles during measurement

The basic observation of textiles during air permeability measurement shows that the surface of the sample is deformed under the pressure applied. This phenomenon is mentioned in a number of articles from various points of view. They are summarised, for example, in the work of Havrdová [12]. The most important is the horizontal and vertical increase in porosity.

The horizontal increase in porosity is caused by the bulging of the sample in the fastening clamp when air passes through during the air permeability measurement. The pores tend to open in the sample tested and, thus, increase in size. Therefore more air can pass through the enlarged pores, which may significantly influence the outcome of the measurement. Some devices contain a supportive grid in the shape of a cross placed on the axis of the fastening clamp. Havrdová determines in her works [11, 12] how important this supportive grid is and proposes further additional support of the sample measured. In her works she describes the bulging of the sample as a spherical cap. The size of the bulge, however, is not measured, only estimated. On less permeable textiles the bulge plays an important role and should not be neglected.

The vertical increase in porosity relates to the longer sections of yarn, which move during the measurement due to the air passing through,thus dilating these sections further apart. New pores arise in consequence of this dilation, and these may change in the course of the measurement. Havrdová – Havlová describes this phenomenon in detail in her work [13] and models other additional pores than those mentioned by Backer [14]. The pore cells analysed in Becker's work are a basis for many further works, for example [15].

Devices for air permeability measurement

Currently many devices are available on the market, which are standardised, to measure air permeability according to standards for measurement of textile air permeability.

Most of these devices are controlled partially or fully by the operator. Their use is single-purpose.

Devices available at the Faculty of Textile Engineering of the Technical University of Liberec serve only to measure the air permeability of textiles as such, and it is impossible to observe further phenomena which are connected with air permeability measurement, such as the change in the pore size or textile deformation.

With the aim to construct a device which would have broader use in the area of science and research, a new device for textile air permeability measurement was developed. Our quest was to minimise the errors caused by incorrect operation of the device, and we wanted this instrument to enable to observe textile behaviour during air permeability measurement.

Device MPT01

Our new device for air permeability measurement of textiles, which was named MPT 01, consists of intelligent sensors and components communicating with a PC. Thus automated measurement is enabled. Furthermore, the device is equipped with components that enable to observe the structure of the textile in the course of the measurement. The first version of the device was designed and described in work [16].

This device was developed with the aim to measure the air permeability of textiles and to investigate the behaviour of the structure of the textile sample in the fastening clamp. The main goal was to make the entire air permeability measurement as automated as possible, thus minimising errors in measurement which may arise due to improper manual settings and reading of the values measured. In addition, the device is equipped with further elements enabling to observe the structure and measure changes in the textile during the air permeability measurement itself. The program processes the data obtained and stores them in a text file, where it is accessible for further processing. The principal of the measurement is to create pressure under the textile, thus pushing air through the clamped textile. The principal of the device is shown in a block diagram (***Figure 2***).

The compressed and purified air is fed to the flow meter and then to the regulator. The regulator controls the amount of air passing through the sample. The clamp holds the sample of the textile investigated. The pressure difference on opposite sides of the textile is measured by a differential pressure sensor with one input under the textile sample and the comparing input of atmospheric pressure above the fastening clamp (above the sample). As the amount of air passing through the regulator changes, the pressure difference on opposite sides of the textile also changes. When the pressure difference desired is achieved, the permeability of the textile is calculated. The device is equipped with three differential pressure sensors, between which the user can choose with respect to the type of measurement, depending on the permeability of the textile investigated and require-

