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Influence of the Structure of Woven Fabrics on Their Thermal Insulation Properties

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Abstract

In the present work, fabrics of intentionally changed structure were measured in the range of their basic structural parameters and thermal insulation properties. Cotton woven fabrics of different weaves, linear densities of the weft and different weft densities were the objects of the investigation. The thermal insulation properties of the fabrics were measured by means of an Alambeta. On the basis of the results, the influence of the fabric structure on values of particular thermal insulation parameters was analysed. Statistical analysis demonstrated that the weave and linear density of weft yarn significantly influence the thermal properties of woven fabrics. A strong and statistically significant correlation was found between the thermal insulation properties of the fabrics and such structural parameters as the average percentage filling and integrated fabric structure factor.

Key words: *thermal comfort, woven fabrics, fabric structure, thermal insulation properties.*

Introduction

The human body is an active system which responds to environmental input in a way which is monotonically related to the level of physical factors. Such factors of the environment as temperature, humidity, air movement and radiation influence the physiological comfort of a human being. Physiological comfort is strongly connected with thermal comfort, which is considered as a state of satisfaction from the thermal conditions of the environment [1 - 4]. Thermal comfort depends on many factors. A crucial role is played by the thermal insulation of clothing, which creates a barrier between the human organism and the environment. Clothing influences heat and moisture exchange between the human body and surroundings and protects the human body against cold and warmth discomfort, wind, rain and radiation, especially UV. The influence of clothing on the comfort of a human being is a complex phenomenon that depends on the material and structure of clothing [5]. The structure of clothing means its size, cut, fitting to the user's body, number of layers etc. The material of clothing should be considered in two ways: a raw material and a kind of fabric creating particular layers of clothing.

The influence of raw material on the thermal insulation of clothing results from the different thermal properties of fibres and polymers. The kind of material used in particular layers means not only knitted, woven or nonwoven fabrics but also their structure: thickness, tightness, porosity, etc [6, 7]. The kind and structure of fabrics directly influence their thermal insulation. Thermal resistance, water-vapour resistance and air permeability are considered as crucial comfort-related properties of fabrics [5, 8 - 10]. There are other properties which influence the thermal comfort of the clothing user, e.g. thermal conductivity, absorptivity, and diffusivity. There are also different instruments for measurement of the thermal insulation properties of textile materials. The sweating guarded hotplate test, called the "skin model", is commonly accepted and used all over the world. Other instruments such as the Alambeta, Thermo Labo II and Permetest are relatively new, and their application still is not widespread [7 - 10].

The aim of the present work was to analyse the relationships between the thermal insulation properties of woven fabrics and fabric structure.

Material and methods

Material

In the present work fabrics with an intentionally changed structure were measured in the range of their basic structural parameters and thermal insulation properties. 19 variants of cotton woven fabrics of different weaves, linear densities of the weft and different weft densities were the object of the investigation. The fabrics were manufactured on the basis of the same warp: linear density – 50 tex, and number of treads – 320/dm. All fabric variants were dyed and finished in the same way. The set of fabrics measured is presented in ***Table 1***.

Methods used

All the fabric variants were measured in the range of the basic structural parameters: the real warp and weft density, mass per square meter, warp and weft take up and fabric thickness, according to standardised procedures.

Measurement of the thermal insulation properties of the fabrics was done by means of an Alambeta, which is a computer-controlled instrument for measuring the basic static and dynamic thermal characteristics of textiles [4, 10]. This method belongs to the so-called 'plate methods', the acting principle of which relies on the convection of heat emitted by the hot upper plate in one direction through the sample being examined to the cold bottom plate adjoined to the sample.
The instrument directly measures the stationary heat flow density (by measuring the electric power at the known area of the plates), the temperature difference between the upper and bottom fabric surface, and the fabric thickness. The device calculates the real thermal resistance for all fabric configurations. The other thermal parameters such as thermal conductivity, thermal absorptivity and thermal diffusivity are calculated using algorithms appropriate for homogeneous materials [4, 11]. The procedure for the measurement of thermal properties by means of an Alambeta is standardised in the Internal Standard of the Textile Faculty of the Technical University of Liberec [12].

By means of an Alambeta, the following thermal insulation properties of the fabrics were determined:
- thermal conductivity,
- thermal absorptivity,
- thermal resistance,
- fabric thickness.

