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Air Permeability & Porosity in Spun-laced Fabrics

Abstract
The relationship between air permeability and fabric characteristics such as fabric weight, thickness and density in a variety of nonwoven types has already been investigated. The effect of porosity on air permeability has also been thoroughly evaluated in numerous research works. However in this paper, we report the effects of the specific energy in hydroentanglement on the air permeability of the resultant fabric. It is shown that within the ranges of the measurements, energy is not the only factor that affects the permeability. Although the same web weight is used in all trials, fabric weights and thicknesses did not show any clear or linear decrease when the energy given to the fabric was increased. The alteration of web weights and thicknesses under enhanced energy shows that entanglement mechanism in these nonwovens is not not as simple as we had expected. It is thought that the flow corridors in nonwovens are certainly very complex. This increased intricacy may be due to the randomness of nonwoven structures or the method of bonding such as the random hydroentanglement of spun-laced fabrics.

Key words: *air permeability, specific energy, spun-lace nonwovens, porosity.*

Introduction

Porosity and air permeability are vital properties in some end-use applications such as filtration, thermal insulation and fluid barriers. The application of various permeability tests to textiles and textile materials has been practiced in the industry for years, and determining permeability and porosity have long been subjects of interest in this field. Several papers have been published on the measurements of both properties for the nonwovens. Since nonwoven structures are being increasingly used in many technical applications, it is very important for the producer to understand specific properties such as permeability in detail. This paper gives a brief literature review on the relationship between structural properties, porosity and permeability of nonwovens, and intends to find answers especially concerning the relationship between hydroentanglement energy and air permeability in spun-laced nonwovens.

Previous studies investigated the relationship between air permeability and structural characteristics of nonwovens such as fabric weight, thickness, density and fibre diameter [1 - 6]. It has generally been demonstrated that air permeability decreases as thickness, weight or fabric density increase. However in some studies, it is found that there was a non-linear relation between the properties, whereas some other studies show them to be linear. It was demonstrated in one paper that fabric weight is the most significant factor for air permeability, more than thickness, density and fibre diameter [5]; by using the same data, fabric density is found to be the second most important factor after fabric weight [2].

The hydroentanglement process is very suitable way of converting not only the textile fibres but also new-generation and high-performance fibres and their blends into nonwovens without damaging them, and without the need for a binder. The physical characteristics of hydroentangled nonwoven fabrics, such as softness, flexible hand, high drape and bulk, conformability and mouldalibity, high strength without binders and delamination resistance, make this process unique among the processes for nonwovens [7]. The characteristics of fabrics can be engineered according to the end-use requirements.

The amount of energy delivered to the web is a crucial parameter influencing the fabric structure and properties since it affects the completeness of fibre entanglement. 'Completeness' is a term that is defined as the portion of fibres that are tied together. Water pressure is another parameter related to fabric energy intake. Several water pressure levels are used [8].

Up to a certain point, higher energy levels result in stronger fabrics. Additionally, shifting the balance of energy input to the second side (low specific energy ratio) can significantly decrease fibre loss. The benefits of different energy ratios are not so clear [9]. Higher water pressure machines are mostly used, since energy can be delivered into a web with fewer water needles and less water consumption, which is more economically beneficial [8].

As the target weight and density of product increases, so does the water energy requirement, to a point where web penetration can no longer be achieved without major fibre damage. This results in a fabric of skin-core effect, with fibres bonded at the surfaces but with little or no entanglement at the centre. Such fabrics easily delaminate and have no commercial value. By selecting the optimum orifice size, shape, concentration and energy distribution, it has been possible to gradually build up the entanglement with heavy weight webs, to produce unique fabrics with a dense, uniform structure throughout the cross-section [10].

For lightweight fabrics, the industry trend is to apply the entanglement energy in the form of a multitude of injectors, working at comparatively low pressure. Energy applied in this way to heavy weight webs results in good surface entanglement but weak delaminating core structures. Another basic process parameter which influences the fabric is the speed of the line. If a constant amount of energy is being delivered to a fabric, the speed of the fabric determines how much energy will be absorbed per fabric unit area. Logically, the higher the line speeds, the less the energy that is absorbed by the fabric, and thus the lower the fabric strength that is achieved.

The total specific energy of water applied to the fibre web is a key process variable responsible for the efficiency of the transfer of the patterns onto the fabric surface. Naturally, the energy will also have a profound effect on the physical and structural properties of the fabrics.

