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Evaluation of liquid moisture transport in textile structures

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The present study is focused on the investigation of liquid moisture transport in textile materials by means of thermography and microtomography systems. The new vertical wicking method which combines the thermography system and the image analysis system is presented in this study. Further, porosity analysis of knitted fabrics by microcomputed tomography system is carried out to support understanding of liquid moisture transport phenomena. Textile structures used for functional underwear for sports and for special non-flammable hi-tech underwear have been selected to tested group. Results indicate that the distribution of pore thickness can be useful to uncover complex behaviour of textile structures during moisture transport into their structure.

Keywords: Cotton, Functional underwear, Knitted fabrics, Lyocell, Microtomography, Polyester, Polypropylene, Thermography, Wickability, Wool

1 Introduction

Flow of moisture through the apparel fabric is important in the textile applications from the comfort point of view. The efficiency of liquid moisture transport through textile structure is significant particularly for first layer of clothing system. First layer usually consists of functional underwear. Mainly such underwear is used for sports clothing systems, however, other important user group consists of workers such us fire fighters, soldiers, policemen and industrial workers (in the metallurgical, oil, chemical industries, etc.) who work in extreme conditions. Non-flammable functional underwear is used as a secondary heat barrier and, together with an outer layer of protective clothing, provides optimal protection required, apart from flame resistance. The physiological comfort of both underwear in sportswear and protective clothings is one of the most significant factors for ensuring the best conditions for the wearer while they are active[1, 2]. Functional underwear is supposed to drain sweat away from skin by the capillary method. Wicking behaviour belongs to well-known methods that use the capillary phenomenon to evaluate liquid transport properties of fabrics. In general, wicking takes place when a liquid travels along the surface of the fibre but is not absorbed into the fibre. Physically, wicking is a spontaneous flow of a liquid in a porous substrate, driven by capillary forces. The type of flow in any porous medium, caused by capillary action, is governed by the properties of the liquid, liquid-medium surface interactions, and geometric configurations of the pore structure in the medium[3, 4]. The rate (distance per unit time) of liquid which travels along and /or through a fabric specimen is visually observed according to a standardized wicking method, and manually timed and recorded at specific intervals. There are many alternative wicking test methods. Some of them deal with measuring water transport along textile fibres by an electrical capacitance that consists of an apparatus with a specially designed electrical amplifier circuit and condenser electrodes, between which sample fibres are placed[5, 6]. Further, there exists wicking methods based on electrical resistance[7, 8]. Different authors have used image analysis system to capture vertical wicking[9, 10]. The colour of tested fabrics can influence the accuracy of test results obtained by image analysis, in particular in case of inadequate contrast between the wetted area of a sample and the rest of a sample (the dry area without a drop of water). There exists a different approach of testing the capillary flow in textiles[11] The use of lighting system (UV lamp) gives a good resolution and quality of image without addition of a dye. Hamdaoui and Ben[11] also developed a mathematical model for predicting the complete profile of vertical wicking through woven fabrics considering different influencing parameters (composition and structure). This model can also

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determine the diffusion parameters and the height attained by the water at equilibrium without the addition of dye. The sorption ability of the woven fabrics is considered as well. Sharabaty *et al.*[12] have taken measurements of capillary rise on two layered fabric. These fabrics have been studied to manage human perspiration transport leading well to the design of physiological comfort of fabrics. Clothing is particularly intended for next to skin applications and hence researchers study not only liquid transfer properties but also drying behaviour of knitted fabrics[13].

In a further development, a technique based on the combination of thermography system and image analysis was developed for the evaluation of vertical wicking of fabrics to eliminate above mentioned. The use of infrared cameras for monitoring the spread of liquid in the fabric is possible due to the visibility of physical phenomena in infrared spectrum wavelengths[14]. Thermography system takes the advantage of physical principles, that during water evaporation heat decreases. This process is possible to be captured on a thermograph by a thermography system. The thermographs obtained can be evaluated by an image analysis system to find moisture management parameters of textile materials[15].

The water capillary rise can be studied based on three scales of porosity in woven fabric in which the water molecules can be diffused, namely macro pores – empty spaces between yarns in the structure, meso pores – pores between fibres in the yarns, and micro pores – accessible sites of amorphous regions[11]. Porosity of textile materials is one of the most important parameters that affect the moisture management of textiles. 3D structure image of fabric, parameters of 3D porosity and distribution of pores size by microtomography system allow more detailed understanding of the material behaviour affecting the spreading of liquid moisture management[16-18]. For the present study, a non-destructive method of computer microtomography has been selected from the existing detection methods for analysing porosity parameters. This research is focused on the application of sophisticated textile metrology such as thermography and microtomography in order to examine the influence of different knitted patterns (used for functional underwear) on transport of sweat.