Measurement by the Alambeta was performed in standard climatic conditions. For each fabric variant 3 repetitions of the measurement were made. As a result the arithmetic mean was calculated from the individual measurement results.

On the basis of the laboratory results and calculated values of the factors characterising the fabric structure, a statistical analysis was carried out in order to assess the relationships between the thermal insulation properties of the fabrics and their structure.

The analysis of the results was divided into two parts: The first concerned the influence of the weave and linear density of the weft yarn on the thermal insulation properties of the fabrics, which was performed on the basis of the results for 12 fabric variants. The second part concerned the correlation between the parameters characterising the woven fabric structure and thermal insulation parameters of the fabrics, based on the results for all 19 fabric variants.

Table 1. *Set of fabric variants investigated.*

No	Weave	Linear density of		Nominal density of	
		warp, tex	weft, tex	warp, dm^{-1}	weft, dm^{-1}
1	plain	50	100	320	110
2	plain		60		110
3	plain		100		90
4	plain		100		70
5	twill 3/1 S		100		70
6	twill 3/1 S		100		90
7	twill 3/1 S		100		110
8	twill 3/1 S		60		
9	twill 3/1 S		50		
10	twill 3/1 S		40		
11	twill 3/1 S		30		
12	twill 2/2 S		100		
13	twill 2/2 S		60		
14	rep 1/1 (0,1,0)		100		
15	rep 1/1 (0,1,0)		60		
16	rep 2/2 (2)		100		
17	rep 2/2 (2)		60		
18	hopsack 2/2 (0,2,0)		100		
19	hopsack 2/2 (0,2,0)		60		

A statistical analysis of the influence of the weave and linear density of the weft yarn on the thermal insulation properties of the fabrics was carried out using Multi-Factor ANOVA. In general, the purpose of the analysis of variance (ANOVA) is to test for significant differences between means. However, in order to test for this, the variances were actually compared using the *F* test. This is accomplished by analysing the variance, that is, by partitioning the total variance into the component that is due to true random error (i.e., within-group *SS*) and the components that are due to differences between means [13]. The *SS* is calculated according to the equation:

$$SS = \sum_{i=1}^{k} \sum_{j=1}^{n_i} \left(x_{ij} - \overline{x_i} \right)^2 \qquad (1)$$

where:
SS – sums of squares,
x_{ij} – individual result in *i* group,
$\overline{x_i}$ – mean value from the results in *i* group,
i – number of groups ($i = 1,2,...,k$),
j – number of elements in group ($j = 1,2,...,n_i$).

The between-group's variability *MS* is calculated according to the formula:

$$MS = \sum_{i=1}^{k} \left(\overline{x_i} - \overline{\overline{x}} \right)^2 n_i \qquad (2)$$

where:
MS – Mean Square effect - between-group's variability,
$\overline{\overline{x}}$ – mean value from all results,
$\overline{x_i}$ – mean value from the results in *i* group,
n_i – number of elements in *i* group.

The statistical analysis was performed using STATISTICA version 7 software. The analysis was based on the individual measurement of particular samples. According to the software applied, the analysis is based on a comparison of the variance due to the between-group's variability (called the *Mean Square Effect*, or MS_{effect}) with the within-group's variability (called *Mean Square Error*, or Ms_{error}). Under the null hypothesis (that there are no mean differences between groups in the population), some minor random fluctuation in the means for the two groups is still expected when taking small samples. Therefore, under the null hypothesis, the variance estimated based on the within-group's variability should be about the same as that due to the between-group's variability. STATISTICA compares those two estimates of variance via the *F* test, which tests whether the ratio of the two variance estimates is significantly greater than 1. These latter variance components are then tested for statistical significance, and, if significant, the null hypothesis of no differences between means is rejected and the alternative hypothesis is accepted that the means (in the population) are different from each other [13].

Table 2. Results of the measurement of basic structural parameters of the woven fabrics investigated.