The energy transferred to the web can be controlled by

1. manifold pressure,
2. residence time,
3. number of manifolds and passes.

As the target weight and density of product increases, so does the water energy requirement, to the point where web penetration can no longer be achieved without major fibre damage. The theoretical simplified formula for specific energy, E, in Jkg^{-1} applied to the fibre web by water jets in a manifold is given by [11]:

$$E = 6.66 \times 10^4 \frac{C_d\, d^2\, N\, P^{3/2}}{\sqrt{\rho}\, W\, S} \qquad (1)$$

where C_d is the orifice discharge coefficient (assumed 0.7), d is the diameter of the jet orifice, m; N is the number of jets/m per manifold; P is the water pressure Nm^{-2} in the manifold; ρ is the water density, kgm^{-3}; W is the basis weight of the web, gm^{-2}; and S is the line speed in $mmin^{-1}$. The total specific energy (E_t) applied to the fabric, Jkg^{-1} is calculated by Equation (2):

$$E_t = \sum_{i=1}^{p} \sum_{j=1}^{m} E_{ij} \qquad (2)$$

where E_{ij} is the specific energy applied to the fibre web by manifold, j ($j = 1,2,\ldots.m$), calculated by Equation (1), in the pass i ($i = 1,2,\ldots.p$).

It is logical to expect that structural characteristics have an impact on air permeability; this is dependent on porosity. However there is limited experimental evidence in the literature that these properties correlate. It is also certainly true that from the practical point of view of the non-woven fabric manufacturer, it is generally difficult to manipulate web weight for various reasons such as price, weight specification, etc. so that the manufacturer can select perhaps the most economic combination for a given end use. In the case of spun-lace production, for example, by changing the type of structure or by altering the web density (perhaps by hydroentangling to a greater or lesser extent), it may be possible to use a lighter and hence cheaper web, to give identical air permeability to that required for any particular application. There has been very limited study on spun-lace fabrics in open literature; therefore in this study, we have aimed to investigate the effect of hydroentangling energy on the air permeability of spun-laced fabrics.

Materials and methods

The samples were produced at the NC State College of Textiles' Nonwoven Laboratory. 1,5 dpf PET and Bleached cotton were used as the materials. The polyester and bleached cotton fibres were first opened, carded (by a flat top card) and cross-lapped in order to obtain webs with a bimodal fibre orientation. After forming the web, a pilot-scale Honeycomb hydroentangling machine was used to produce fabrics under varying pressures and numbers of passes. The speed of the line was 30 $feet/min^{-1}$ (9.14 m/min^{-1}). The machine has three manifolds; the pressure of each manifold can be independently controlled. The jet strips have two lines of orifices. The orifice diameter is 0.127 mm and the density of the jets is 16 orifices/cm. The pressure can be as low as 1.3 MPa for pre-wetting, and as high as 11 MPa for hydroentangling.

We produced fabrics at 16 (for PET) and 15 (for Cotton) different specific energy levels (by using various jet pressures and passes). The experimental design is given in Table 1. The pressure values in Table 1 are given in psi, since the machine is adjusted in BS units. All the calculations are made in BS units and then converted to SI units.

All the fabrics were manufactured from the same web with 50 gm^{-2} nominal weight. All specific energy levels (calculated from the equation above) and fabric properties measured are given in Table 2.

Air permeability was measured using a Frazier high-pressure air permeometer, as specified in ASTM D7371, using a pressure differential of 12.7 mm of water. A porometer was used to measure pore size characteristics as specified in ASTM E1294-89. ASTM E1294-89 is a liquid extrusion method of analysis for measuring the porosity of membrane filters which is also used effectively to evaluate the porosity of textile materials, and hence nonwovens (Figure 1).

In determining porosity, tests are carried out with dry and wet samples. The specimen is wetted first with a liquid of low sur-

Table 1. *Experimental design; the pressure in the table are given in psi as the machine has been adjusted in BS units. All calculatuions were solved in BS units and next changed to SI units.*