2 Materials and Methods

Ten types of knitted fabrics divided in to three groups (Table 1) were analysed in terms of their efficiency of vertical wicking behaviour by thermography system and parameters of porosity by microtomography system. The materials investigated were designed for functional underwear for the first layer next to human skin in order to transport moisture as soon as possible. Moisture management of tested materials is one of several properties that can influence total wearing comfort.

First group (A, B and C knitted fabrics) is made of the same raw material and the same yarn linear density (tex); however, all knits have different patterns. The structural parameters of specimens enable investigation of the effect of pattern and density on speed of moisture transport. Second group of specimens (fabrics D and E) contains special non-flammable or flame retardant fibres in order to protect human beings under extreme conditions, such as fire

Table 1 — Characteristics of tested knitted fabrics

Fabric	Fabric code	Pattern	Density (courses × wales)/dm^{-1}	Weight g/m^2	Thickness mm
Group I					
Cotton/Lyocell with PCM/Lyocell with SeaCell Pure (50/30/20)	A	Interlock	170 × 150	182	1.08
Cotton/Lyocell with PCM/Lyocell with SeaCell Pure (50/30/20)	B	Piqué – single jersey	140 × 120	153	0.84
Cotton/Lyocell with PCM/Lyocell with SeaCell Pure (50/30/20)	C	Single jersey fabric	180 × 150	131	0.69
Group II					
Cotton/Modacrylic (flame retardant) (40/60)	D	Double jersey	160 × 180	164	0.71
Aramid imide (kermel)/viscose (flame retardant) (50/50)	E	Interlock	150 × 140	273	1.28
Group III					
Polyester (polartec)	F	Interlock	150 × 110	179	0.92
Cotton	G	Single jersey fabric	170 × 140	172	0.60
Wool (merino)	H	Single jersey fabric	200 × 190	150	0.45
Polyester (coolmax)	I	Double jersey patterned	220 × 170	145	0.65
Polypropylene	J	Double jersey patterned	220 × 160	115	0.90

fighters, policemen, rescuers, etc. It is interesting to examine how these special fibres influence the ability of liquid moisture transport in comparison to the "classical" underwear materials. The last group (F, G, H, I and J) represents typical materials for functional sport underwear. All structures belong to common knits for underwear available in the market.

Before being measured, the samples were washed and air-conditioned for 24 h. The measurement was carried out in an air-conditioned room under constant relative humidity of 65 % and temperature of 21° C.

The liquid moisture transport of knitted fabrics was investigated by following two ways:

(i) 3D porosity of knitted fabrics was measured by microcomputed tomography system
(ii) New vertical wicking method was used, which combines the thermography system and the image analysis system

The results of the above-mentioned methods were compared and discussed in order to detect the real behaviour of tested knits during liquid transport within their structures. Final values (means) of all tested parameters correspond to five measurements on average.

2.1 3D Porosity of Knitted Fabrics by Microtomography System

Porosity of textile structures is a key parameter which affects its air and water vapour permeability, water transport in liquid form, thermal resistance, etc. Microcomputed tomography (microCT) provides special detailed illustration of the 3D configuration of textile structures and allows the analysis of both intra and inter-particulate pore characteristics. MicroCT has become a standard for the assessment of microarchitecture and composition of structures in general. It represents 3D microscopy, where very fine scale internal structure of objects is imaged non-destructively. X-ray computed micro tomography system SKYSCAN 1272 was used to investigate the influence of fabric porosity on the efficiency of liquid transport in textile structures. The method of finding values of flow permeability of porous materials based on numerical solution of fluid flow through the actual 3D pore geometry of material samples observed using X-ray micro-tomography, appears useful especially in cases where experimental results are not available or difficult to obtain[20]. Industrial tomographs available in the market mostly have a similar construction. The system obtains multiple x-ray “shadow” transmission images of the object from multiple angular views as the object rotates on a high-precision stage (Fig. 1). From these shadow images (often hundreds), cross-section images of the object are reconstructed, thus creating a complete 3D representation of internal microstructure and density over an investigator-selected horizontal region in the transmission images.