No of variant	Real warp density, dm^{-1}	Real weft density, dm^{-1}	Warp take up	Weft take up	Mass per square meter, gm^{-2}	Fabric thickness, mm
1	312	115	14.2	2.9	292	0.67
2	316	117	8.8	3.7	240	0.61
3	314	94	9.6	2.7	269	0.69
4	314	73	7.0	2.4	242	0.71
5	315	74	4.7	2.8	241	0.80
6	318	94	6.2	2.9	266	0.79
7	317	116	7.9	3.3	292	0.78
8	317	117	5.5	3.8	238	0.70
9	317	116	5.0	3.6	225	0.67
10	320	118	4.5	3.2	215	0.65
11	318	118	4.1	4.3	198	0.61
12	319	116	7.0	2.7	287	0.79
13	319	118	5.9	3.9	238	0.73
14	311	115	7.3	1.2	284	0.83
15	317	118	6.1	2.4	237	0.74
16	317	119	9.8	3.9	293	0.65
17	320	118	6.8	5.4	242	0.58
18	316	117	6.4	2.3	287	0.79
19	316	117	5.3	3.2	234	0.72

Table 3. Results of the measurement of thermal insulation properties of the fabrics investigated.

No of variant	Average thermal		
	conductivity λ, W m^{-1}K^{-1} 10^{-3}	absorptivity b, Wm^{-2} s$^{1/2}$ K^{-1}	resistance R, W^{-1} Km^{2} 10^{-3}
1	72.9	287	9.4
2	69.6	268	8.5
3	71.5	264	9.8
4	65.9	227	11.4
5	60.6	210	13.9
6	65.2	228	12.7
7	68.5	241	12.1
8	68.0	243	10.9
9	64.3	227	11.0
10	61.7	213	11.1
11	59.7	220	10.5
12	68.9	236	12.2
13	65.4	222	11.7
14	65.9	224	13.6
15	62.6	223	12.5
16	69.8	279	9.6
17	66.6	273	8.9
18	66.3	243	12.9
19	60.4	215	12.7

Table 4. Set of fabric variants analysed from the point of view of the influence of the weave on the thermal insulation properties of the fabrics.

No of variant	Weave	Linear density of weft, tex	Average thermal		
			conductivity, W m^{-1}K^{-1} 10^{-3}	absorptivity, Wm^{-2} s$^{1/2}$ K^{-1}	resistance, W^{-1} Km^{2} 10^{-3}
1	Plain	100	72.9	287	9.4
2		60	69.6	268	8.5
7	twill 3/1 S	100	68.5	241	12.1
8		60	68.0	243	10.9
12	twill 2/2 S	100	68.9	236	12.2
13		60	65.4	222	11.7
14	rep 1/1 (0,1,0)	100	65.9	224	13.6
15		60	62.6	223	12.5
16	rep 2/2 (2)	100	69.8	279	9.6
17		60	66.6	273	8.9
18	hopsack 2/2 (0,2,0)	100	66.3	243	12.9
19		60	60.4	215	12.7

Results

Results of the measurement of fabric structural parameters are presented in ***Table 2***.

Results of the measurement of thermal insulation properties of the fabrics investigated are given in ***Table 3***.

Analysis of the results

Influence of the fabric weave and linear density of weft yarn on the thermal insulation properties of fabrics

The influence of the weave and linear density of weft yarn on the thermal insulation properties of fabrics was assessed on the basis of results for 12 fabric variants with a weft density of 110 dm^{-1}, made of weft yarns: 60 tex and 100 tex, and manufactured in 6 different weaves. The set of fabric variants analysed in this part of the investigation are presented in ***Table 4***.

Tables 5, 7 and ***8*** present the results of the ANOVA generated by STATISTICA version 7. In the tables, the symbol *df* expresses the degrees of freedom. The degrees of freedom of a set of observations are the number of values which could be assigned arbitrarily within the specification of the system.

According to the software applied, the interpretation of the results generated is as follows:

- when $p \leq 0.05$ – there is a statistically significant difference between the within-group's and between-group's variability,
- when $p > 0.05$ – the difference between within-group's and between-group's variability is statistically insignifcant.

In the tables, the relationships statistically significant at a probability level of 0.05 are emphasised in bold italics.

Table 5 presents the results of the ANOVA for thermal conductivity.

On the basis of the results, it was noted that both factors: the weave and linear density of weft yarn significantly influence the thermal conductivity of the woven fabrics. The highest thermal conductivity was noted for plain fabrics. The second highest thermal conductivity was found for the rep 2/2 (2) and twill 3/1 S weave fabrics (***Figure 1***).