Sample designation	Weight, gm^{-2}	Sample designation	Weight, gm^{-2}	Passes	Pressure, psi			Specific energy, 10^3 x $kJkg^{-1}$ for	
					Manifold				
					#1	#2	#3	Cotton	PET
Cot.1	51.7	PET 1	47.3	1	200	400	400	1.94	2.12
				1	400	400	400		
Cot.2	44.2	PET 2	47.1	1	200	400	400	4.82	4.51
				3	400	400	400		
Cot.3	53.9	PET 3	36.8	1	200	400	400	6.04	8.85
				5	400	400	400		
Cot.4	48.6	PET 4	46.3	1	200	400	400	9.00	9.46
				7	400	400	400		
Cot.5	37.2	PET 5	46.1	1	200	400	400	14.8	11.95
				9	400	400	400		
Cotton is destroyed	-	PET 6	44.8	1	200	400	400	***	14.8
				11	400	400	400		
Cot.7	47.7	PET 7	51.9	1	200	800	0	2.66	2.25
				1	0	800	0		
Cot.8	44.6	PET 8	49.2	1	200	800	800	5.87	5.44
				1	800	800	800		
Cot.9	38.0	PET 9	45.9	1	200	800	800	12.34	11.81
				3	800	800	800		
Cot.10	51.2	PET 10	47.3	1	200	800	800	18.53	18.18
				5	800	800	800		
Cot.11	49.8	PET 11	45.7	1	200	800	800	24.91	24.55
				7	800	800	800		
Cot.12	48.1	PET 12	51.5	1	200	1200	0	4.42	4.03
				1	0	1200	0		
Cot.13	45.3	PET 13	49.0	1	200	1200	1200	10.30	9.88
				1	1200	1200	1200		
Cot.14	39.1	PET 14	47.7	1	200	1200	1200	22.09	21.58
				3	1200	1200	1200		
Cot.15	37.4	PET 15	43.8	1	200	1200	1200	33.82	33.29
				5	1200	1200	1200		
Cot.16	46.9	PET 16	44.0	1	200	1200	1200	45.38	44.99
				7	1200	1200	1200		

Table 2. Spunlaced nonwoven characteristics.

Cotton			PET		
Specific energy, 10^3 x $kJkg^{-1}$	Basis weight, gm^{-2} (Standard error)	Thickness, mm (Standard error)	Specific energy, 10^3 x $kJkg^{-1}$	Basis weight, gm^{-2} (Standard error)	Thickness, mm (Standard error)
1.94	51.73 (1.33)	0.84 (0.007)	2.12	47.27 (0.83)	0.823 (0.007)
2.66	47.66 (0.43)	0.68 (0.005)	2.25	51.92 (0.75)	0.873 (0.004)
4.42	48.05 (1.22)	0.67 (0.003)	4.03	51.53 (1.01)	0.890 (0.005)
4.82	44.17 (0.90)	0.73 (0.008)	4.51	47.08 (0.65)	0.713 (0.004)
5.87	44.56 (1.12)	0.66 (0.006)	5.44	49.21 (0.66)	0.850 (0.003)
6.04	53.86 (1.38)	0.76 (0.013)	8.85	36.81 (0.58)	0.610 (0.004)
9.00	48.63 (0.93)	0.66 (0.006)	9.46	46.30 (0.45)	0.631 (0.005)
10.30	45.33 (1.27)	0.60 (0.006)	9.88	49.01 (0.92)	0.870 (0.006)
12.34	37.97 (0.88)	0.56 (0.008)	11.81	45.91 (0.58)	0.714 (0.004)
14.80	37.21 (0.75)	0.58 (0.007)	11.95	46.11 (0.48)	0.614 (0.006)
18.53	51.15 (0.92)	0.56 (0.003)	14.80	44.75 (1.21)	0.569 (0.004)
22.09	39.13 (0.99)	0.54 (0.006)	18.18	47.27 (0.78)	0.719 (0.004)
24.91	49.79 (1.23)	0.55 (0.005)	21.58	47.66 (1.01)	0.772 (0.005)
33.82	37.39 (1.53)	0.50 (0.004)	24.55	45.72 (0.66)	0.673 (0.006)
45.38	46.88 (1.25)	0.55 (0.003)	33.29	43.78 (0.83)	0.672 (0.004)
-	-	-	44.99	43.98 (0.71)	0.685 (0.005)