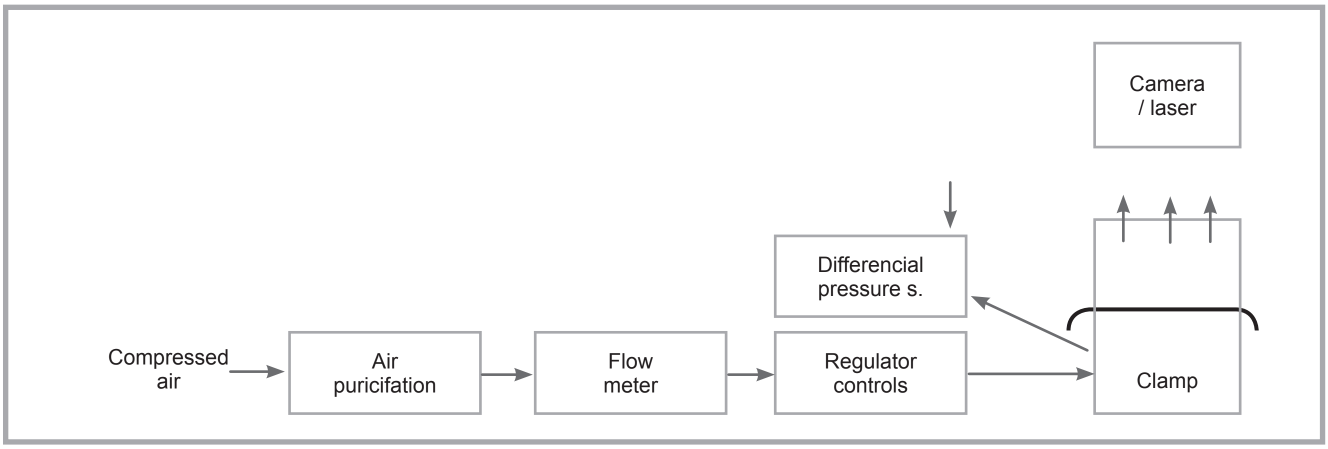

Figure 2. Block diagram of the MPT 01 device.

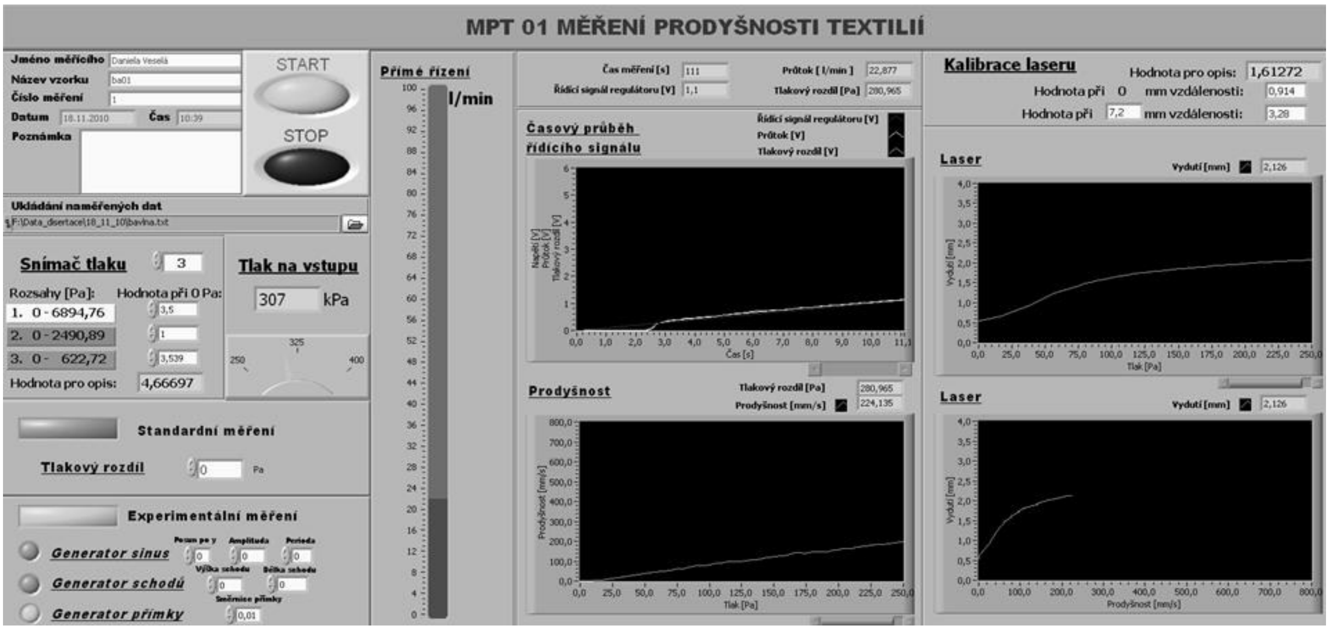

Figure 3. GUI (Graffical user interface) for controlling the MPT01 device.

ment for accuracy of the measurement. In the case of measurement according to common standards concerning air permeability measurement, that is at a pressure difference of 100 or 200 Pa, sensor n. 3 is used, which has a range of 0 – 2,5 in H_2O (0 - 622 Pa). For experimental measurement of low-permeable textiles the other two sensors are used.