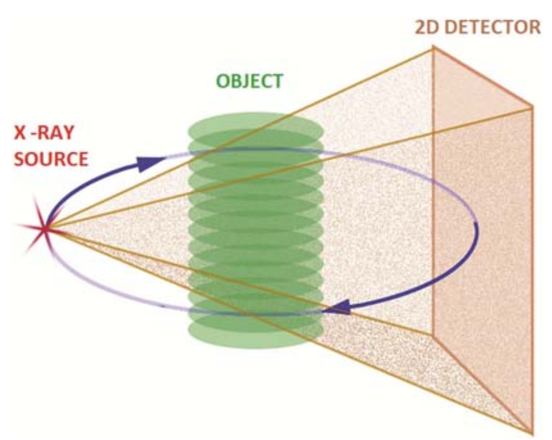


Fig. 1 — Schematic diagram of basic principle of microtomography[19]

Measurements were taken under the following settings: image pixel size 8 μm, rotation step 0.2°, rotation degrees 180°, frame averaging 3, exposure 320 ms and voltage source 40 kV. These conditions appeared as the best for improved scanning speed and the quality of the scanned image. The above-mentioned conditions are common for all tested materials.

Both parameters namely porosity (%) and distribution of pore thickness [per cent volume in range of pores (%)] were established for all tested specimens. To verify the correctness of porosity results of textile structures by microtomography system [affected by setting of above-mentioned conditions of scanning, reconstruction and analysis, such as threshold, set of ROI (region of interest) etc.], a mathematical volume model developed in our previous research was used[18]. Only 6% difference between porosity measured by μCT and porosity calculated from the mathematical model (by Neckar and Das[21]) was obtained. Hence, it can be stated that the μCT method is suitable for measuring the porosity of knitted fabrics.

2.2 Vertical Wicking Method by Thermography System

The rate of water transport is measured according to a vertical strip wicking test. One end of a fabric strip is secured vertically while the opposite end dangles in a dish containing distilled water. The capillary rise at different times was observed and measured by taking a video with the thermocamera. The time and the corresponding capillary rise were

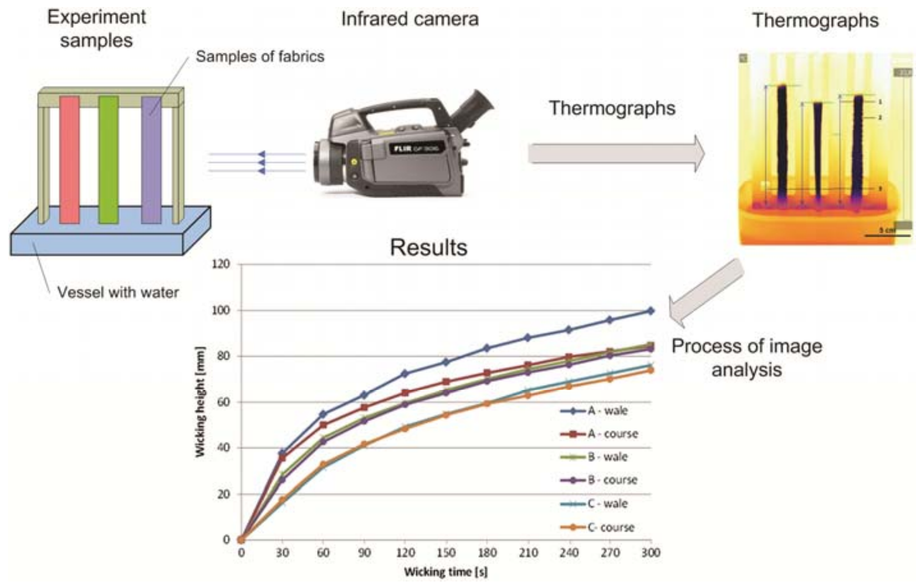


Fig. 2 — Schematic diagram of vertical wicking evaluation by thermography system[14]

recorded continually for 600 s. The results were reproduced in millimetres (mm). Higher wicking values show greater capability for transporting liquid water. Thermal imaging is used to monitor moisture transport when wicking cannot be easily detected with the naked eye. The height of liquid at different times is determined by images processing based on the difference of colour level. Figure 2 represents schematic diagram of the thermography method[14].

3 Results and Discussion

3.1 Porosity of Knitted Fabric by Microtomography System

Porosity of textile materials considerably influences transport phenomena in clothing systems. There are a lot of methods to determine this parameter. Majority of these methods express porosity only by one number in the percentage unit. Two textile materials with the same parameter of porosity can often show different behaviour from transport phenomena point of view. Therefore, pore thickness (diameter) and pores distribution have been investigated by means of microtomography system to uncover the connection between porosity and wickability of textile structures.

The fixed specimens of knits were scanned by high resolution microcomputed tomography system (SkyScan 1272). Subsequently, the 3D reconstructions of scanned images were carried out by software Nrecon. For quantifying the dimension and distribution of pores in knittted structures, the parameters defined by manufacturer of the µCT system such as porosity parameter and distribution of pore thickness (diameter) were determined using relevant software. CTAn values for all tested materials are given in Tables 2 and 3. The fabrics having porosity in range 56 – 71 % are shown in Table 2 and fabrics having porosity range 30 – 50 % are shown in Table 3.