Plain and rep 2/2 (2) fabrics are characterised by the highest specific mass (***Figure 2***), meaning that in a volume unit they contain the biggest amount of fibrous material, in which thermal conductivity takes place. This proves that plain and rep 2/2 (2) weave fabrics have the highest thermal conductivity. The high thermal conductivity of twill 3/1 S fabrics is difficult to explain at the moment. Twill 3/1 S fabrics are characterised by a loose structure, with a big amount of air inside them. The results of the thermal conductivity were checked using another device – Thermo Labo II. The measurement using a Thermo Labo II confirmed the high – comparable with rep 2/2 (2) weave fabrics – thermal conductivity of twill 3/1 S weave fabrics. It is probable that the reason for such a relatively high thermal conductivity of twill 3/1 S fabrics is the interaction between different structural factors thereof. This phenomenon will be the object of further investigation.

The lowest thermal conductivity occurred in the case of hopsack 2/2 (0,2,0) and rep 1/1 (0,1,0) weave fabrics. As can be seen in fig. 2, hopsack 2/2 (0,2,0) and rep 1/1 (0,1,0) weave fabrics have the lowest specific mass. The results presented demonstrate that the thermal conductivity of woven fabrics made of the same material (fibres) depends on the specific mass of the fabrics.

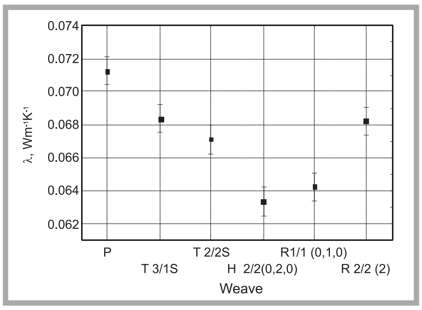

Figure 1. *Influence of weave on the thermal conductivity of woven fabrics.*

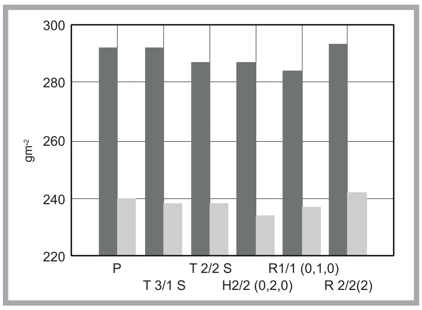

Figure 2. *Specific mass of the fabrics investigated in the function of the weave: ■ - weft yarn 100 tex, ■ - weft yarn 60 tex.*

Table 5. *Results of the Anova for the thermal conductivity of woven fabrics.*

	SS	df	MS	F	p
constant	***0.161990***	***1***	***0.161990***	***153481.0***	***0.000000***
weave	***0.000254***	***5***	***0.000051***	***48.1***	***0.000000***
weft	***0.000099***	***1***	***0.000099***	***93.4***	***0.000000***
weave×weft	***0.000023***	***5***	***0.000005***	***4.3***	***0.006257***
error	0.000025	24	0.000001		

Table 6. *Percentage changes in the thermal insulation properties of the fabrics due to changes in the linear density of the weft yarn.*

Fabric weave	Δλ, %	Δb, %	ΔR, %
Plain	4.74	7.09	10.59
Twill 3/1S	0.74	-0.82	11.01
Twill 2/2 S	5.35	6.31	4.27
Rep 1/1 (0,1,0)	5.27	0.45	8.80
Rep 2/2 (2)	4.80	2.20	7.87
Hopsack 2/2 (0,2,0)	9.77	13.02	1.57

Table 7. *Results of the Anova for the thermal absorptivity of woven fabrics.*

	SS	df	MS	F	p
constant	***2182169***	***1***	***2182169***	***15946.25***	***0.000000***
weave	***17654***	***5***	***3531***	***25.80***	***0.000000***
weft	***1023***	***1***	***1023***	***7.48***	***0.011565***
weave*weft	1010	5	202	1.48	0.234204
error	3284	24	137		

The linear density of weft yarn also influences the thermal conductivity of fabrics. Fabrics made of weft yarn of 100 tex are characterised by a higher thermal conductivity than those made of weft yarn of 60 tex. Changes in the thermal conductivity of fabrics caused by a change in the linear density of the weft yarn depend on the fabric weave. Percentage differences in the thermal conductivity of fabrics with different weaves due to a change in the linear density of the weft yarn are presented in ***Table 6***. The percentage difference between the thermal conductivity of fabrics with different weft yarns were calculated according to the ***Equation 3***:

$$\Delta\lambda = \frac{\lambda_{weft100} - \lambda_{weft60}}{\lambda_{weft60}} \cdot 100 \qquad (3)$$

where:

$\Delta\lambda$ – percentage difference between the thermal conductivity of fabrics,
$\lambda_{\mathrm{weft100}}$ – thermal conductivity of fabric made of weft yarn of 100 tex,
$\lambda_{\mathrm{weft60}}$ – thermal conductivity of fabric made of weft yarn of 60 tex,

Percentage changes in other thermal insulation properties of the fabrics caused by a change in the linear density of the weft yarn were calculated in the same way. All results are presented in ***Table 6***.