The construction of the fastening clamp and the adjacent setup in the form of a specialised stand (holding either the camera or the laser) enables to follow the behaviour of the textile during the measurement.

All the sensors and the regulator are so-called intelligent components and are connected to a PC. The computer communicates with the components exploiting LabVIEW software, which controls the entire measurement; a program designed by the author and created in this environment (***Figure 3***, based on a joint work [17]) which controls the measurement, stores the data measured, processes and analyses the values and, last but not least, follows the entire process of measurement and provides electronic protection to all components from possible damage.

Following the structure of the textile

The device enables to observe the movement of the textile in two ways. The first option is to observe the structure of the textile using a camera, which visually depicts changes occurring in the textile in the horizontal plane, meaning in the plane determined by the x & y axes.

The second possibility is to observe the movement of the textile in the z axis using a laser, which measures the size of the bulge in the sample in the course of measurement of air permeability (from now on we denote the size of the bulge *v*).

The operator has to pick one of these options, but in our setting it is technically impossible to realise simultaneously the visual recording and measurement of the amplitude of the bulge.

To allow visual recording of behaviour of the textile using a camera, the clamp for fastening the textile sample had to be equipped with an illumination apparatus with the possibility for set intensity of the light applied (***Figure 4***).

Visual recording of the structure of the textile is provided by a camera with accessories, which is fitted above the fastening clamp. The camera communicates with the PC using 'Nis-Elements' software. The camera can be coupled with specialised objectives and filters to provide the imaging desired. The assembly also contains illumination from above, which is provided by an illumination circle. In (***Figure 5***) you can see examples of the images obtained by the camera. In the left photo, we can see a highlighting of the 2D projection of the pores between yarns, whereas in the right photo, we can see the behaviour of hair and yarns on the surface of the textile.

The structure is observed continuously during the measurement. It is possible to store recorded sequences, or to store individual images for further processing. To investigate the behaviour of the textile in the direction of air flow (z axis), measurement of the bulge amplitude is more important than the visual observation of changes in structure.

To provide an exact measurement of the bulge amplitude of the sample during the air permeability measurement, a laser distance sensor is used (***Figure 6***). This sensor is placed on a micro-sledge clamped to the stand, and thus its movement in directions x, y, z is enabled. The laser aims at the centre of the area in the fastening clamp.

The textile in the fastening clamp moves in the direction of the flow of air passing through the sample (vertical direction from bottom to top) due to the higher pressure under the textile (***Figure 7***). Changes are apparent when the pressure difference varies.

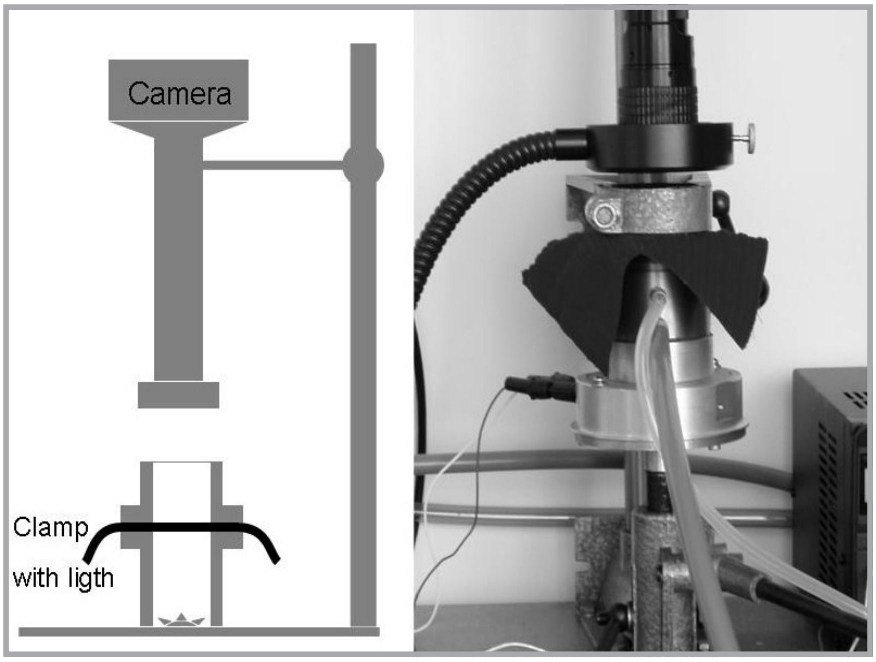

Figure 4. *Fastening clamp adjusted to enable observation of the structure of the textile.*