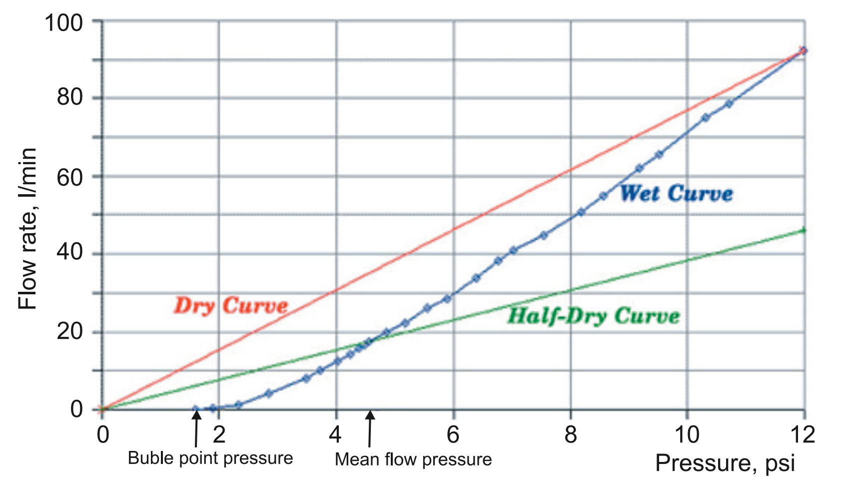

***Figure 1.** Calculation of maximum pore size and mean pore size (from PMI); according to Akshaya Jena and Krishna Gupta, Liquid Extrusion Techniques for Pore Structure Evaluation of Nonwovens, International Nonwovens Journal, Fall, 2003, pp 45-53.*

face tension (Silwick (19.8 dynes per cm surface tension)), and then extruded under increased air pressure. The maximum pore size is determined according to the first air flow, which is characterised as the bubble point. As smaller pores are emptied, air flow through the sample increases, and the air flow is recorded as a function of air permeability. All these results are compared with that of the dry sample. The following data is used to determine the pore size distribution: the variation of flow rate with pressure for a dry sample, and a half-dry curve which is computed from the dry curve to yield half of the flow rate through the dry curve at a given differential pressure. The intersection of the wet curve and the half-dry curve gives the mean flow pressure that corresponds to mean pore diameter [12]. Pores smaller than the mean pore diameter are responsible for half of the flow.

A theoretical and calculated value for porosity can be determined; this is defined as the ratio of air space to the total fabric volume, expressed as a percentage. The terms used in the calculation here are the specific gravity of the component fibres and the weight and thickness of the specimen, which is given by the following formula [13]:

$$p = 100 - (d_{fabric} / d_{fibre})$$

where:

p - calculated porosity,
d_{fabric} - fabric density and
d_{fibre} - fibre density.

Fabric density is expressed in grams per cmł, calculated so that the fabric weight is divided by the fabric thickness.

Pearson correlation coefficients are determined in Table 3, and the significance of these coefficients are given under Table 3 by the following procedure as given below:

The value of the random variable t_{obl} is calculated as follows,

$$t_{obl} = \frac{R}{\sqrt{1-R^2}} \cdot \sqrt{n-2}$$

where: R – the value of the linear correlation coefficient calculated on the basis of the measurement results.

A hypothetical statement about a correlation of the variables X and Y in the total general population is in the form of H_0: $R = 0$. If the hypothesis H_0 is true, then the computational value of the variable t_{obl} is smaller than the critical value (from the t-Student distribution table, at the significance level $\alpha = 0.05$ and the number of the degrees of freedom $k = n - 2$, that is, $t_{obl} < t_\alpha$). Whereas if: $t_{obl} > t_\alpha$, then it can be accepted that the variables X and Y are correlated, and then the linear correlation coefficient for the total general population is different from zero, that is, $R \neq 0$. This also means that, for example, feature X (the specific energy) influences the feature Y, such as the area weight thickness, the density, the air permeability, the porosity, the size and distribution of pores, etc. t_α is the critical statistical value (selected from the t-Student distribution table, for the significance level $\alpha = 0.05$ and the number of the degrees of freedom $k = n - 2$).