The lowest changes in the thermal conductivity of the fabrics caused by a change in the linear density of the weft yarn were found for twill 3/1 S weave fabric, which can be considered as a lack of change. For other weaves, the changes in thermal conductivity due to a change in the linear density of the weft yarn are in the range of 4.74% to 9.77%.

It should be mentioned here that in the experiment presented, the linear density of the weft yarn was changed from 60 tex to 100 tex, which means an increase of 66%. Nevertheless the share of the weft yarn in the total fabric structure is ca. 30% (***Table 10,*** see page 52), which means that changes in the fabric structure due to a change in the linear density of the weft yarn were practically ca. 20%.

The percentage changes in thermal conductivity due to a change in the fabric weave are at the same level. The highest percentage difference (15.23%) was noted between the thermal conductivity of plain and hopsack 2/2 (0,2,0) fabrics

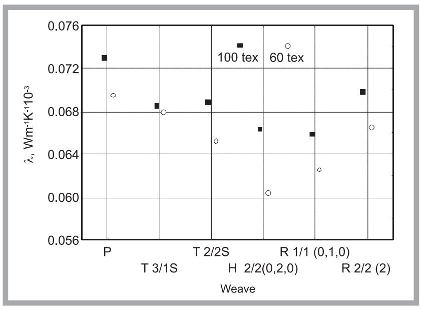

Figure 3. *Influence of weave and weft linear density on the thermal conductivity of woven fabrics.*

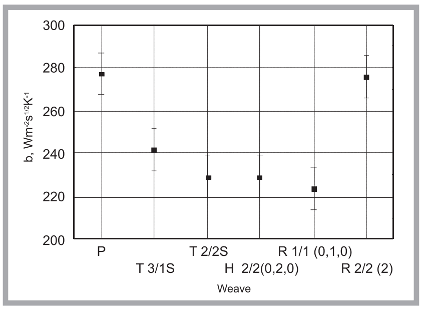

Figure 4. *Influence of the weave on the thermal absorptivity of woven fabrics.*

Table 8. *Results of the Anova for the thermal resistance of woven fabrics*

	SS	Df	MS	F	p
constant	***0.004560***	***1***	***0.004560***	***112341.3***	***0.000000***
weave	***0.000093***	***5***	***0.000019***	***456.2***	***0.000000***
weft	***0.000005***	***1***	***0.000005***	***128.8***	***0.000000***
weave*weft	***0.000001***	***5***	***0.000000***	***4.7***	***0.004104***
error	0.000001	24	0.000000		

made of weft yarn of 60 tex (variant 2 and 19), whereas the lowest difference (- 4.44%) was found between plain and rep 2/2 (2) fabrics made of weft yarn of 100 tex (variants 1 and 16).

The results obtained confirmed that there is a statistically significant interaction between the main factors: the weave and weft linear density. The weave modifies the relationship between the thermal conductivity of fabrics and the linear density of weft yarn (***Figure 3***).

Thermal absorptivity is a property which characterises fabrics from the point of view of a warm/cool feeling at the moment of contact with human skin. The higher the thermal absorptivity, the cooler the feeling. Statistical analysis (***Table 7***) proved that the thermal absorptivity of fabrics is influenced by the fabric weave and linear density of the weft yarn, in addition to which the influence of both structural factors on the thermal absorptivity of fabrics is statistically significant at a probability level of 0.05.

The highest thermal absorptivity and, at the same time, the coolest feeling at the moment of contact of the fabric with human skin was found for plain and rep 2/2 (2) weave fabrics. The warmest feeling is given by rep 1/1 (0,1,0), hopsack 2/2 (0,2,0) and twill 2/2 weave fabrics (***Figure 4***), which is difficult to explain. It is interesting that the lowest thermal absorptivity and warmest feeling occurred for fabrics which are characterised by the same even number (2) of warp and weft overlaps in a repeat.