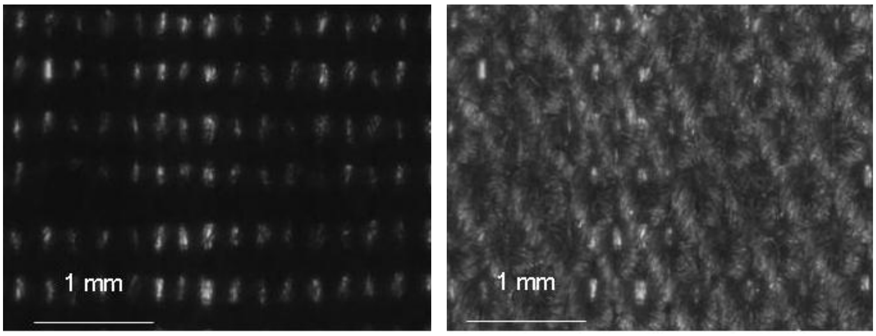

Figure 5. *Photograph of a woven textile without illumination from above (left) and with illumination from above (right).*

Accuracy of measurement on the MPT 01

Considering the uncertainties of measurement and the inaccuracies of the device, we need to take into account two parts of the measurement. The first part is the exact setting of the pressure difference, including determining its uncertainty of measurement. In the second part we determine the uncertainty of the permeability measurement. Another quan-

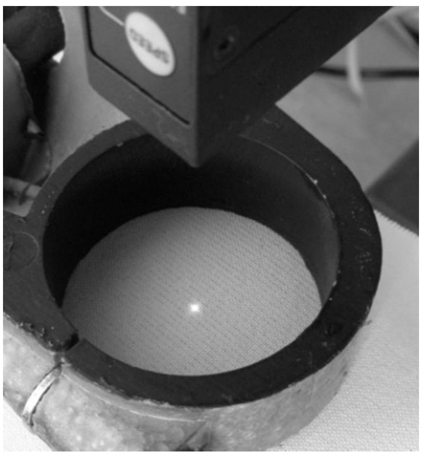

Figure 6. *Bulge measurement using laser.*

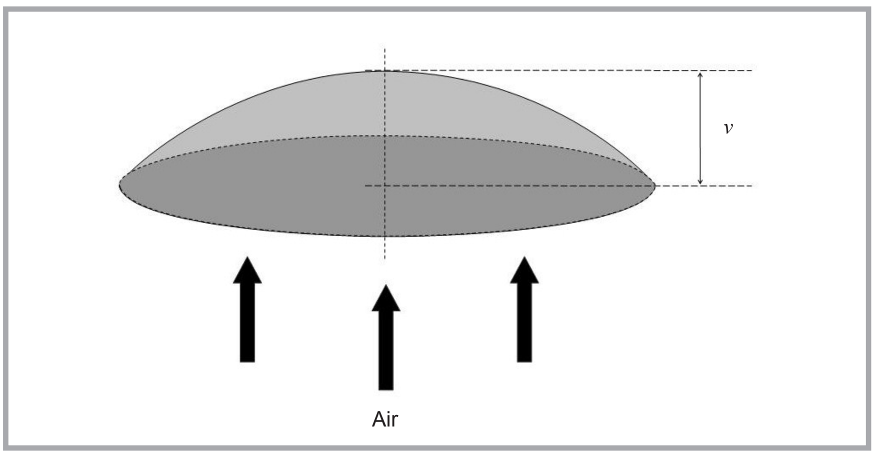

Figure 7. *Schematic image of a sample bulge of magnitude v.*

Table 1. *Determination of the Type B standard uncertainty u_b*;* ***Note****: 1) For reading the data during the measurement manually by the operator.*