Tables 2 and 3 show final 3D images of tested materials (1st column) and colour coded 3D model (2nd column) for structure separation (distribution of pores thickness) in isometric views. The size of 3D images of the tested samples is 5x5 mm, colour coded models are presented in area 3x3 mm. Illustrations of colour coded models are taken from the face side for all materials, back side is displayed only for sample I because of a different pattern.

Generating a color-coded 3D model of pore thickness distribution is performed in 2 steps:

(i) Color-coded images are created and saved for structure separation in CTAn and
(ii) These images (dataset) are loaded in CTVox to create a 3D model.

The 3D pore thickness measurement method is referred to as "sphere-fitting" – pore thickness is defined locally as the diameter of the largest enclosed sphere[22]. Range of pore thickness is categorized into three groups according to pore diameters. Red colour in colour coded model represents the "smallest" pores, green corresponds to "medium" pores and blue one shows the "largest" pores in tested textile structures.

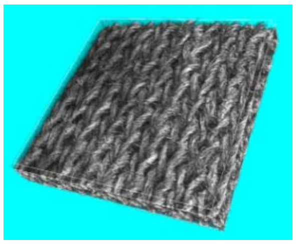
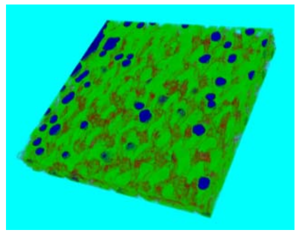
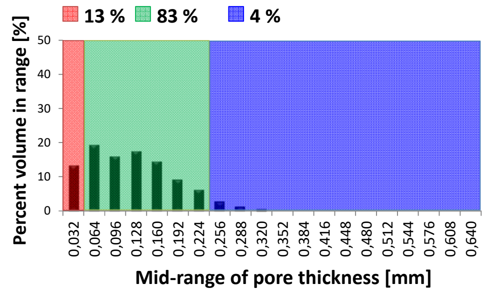
Further, the graphs showing per cent volume in range of pores (%) against to mid-range (mm) of pores are given in 3rd column of Tables 2 and 3. The colours of areas in above-mentioned graphs correspond

Table 2 — Microcomputed tomography characterization of tested knits with porosity in range 56 – 71%

3D image of structure | Colour coded pore dimension | Distribution of pore thickness

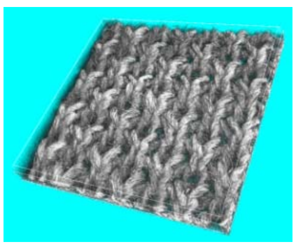
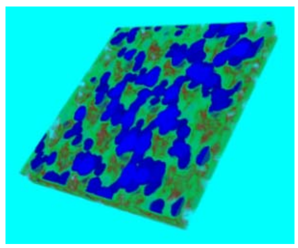
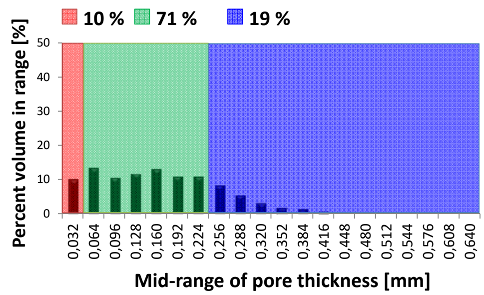
Porosity by µCT 67%

Sample A

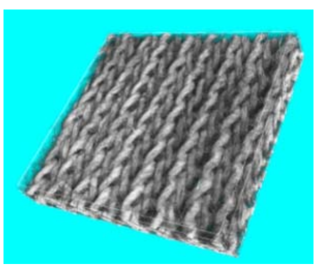
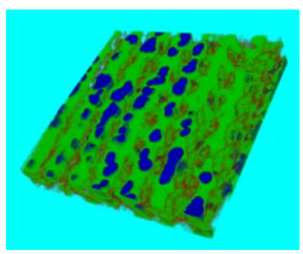
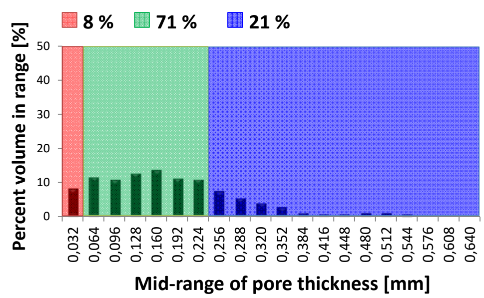
Porosity by µCT 62%