The highest percentage differences in thermal absorptivity caused by a change in the weave were noted between the plain and rep 1/1 (0,1,0) fabrics. Plain fabric made of weft yarn of 100 tex (variant 1) has a 28% higher thermal absorptivity than rep 1/1 (0,1,0) fabric made of the same weft yarn (variant 14).

The thermal absorptivity of fabrics also depends on the linear density of the weft. Fabrics made of weft yarn of 100 tex are characterised by higher thermal absorptivity than those made of weft yarn of 60 tex. The highest percentage change in thermal absorptivity due to a change in the linear density of the weft yarn was observed for hopsack 2/2 (0,2,0) fabrics – 13.02% (***Table 6***).

According to the results above, plain and rep 2/2 (2) fabrics are better for summer clothing than the other fabrics analysed because they give a cold feeling. Rep 1/1 (0,1,0), twill 2/2 S and hopsack 2/2 (0,2,0) weave fabrics are better for winter clothing because they give a warmer feeling than plain, rep 2/2 (2) and twill 3/1S weave fabrics.

It should be emphasised here that there are not any criteria which could enable to assess the fabrics from the point of view of their thermal absorptivity. An investigation performed by Hes [14] showed, for instance, that the thermal absorptivity of rib cotton woven fabrics is in the range 100 – 150 $Wm^{-2} s^{1/2} K^{-1}$, whereas the thermal absortptivity of dry cotton shirt fabrics or heavy smooth wool woven fabrics is in the range 250 – 350 $Wm^{-2} s^{1/2} K^{-1}$. The results obtained fall into the second group.

On the basis of the results for thermal absorptivity, the fabrics investigated cannot be assessed from the point of view of their better or worse quality. The fabrics can only be ranked according to their warm or cold feeling at the moment of contact with human skin.

The fabric weave and linear density of weft yarn significantly influence the thermal resistance of fabrics. Moreover, there is a statistically significant interaction between both independent factors (***Table 8***).

The highest thermal resistance was found for rep 1/1 (0,1,0) and hopsack 2/2 (0,2,0) weave fabrics, whereas the lowest – for plain and rep 2/2 (2) weave fabrics (***Figure 5***). In the case of fabrics made of the same material (fibres), the thermal resistance depends only on fabric thickness and is directly proportional to it. The fabrics investigated are characterised by different thicknesses depending on the weave and linear density of weft yarns (***Figure 6***). The results obtained confirm the above-mentioned correlation between thermal resistance and fabric thickness.

The highest percentage differences in thermal resistance caused by a change in the weave was noted between the plain and hopsack 2/2 (0,2,0) fabrics. Hopsack 2/2 (0,2,0) fabric made of weft yarn of 100 tex (variant 18) has a 49.41% higher thermal resistance than plain fabric made of the same weft yarn (variant 1).

The fabrics made of weft yarn of 100 tex have a higher thermal resistance than those made of weft yarn of 60 tex, which results from the differences in fabric thickness caused by the different linear densities of the weft yarns (***Figure 6***).

Unlike the changes in thermal conductivity and absorptivity, the percentage change in thermal resistance due to a change in the weft linear density of hopsack 2/2 (0,2,0) fabric is the lowest in comparison to other fabrics. The highest percentage differences in thermal resistance caused by a change in the linear density of weft yarn occurred for

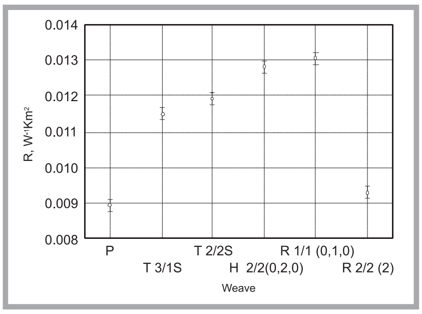

***Figure 5**. Influence of weave on the thermal resistance of woven fabrics.*

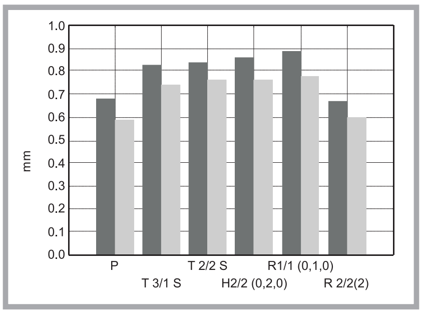

***Figure 6**. Fabric thickness in the function of the weave: ■ - weft yarn 100 tex, ■ - weft yarn 60 tex.*

twill 3/1 S and plain fabrics, 11.01% and 10.59%, respectively.