Item	Sensor / Element	Measuring range	u_b^*
Pressure differences	Differential pressure sensor No. 3	0 - 2.5 in H_20 (0 - 623 Pa)	2 Pa F.S.O. (Full Scale Output)
	Differential pressure sensor No. 2	0 - 10 in H_20 (0 - 2491 Pa)	15 Pa F.S.O.
	Differential pressure sensor No. 1	0 - 1 psi (0 - 6895 Pa)	20 Pa F.S.O.
Air permeability	Flow meter (0 - 100 $l{\cdot}min^{-1}$)	0 - 833 $mm{\cdot}s^{-1}$	5.7 $mm{\cdot}s^{-1}$ F.S.O. (6.4 $mm{\cdot}s^{-1}$ F.S.O.)1
	Size of the area in clamp (0.002 m^2)		
Bulge	Laser sensor	0 - 14 mm	0.004 mm F.S.O.

Table 2. *Example of uncertainties for one measurement of the air permeability and measurement of the bulge of the sample.*

Item	Sensor / Element	u_a	u_b^*	u_c	U (K = 2)	Given measurement with U (K=2)
Pressure difference, Pa	Differential pressure sensor No. 3	0	2 Pa	2	4	**100 ± 4**
Air permeability, $mm{\cdot}s^{-1}$	Flow meter (0 - 100 $l{\cdot}min^{-1}$)	1.5	5.7	5.9	11.8	**107 ± 12**
	Size of the area in clamp (0.002 m^2)					
Bulge, mm	Laser sensor	0.028	0.004	0.029	0.058	**0.87 ± 0.06**

tity measured is the size of the bulge in the sample.

Since the measurement is carried out in an air-conditioned environment and we use relaxed samples for this, the effect of temperature and humidity on the measurement outcome can be neglected.

Determining the uncertainties of the measurement considers error in reading the values – their saving, accuracy of the measuring card used in the PC and the inaccuracy of the sensor introduced by the manufacturer (linearity, hysteresis and repeatability), as well as the uncertainty of measurement of the instrument used for determining the area of the clamp. Each of these uncertainties of type B, marked as u_b (Type B evaluation of standard uncertainty), is evaluated according to relation (1). The a_i value is given by the documentation for the elements and instruments used. Consequently this value is used in relation (2) to evaluate the uncertainty u_b* for individual quantities (given sensor). This provides the user of MPT01 with individual constants and further evaluations are easier [18].

$$u_b(x_i) = \sqrt{\frac{a_i^2}{3}} \quad (1)$$

where, a_i half-width of a rectangular distribution of possible values of input quantity X_i.

$$u_b^{\,*} = \sqrt{\sum_{i=1}^{m}\left[\frac{\partial f}{\partial x_i}u_b(x_i)\right]^2} \quad (2)$$

where, m - the number of uncertainties of the corresponding quantity evaluated (chosen sensor).

Table 1 presents calculated uncertainties u_b* for measuring the pressure difference by the differential pressure sensors, determination of the air permeability R = f(Q,S) according to the relation (3), and evaluating the size of the bulge by the laser sensor.

$$R = \frac{Q}{S}.k \quad (3)$$

where, R - air permeability in $mm{\cdot}s^{-1}$, Q - flow in $l{\cdot}min^{-1}$, S - size of the area in clamp in m^2, k - coverage factor in -.

Furthermore type A standard uncertainty u_a (4), (5) is determined from the repeated measurement of a textile sample on the MPT01 device, and it is then the experimental standard deviation of the mean. The user subsequently uses this value (together with u_b*) when evaluating the combined standard uncertainty of type C u_c (6) and expanded uncertainty U with the coverage factor K (7) to obtain the uncertainty of the particular measurement [18].

$$u_a = \sqrt{\frac{\sum_{j=1}^{n}\left(q_j - \bar{q}\right)^2}{(n-1)n}} \quad (4)$$

$$\bar{q} = \frac{\sum_{j=1}^{n} q_j}{n} \quad (5)$$

where, n number of repeated measurements, q_j j^{th} independent repeated observation q_j of randomly-varying quantity q.

$$u_c = \sqrt{u_a^{\,2} + \left(u_b^*\right)^2} \quad (6)$$

$$U = uc{\cdot}K \quad (7)$$

Table 2 shows an example of uncertainties for one measurement of the air permeability and measurement of the bulge of the sample. We made n = 12 measurements of a textile sample (pressure difference Δp = 100 Pa) with saving the data in the computer memory for consequent processing. The textile sample was a woven fabric made of 100% cotton with twill weave. The warp fineness was 38 tex, the weft fineness - 58 tex, the warp sett - 2400 m^{-1}, the weft sett - 2000 m^{-1}, and the planar weight was 221 $g{\cdot}m^{-2}$.