Sample B

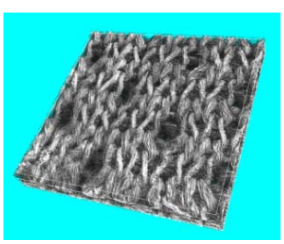
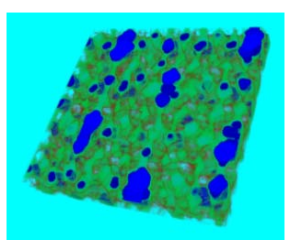
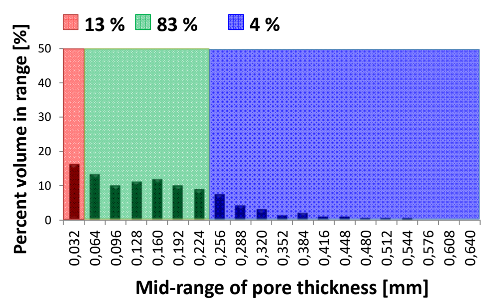
Porosity by µCT 62%

Sample E

Porosity by µCT 56%

Sample F

Porosity by µCT 71%

Sample J

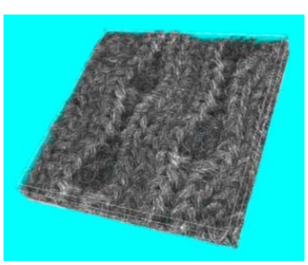
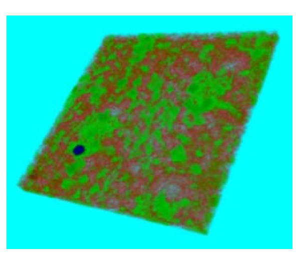
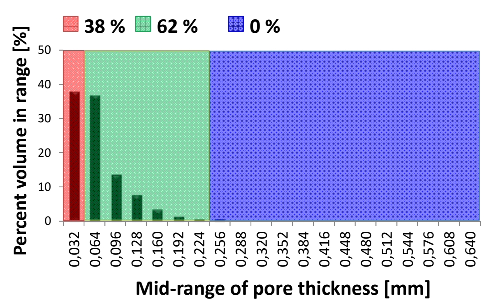
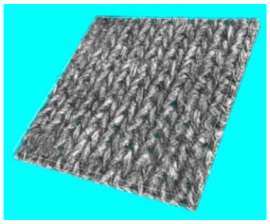




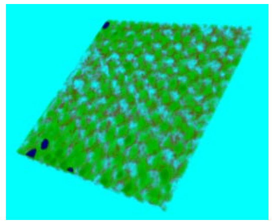
Table 3 — Microcomputed tomography characterization of tested knits with porosity in range 30 – 50%

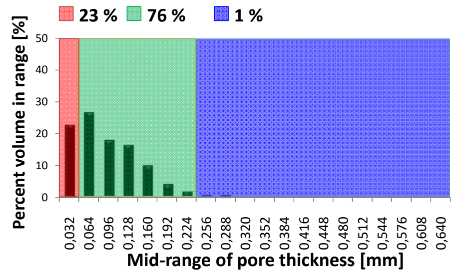
3D image of structure | Colour coded pore dimension | Distribution of pore thickness