At the moment, there is a lack of basis for fabric quality assessment from the point of view of thermal insulation properties. Although the protection of the human body against cold is one of the most important functions of fabrics and clothing made of such, there are not any criteria of fabric assessment available in this aspect. The assessment of fabrics from the point of view of their thermal insulation properties depends on the kind of clothing to which they will be applied and climatic conditions of their usage. The requirements of fabrics destined for winter clothing are quite different from those of fabrics designed for summer clothing. Due to this fact, it is impossible to conclude which fabric structure is better from the point of view of their thermal insulation properties.

However, the results obtained show that it is possible to shape the thermal insulation properties of woven fabrics by changing the density of their structure, the yarn linear density or yarn density. Changing the fabric weave without altering other parameters (such as the kind of yarn and yarn density) also enables significant changes in the thermal insulation properties of woven fabrics – even as much as 50% (the above-mentioned difference in thermal resistance between variants: 18 and 1).

Analysis of the correlation between the parameters characterising the woven fabric structure and thermal insulation parameters of fabrics

The investigation carried out demonstrated that woven fabrics made of the same warp and weft yarns and of the same warp and weft densities are characterised by different values of thermal insulation properties due to the different weaves.

The problem is how to express in a quantitative way the relationships between the thermal insulation properties of woven fabrics and fabric weave. Apart from the measurable parameters such as the mass per square meter, thickness, and warp and weft density, different computational factors are used for the characterisation of a fabric structure. The cover and filling factors should be mentioned here as the most important structural parameters of woven fabrics.

The cover factors are calculated according to the following formulas [15, 16]:

$$Z_{warp} = S_1 \cdot d_1 \tag{4}$$

$$Z_{weft} = S_2 \cdot d_2 \tag{5}$$

$$Z_{total} = Z_{warp} + Z_{weft} - \frac{Z_{warp} \cdot Z_{weft}}{100} \tag{6}$$

were:
Z_{warp} - fabric cover by warp,
Z_{weft} - fabric cover by weft,
Z_{total} - fabric cover by both warp and weft,
S_1 - warp density,
S_2 - weft density,
d_1 - warp diameter,
d_2 - weft diameter.

The cover factors calculated according to the equations above do not take into consideration the weave of fabrics. Due to this fact, the cover factors of fabrics of the same weft and warp yarns and weft and warp densities have the same values irrespective of their weave.

The filling factors are calculated using the following equations [15, 16]:

$$E_{warp} = \frac{d_1 \cdot R \cdot_1 + d_2 \cdot p_2}{R_1} S_1 \tag{7}$$

$$E_{weft} = \frac{d_2 \cdot R_2 \cdot + d_1 \cdot p_1}{R_2} S_2 \tag{8}$$

$$E_{average} = \frac{E_{warp} . T_1 + E_{weft} \cdot T_2}{T_1 + T_2} \tag{9}$$

where:
E_{warp} - percentage filling by warp,
E_{weft} - percentage filling by weft,
$E_{average}$ - average percentage filling,
d_1 - warp diameter,
d_2 - weft diameter.
R_1 - warp repeat,
R_2 - weft repeat,
p_1 - number of warp interlacing points in repeat,
p_2 - number of weft interlacing points in repeat.

Fabric weave is reflected in the filling factors because the weave repeat and number of interlacing points in it are introduced into ***Equations** 7* and ***8***.

In order to characterise the structure of woven fabrics by means of one factor, Milašius proposed an integrated fabric structure factor φ [17 - 21], which is calculated according to the ***Equation 10***, where:
φ - integrated fabric structure factor according to Milašius [17, 18],
P - weave factor, called 'the weave-firmness factor', proposed by Milašius [19],
ρ - overall density of raw materials of threads,
S_1 - setting of warp,
S_2 - setting of weft,
T_1 - linear density of warp,
T_2 - linear density of weft,
T_{av} - average linear density of threads, calculated as ***Equation 11*** [18]:

$$\varphi = \sqrt{\frac{12}{\pi}\frac{1}{P}\sqrt{\frac{T_{av}}{\rho}}\, S_2^{\frac{1}{1+2/3\sqrt{T_1/T_2}}}\, S_1^{\frac{2/3\sqrt{T_1/T_2}}{1+2/3\sqrt{T_1/T_2}}}} \tag{10}$$