Results

Table 2 shows the relationship of the basis weight and thickness change vs. the specific energy given in hydroentanglement. We expect that increasing specific energy would decrease the web weight and so the thickness. As may be seen from Table 2 and Table 3, there is no significant correlation level between these variables in PET fabrics. On the other hand, we obtain significant negative correlation between the specific energy and fabric thickness in cotton fabrics. This may be due to the structural differences of the two fibres under discussion. We obtained a more compact and paper-like material in cotton fabrics when we increased the energy; however, bulkier fabrics are produced from PET fibres even at high specific energy levels. This may be

*Table 3. Pearson's correlation table; * :Correlation is significant at the 0,05 level (2 tailed), ** :Correlation is significant at the 0,01 level (2 tailed).*

Parameter	Cotton		PET	
	Specific energy	Air permeability	Specific energy	Air permeability
Specific energy	1.000	-0.561*	1.000	0.201
Air permeability	-0.561*	1.000	0.201	1.000
Basis weight	-0.289	-0.339	-0.380	-0.420
Thickness	-0.751**	0.275	-0.400	-0.011
Fabric density	0.610*	-0.671**	0.146	-0.301
Mean pore size	-0.595*	0.776**	-0.115	0.632*
Max. pore size	-0.180	0.102	-0.065	-0.550*
Min. pore size	-0.515*	0.499	-0.210	0.004
Calculated porosity	-0.610*	0.671**	-0.236	0.351

partly because of the bending behaviours of cotton and PET fibres. It may also result from the possible deformations which occurred in the fibres during the hydroentanglement processes.

In PET fabrics we do not have any significant correlations between specific energy and other variables or with air permeability (Figure 2). Since we have used a lab-type hydroentanglement machine, the pressure range was narrower than that of a commercial type, and we could not obtain as high energy for hydroentangling PET fibres as we had expected.

Unlike PET fabrics, we obtain good correlations for cotton fabrics with the experimental data we obtained both for specific energy levels and air permeability (Figure 4). An interesting result shows that air permeability of fabrics decreases as specific energy is increased. Although this may seem irrational, a detailed comparative study of the results will reveal that by increasing the specific energy, we decrease both the thickness and the porosity (both minimum and maximum porosity). This result may be explained again by the inherent nature of cotton fabrics. When we increased the energy, we obtained a thinner fabric but a more paper-like structure, which means that the porosity of the fabric was lost.

If air permeability is compared with the porosity especially, the highest correlation among all variables were mean pore size vs. air permeability for both type of fibres (Figure 3 & 5). We get almost the same results as in the literature. Pore structures have a great effect, as was expected. Air permeability is increased as pore size is increased.

Conclusions

We investigated several factors related to the effect of the specific energy level and air permeability of fabrics. Different fibres showed distinct behaviours under almost the same process conditions. In general, increasing pressure and the number of passes results in a better structure up to a certain point, provided that the web is sufficiently consolidated. If the web is not consolidated, higher pressures will result in disturbing the web, changing the structure and thus the character of the resulting web.

Porosity and air permeability have a significant correlation, as stated in the literature. We produced bulkier fabrics