Porosity by µCT 48%

Sample C

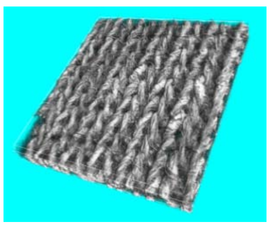


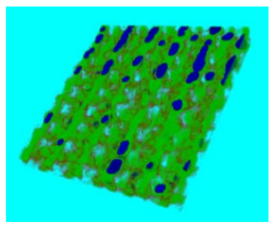


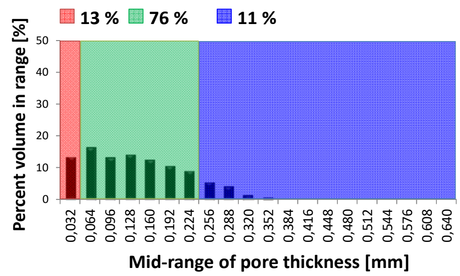


Porosity by µCT 50%

Sample D

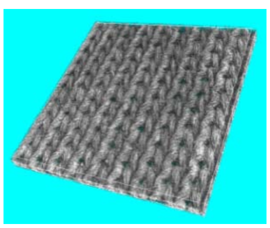


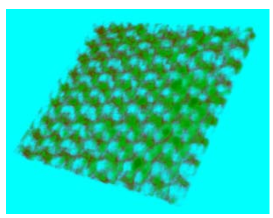


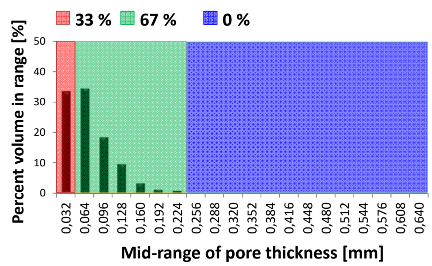


Porosity by µCT 31%

Sample G

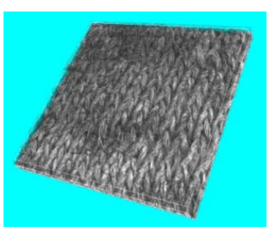


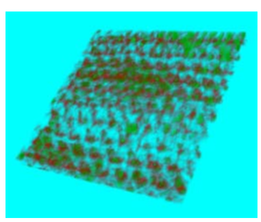


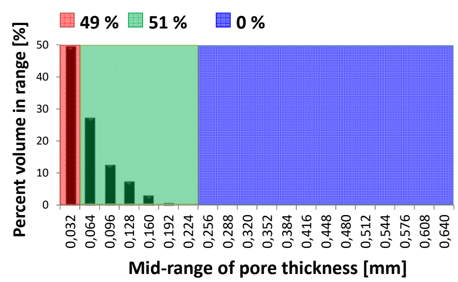


Porosity by µCT 30%

Sample H

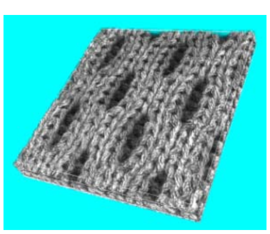






Porosity by µCT 45%

Sample I



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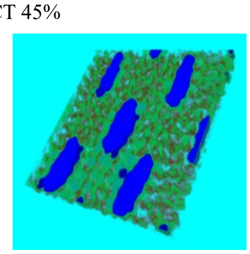

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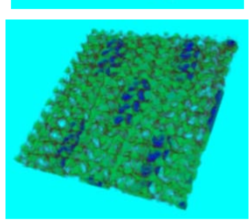

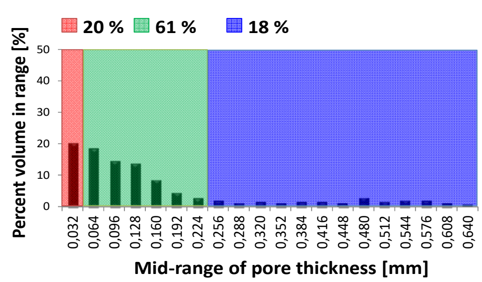

to the colours of pores thickness in colour coded models. Moreover, coloured areas show percentage share for thickness of pores (into three groups) from total pore volume in these graphs. The parameter of porosity for each tested sample was determined and shown in Tables 2 and 3.

3.2 Vertical Wicking Method by a Thermography System

The capillary rise and initial wicking rate in knitted fabrics are investigated in this part of experiment. The results confirm the assumption of the wicking behaviour of hydrophilic (G, H) and hydrophobic (F, I, J) materials. The experimental data of capillary rise as a function of time are presented in Fig. 3. The graphs provide record of the wickability up to 300 s. In time interval from 0 s to 300 s the graph shows the most important progress. The initial wicking rate, which is the tangent slope at the initial time and the ultimate wicking height at 600s are also listed in Table 4. All the results are based on the average of five tests.

As can be seen, the total transport of liquid moisture in a fabric is performed in two stages. The first stage of liquid absorbing capability is expressed as an initial wicking rate, and the second stage as ultimate wicking height. Some of the samples absorb liquid quickly in the beginning of the test, and then the diffusion is attenuated to reach an equilibrium height. The assumption that the hydrophobic materials reach the maximum height faster is confirmed, since they are not able to bind water with specific bonds and do not wet the surface of the fibres. The water is spread in the fibre bundle by capillary forces. Figure 3 indicate that polyester (F, I) presents the best and progressive results of ultimate wicking height and initial wicking rate. The worst results in terms of capillary action are obtained with wool (H) followed by cotton (G). The group of samples A, B, C from the same yarns present the following finding. The interlock knit (A) performs better with immediate