Before the measurement starts, the user chooses the pressure sensor to be used for the measurement. To perform the standard measurement, for example, according to standard [1] or [2], pressure sensor number 3 is the best choice for its lowest uncertainty u_b*. When performing a measurement under extreme pressure conditions, we can, with regard to the pressure difference requested, also choose from pressure sensors number 2 and 1. We could achieve lower uncertainty of the measurement for low pressure differences by replacement of the current pressure sensor with one with a shorter range and better parameters.

Possibilities of usage of the MPT01 device

The MPT01 device provides two basic modes of measurement. The first is standard static air permeability measurement of textiles. The outcome of the measurement is the value of air permeability of the textile clamped in the fastening clamp. The air permeability is measured at a given pressure difference, which is usually set according to the corresponding harmonised standard for air permeability measurement of textiles.

The program we have created further enables so-called experimental dynamic air permeability measurement. In this case the operator can pick from three possibilities of changes in pressure difference depending on the mode selected. The first option enables the setting of the control signal to a sine. The amplitude value and

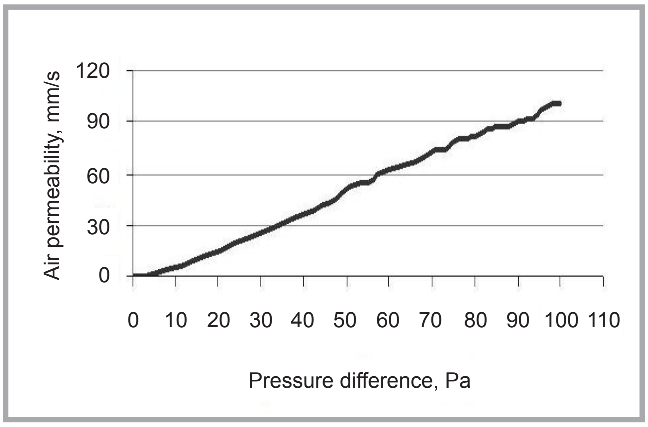

Figure 8. Example of data with a pressure difference measurement step.

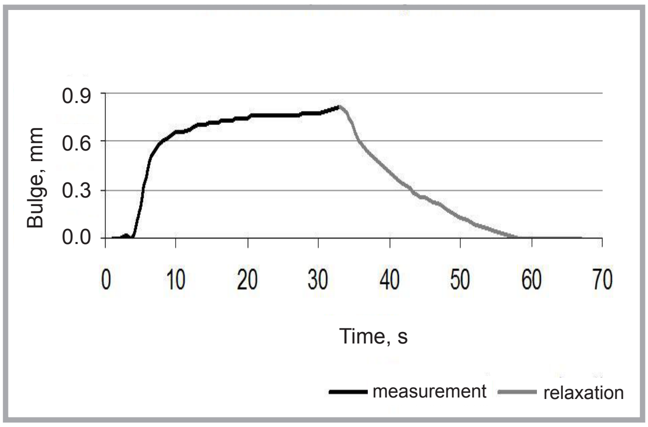

Figure 9. Bulge of the sample and subsequent relaxation, time-dependent.