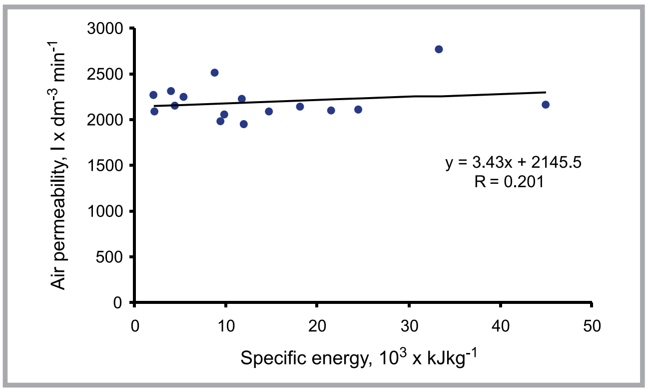

***Figure 2.** Air permeability vs. specific energy in PET fabrics.*

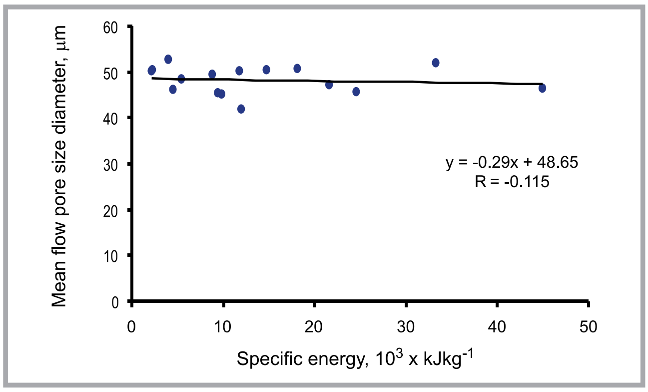

***Figure 3.** Mean flow pore diameter vs. specific energy in PET fabrics.*

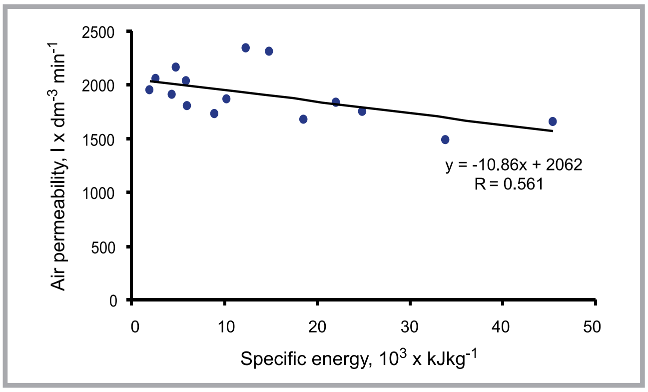

***Figure 4.** Air permeability vs. specific energy in cotton fabrics.*

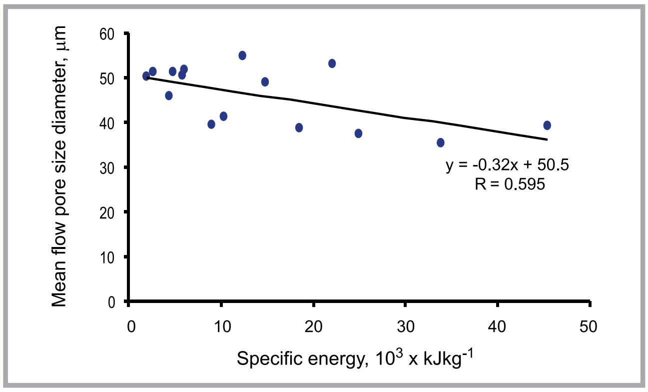

***Figure 5.** Mean flow pore diameter vs. specific energy in cotton fabrics.*

with PET fibres than with cotton fabrics. Generally speaking, better correlations are obtained for cotton fabrics.

The pilot equipment used for the work can only apply pressures of up to 100 bars, unlike current commercial equipment which allows 400 bars or more. Therefore, a further study has been planned to investigate the correlation between specific energy and air permeability of fabrics from a wide variety of fibres using a commercial production line.

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Knitt-Tech 2006
7th INTERNATIONAL SCIENTIFIC-TECHNICAL CONFERENCE

Subject of the Conference: New Techniques and Technologies in Knitting

The 7th Knitt-Tech International Scientific-Technical Conference was held from 20 June to 1 July 2006 in Ciechocinek, Poland. This regular/annual event, which has been organised since 1994, was dedicated this time to the theme of 'New techniques and technologies in knitting'. It was organised by the Department of Knitting Technology and Structure of Knitted Products (DKTSKP) at the Technical University of Łódź (TUŁ) in cooperation with the Tricotextil Institute of Knitting Techniques and Technologies, Łódź.

120 scientists, technologists, and representatives of the industry from Poland, France, Italy, Germany, and India participated in the Conference. The guest lectures of the plenary session were devoted to the following four groups of topics:

- Prospects for the textile-clothing branch during globalisation, and the rules concerning partial financial support for institutions by the European Union. The projects and achievements of the Polish Technological Platform of the Textile Industry after one year/its first year of activity were also listed.
- Modern technologies in knitting, especially concerning knittings for special applications, super-soft cotton knittings manufactured from drawn spinning rowing and ecologically-friendly methods of purifying textile waste-waters.
- Development strategy of the worldwide textile industry, based on examples from Italian and Indian enterprises.
- An outline of education for textile engineers at the Faculty of Textile Engineering and Marketing TUŁ, which considers the current needs of the industry and the research and development centres.

Within the scope of the panel discussion carried out as a part of the LORIS TEX project dedicated to "Transformation of the textile industry from labour-consuming to 'science-consuming", the question of prospects for the development of the textile-clothing industry over the next 25 years were discussed.

The poster session of the Conference was dedicated to presenting the results of recent and current research conducted by R&D units, especially those of the Institutes and the DKTSKP.

The conference deliberations were accompanied, as at all of our earlier conferences, by a rich social programme of friendly meetings. Bonfires with singing, including the participation of a professional artistic friendly society, dinner with dancing and a performance by Bogdan Mec, a well-known professional singer, contributed to the integration of the knitting society, and meant that the conference participants left Ciechocinek with good impressions, and in their opinions reinforced the high scientific and organisational levels of the conference.

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