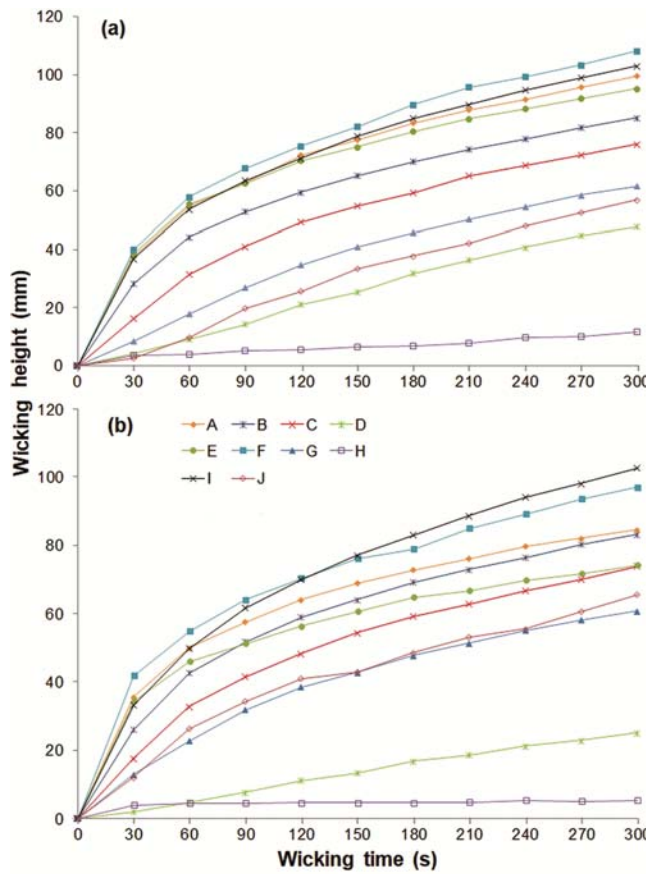

Fig. 3 — Wicking height and time curve in 300 s (a) wale, and (b) course

Table 4 — Detailed parameters of wicking evaluation

Fabric/statistical characteristics	A	B	C	D	E	F	G	H	I	J
Ultimate wicking height, mm										
Wale										
Mean	130.7	114.6	106.4	78.2	126.7	138.5	81.7	26.3	125.4	112.1
St.dev.	3.90	4.51	5.89	8.71	7.96	1.14	5.59	2.91	6.14	4.17
Course										
Mean	104.9	108.3	96.70	43.3	92.5	135.1	82.1	5.2	130.5	92.7
St.dev.	0.83	2.30	0.54	5.49	0.42	1.87	3.38	1.04	3.44	2.97
Initial wicking rate, mm/s										
Wale										
Mean	1.26	0.95	0.54	0.14	1.29	1.34	0.28	0.12	1.23	0.09
St.dev.	0.11	0.04	0.05	0.02	0.04	0.04	0.13	0.03	0.11	0,03
Course										
Mean	1.19	0.87	0.59	0.06	1.15	1.39	0.43	0.13	1.11	0.4
St.dev.	0.08	0.03	0.05	0.02	0.09	0.03	0.09	0.01	0.1	0.03

water absorbing capability than piqué – single jersey knit (B) and single jersey fabric (C), while knit (C) is found the worst. Fabrics (D) and (E) contain two different components of fibres and therefore wickability in wale and course is different. The experimental results show that an interlock knitted fabrics (knit A, E, F) show better initial wicking rate and water transportation. But a single jersey (knit G, H) shows very low ability to spread moisture into fabric.

Generally, the sorption of fabric is related to the composition of the fibres, condition of their surface, accessibility of hydrophilic groups, loosening of surface, distribution of pore, temperature and time. Therefore, the wicking behaviour of each fabric must be determined individually. The next study is about interrelation between the content of the pore (%), different pore size and the progress of wickability. In subsequent analysis the initial rate as an average from results of wale and course are presented. The results along the wale and course tend to be similar.

3.3 Porosity and Vertical Wicking Method

First, the relationship between 3D porosity by μCT and wickability of tested samples by thermography has also been analysed. According to Fig. 4(a), it is noticed that wickability is dependent on porosity. The coefficient of determination (R^2) is 0.98. It is valid only for samples of first group (A, B and C) that are made of the same raw material and the same yarn linear density; however knits have different patterns [Fig. 4(a) and Table 1]. On the contrary, Fig. 4(b) shows low dependence, R^2 is only 0.37 for all materials tested. Predictably, the results reflect non-uniformity of the tested group that is given by different material composition, pattern, density, etc. The group of samples tested has been chosen purposely to contain common knits for underwear available in the market.