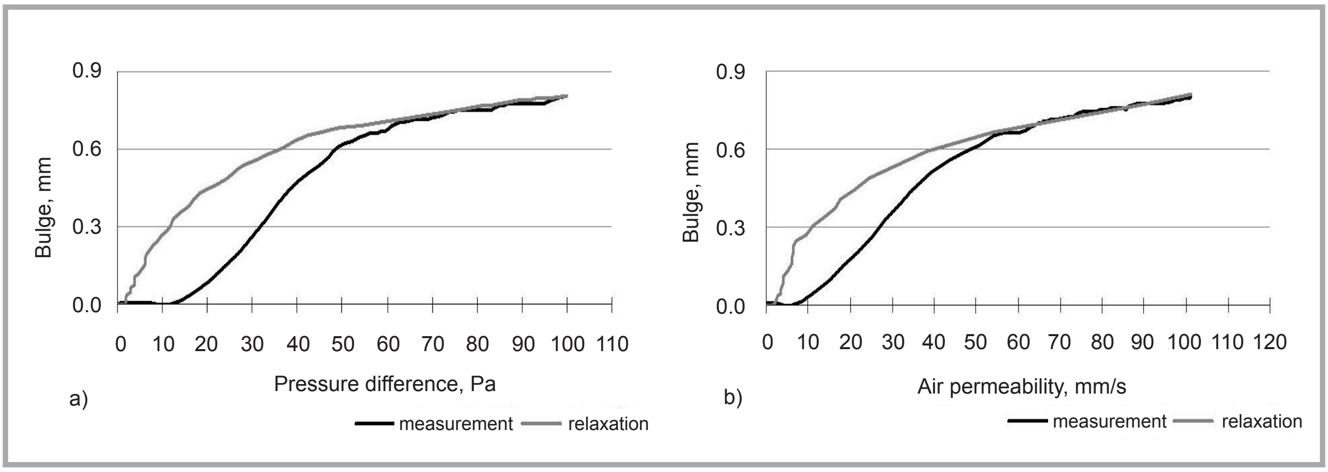

Figure 10. Example of graphs depicting the bulge of the sample depending on increasing pressure (a) and air permeability (b).

other parameters must correspond to the range of the control signal, which is fed to the regulator (0 - 100 l/min). This type of control was designed for experimental dynamic methods of measurement, which are yet to be tested. Another mode enables the measuring of air permeability depending on a step increase in the control signal for the regulator. The size and time span of one step is chosen by the operator and depends on the requirements of the experiment. This option is used mostly to observe the dependence of air permeability on the increasing pressure difference applied step-wise.

The mode (apart from the standard mode) hitherto mostly used is an increase in the control signal linearly according to the tangent of this increase chosen by the operator. This measurement enables to observe the dependence of air permeability on the pressure difference (***Figure 8***). ***Figures 8 – 10*** show textile sample measurement specified in the chapter "Accuracy of measurement on the MPT 01".

Also a graph depicting the time dependence of the bulge where the "direct control" was used is of informational value. This mode enables the operator to adjust the signal in the course of the measurement. For example, during a step increase in the pressure difference the operator decided to interfere (when 100 Pa was reached) and set the control value to zero. This stopped the air supply in the system, then the pressure difference dropped quickly to zero, and the sample was observed during the relaxation phase (***Figure 9***).

The data obtained can be further processed, for example, along with the those for the bulge of the sample, where we can observe the bulge of the sample depending on the pressure difference (***Figure 10.a***) or air permeability (***Figure 10.b***). The movement of the textile and corresponding increase in pores can be calculated, which is based on measurement of the bulge by the laser sensor. The increase in the area of the clamped sample is given by the ***Equation 8***, and with this size the area of the pores is extended. Bigger pores lead to higher textile air permeability.

$$P_p = \pi \cdot v^2 \quad (8)$$

where, P_p - increase in the area in mm^2, v - bulge in mm.

In case we are not interested in the bulge, we can concentrate on observing the structure of the textile visually (using the camera) during the air permeability measurement. Further improvement of the construction of the device optics will enable not only to visually observe the fabric behaviour, but also to evaluate the changes in, for example, the 2D projection of the pores during the measurement.

Conclusions

The new MPT01 device enables the user to conduct comfortably the measurement of static air permeability with storing of the data measured on a computer. Here the data is available for further processing. Unlike standard devices, where only the static air permeability can be measured, the MPT01 enables also dynamic air permeability measurement, which is possible in several modes. Dynamic air permeability measurement can be conducted in a mode of increasing and decreasing pressure difference in a wide range of the pressure difference sensors with respect to the range of the flow meter, which measures the amount of air passing through the textile. Deformation changes in the textile can be observed along with the air permeability measurement. The device described offers the possibility to observe the structure of the textile during the measurement using a camera, or to measure its bulge. The most important property is the bulge of the textile in the z axis. Due to the bulge, the pores in the textile open, and thus the space for air to pass through the textile increases. Based on the mathematical relations and exact knowledge of the bulge, we can determine the effect of the bulge of the textile during the measurement on the increase in pore size caused by this bulge. This extension of the pores also results in an increase in the air permeability This device is intended for further use in researches dealing with the issue of the bulge of a sample during dynamic air permeability measurement.

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