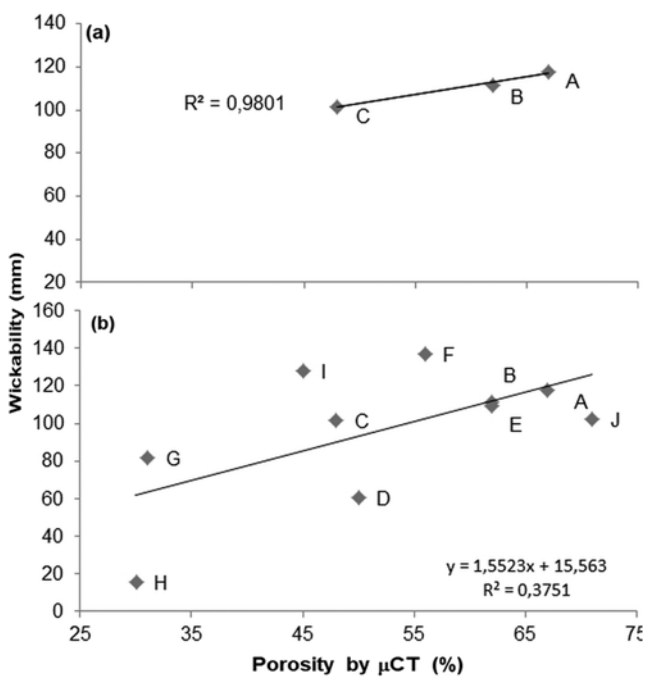

Fig. 4 — Porosity and wickability (a) for samples A, B and C, and (b) for all tested materials

The samples with similar porosity (for example group of H and G or group of I, C and D) have different ability of wicking [Fig. 4(b)]. The wickability is defined as an average value of ultimate wicking height in wale and in course. It means that moisture transport into textile structure cannot be predicted only by porosity parameter. It is affected by both material composition (hydrophilic or hydrophobic material) and structural parameters such as pattern, density, etc. The investigation of distribution of pores thickness would be useful to find out the explanation for the above mentioned behaviour. The following results of distribution of pore thickness by μCT uncover few key issues for understanding how moisture transports into textile structure, as in Tables 2 and 3.

If textile structure contains a high percentage volume of pores with very low thickness in combination with high content of hygroscopic fibre, for example samples C, H and G (cotton, wool), wickability decreases with low wicking speed and lack of binding with the fibres (Fig. 5). Moreover, this fact is supported by a low value of porosity. Nevertheless, if fabric contains a high percentage volume of pores with very low thickness (sample J) in combination with high content of hydrophobic fibres (polypropylene) and material shows high porosity (71%), the wickability is very good. It can be caused

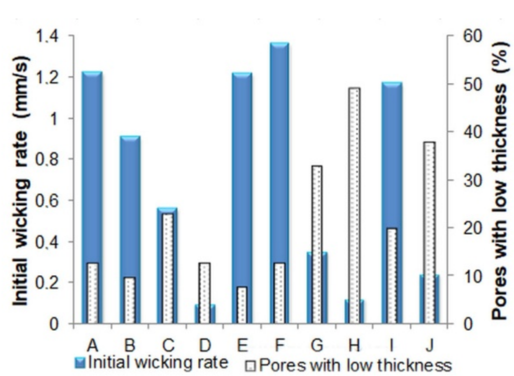

Fig. 5 — Initial wicking rate and pores with low thickness

by surface modification of fibre that helps in binding of moisture and helping the capillary behaviour. When comparing materials (A, B and C), a gentle decrease of wickability depending on the frequency of the very small pores can be seen.

The results of the hydrophobic materials (F, I, J) can support the hypothesis that the pores with low thickness cause a slow initial capillary action (Fig. 5). Knit (J) contains pores with low thickness (38%), therefore the lowest initial wicking rate is observed. In knit (F) the content of the pores with low thickness is only 13% which results in highest initial wicking rate and the highest absolute wicking height.

4 Conclusion

The study confirms the possibility of combination of two methods for investigation of liquid transfer behaviour in textile structures. Vertical wicking method by a thermography system gives values of absorbing capability and ultimate wicking height of tested fabrics. Porosity of these knitted fabrics by microtomography system describes their pore thickness (diameter) and pores distribution. A combination of all results gives synergistic effects and shows that the distribution of pores in fabrics and pore diameters are very important parameters to uncover liquid transport behaviour in textile structures.

The present study also confirms previous findings and contributes additional evidence that the porosity expressed as a single parameter value is not sufficient for determining the rate of liquid moisture transport into the fabric. It is necessary to define different classes (categories) of pore thickness to determine the wicking rate depending on the degree of porosity. As it turned out, pore thickness (diameter and pore distribution) is a major influencing factor. Further experimental investigations are needed to define the pore thickness categories and to define their degree of influence on the liquid transport behaviour.

The distribution and transport of liquid moisture in textile structure is fundamentally affected by the material composition and pattern type. Future research should therefore concentrate on the investigation of moisture transport monitoring affected by the degree of porosity or pore thickness and pore distribution. Distribution of these pores will be proposed in relation to the fabric parameters, i.e. material composition, thickness of fabric and the pattern type. Further research should be carried out to establish the influence of an isolated single parameter from all of the possible influencing parameters.

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