Equation: 10.

$$T_{av} = \frac{T_1 \cdot S_1 + T_2 \cdot S_2}{S_1 + S_2} \qquad (11)$$

In order to assess the relationships between fabric structure and thermal insulation properties, the above-mentioned structural parameters were calculated on the basis of the results obtained by laboratory measurement. For the calculation, theoretical values of the yarn diameter were obtained according to Ashenhurst's equation [15, 16]:

$$d = \frac{c}{\sqrt{1000}} \cdot \sqrt{T} \qquad (12)$$

where:

d - yarn diameter in mm,

c - constant value for given yarn, for cotton yarn c = 1.25,

T - linear density of yarn in tex.

Values of the integrated fabric structure factor were calculated twice:

Table 9. Values of weave factors P and P'.

Weave	P	P'
Plain	1.000	1.000
twill 3/1 S	1.333	1.333
twill 2/2 S	1.265	1.265
rep 2/2 (2)	1.124	1.118
rep 1/1 (0,1,0)	1.124	1.249
hopsack 2/2 (0,2,0)	1.359	1.359

- on the basis of the first formula of weave factor P, proposed by Milašius in 2000 [17, 18] – φ,
- on the basis of the new formula of weave factor P', proposed by Milasius in 2008 [19] - φ_1.

Values of weave factors P and P' were calculated using software available on the web page of Kaunas University. The values of weave factors P and P' are given in ***Table 9***.

Table 10. *Calculated values of the cover factors of the fabrics investigated.*

No of variant	Z_{warp}	Z_{weft}	Z_{total}	E_{warp}	E_{weft}	$E_{average}$	φ	φ_1
1	87.21	45.46	93.02	210.54	77.60	121.91	62.68	62.68
2	88.32	35.82	92.51	185.08	68.53	121.51	61.46	61.46
3	87.77	37.16	92.31	211.89	63.43	112.92	53.92	53.92
4	87.77	28.86	91.30	211.89	49.26	103.47	44.63	44.63
5	88.05	29.25	91.54	150.30	39.59	76.50	33.85	33.85
6	88.88	37.16	93.01	151.73	50.29	84.11	40.58	40.58
7	88.60	45.85	93.83	151.26	62.06	91.80	47.51	47.51
8	88.60	35.82	92.69	137.13	52.18	90.79	46.16	46.16
9	88.60	32.42	92.30	132.91	48.63	90.77	45.71	45.71
10	89.44	29.50	92.56	129.44	45.99	92.35	46.32	46.32
11	88.88	25.55	91.72	123.31	42.04	92.83	46.46	46.46
12	89.16	45.85	94.13	152.21	62.06	92.11	50.14	50.14
13	89.16	36.13	93.08	138.00	52.62	91.43	49.02	49.02
14	86.93	45.46	92.87	148.39	77.60	101.20	55.72	56.02
15	88.60	36.13	92.72	137.13	69.11	100.03	55.05	55.34
16	88.60	47.04	93.96	213.91	63.67	113.75	57.45	51.70
17	89.44	36.13	93.26	187.42	52.62	113.89	55.23	49.70
18	88.32	46.25	93.72	150.78	62.60	91.99	46.87	46.87
19	88.32	35.82	92.51	136.70	52.18	90.60	45.23	45.23

Table 11. *Correlation coefficients between the values of the parameters characterising the fabric structure and thermal insulation parameters.*

	λ	b	R
Mass per square meter	***0.71***	***0.51***	0.10
Thickness	-0.08	***-0.46***	***0.89***
Warp density	-0,31	-0,18	-0,14
Weft density	0,10	0,23	-0,28
Z_{warp}	-0.31	-0.18	-0.14
Z_{weft}	***0.66***	***0.51***	0.05
Z_{total}	***0.49***	0.42	-0.03
E_{warp}	***0.72***	***0.78***	***-0.57***
E_{weft}	***0.67***	***0.55***	-0.15
$E_{average}$	***0.68***	***0.84***	***-0.79***
Φ	***0.65***	***0.75***	***-0.64***
φ_1	***0.63***	***0.64***	***-0.55***

Calculated values of the factors characterising the structure of the woven fabrics investigated are presented in ***Table 10***.

On the basis of the measurement results and calculated values of the structural parameters, a correlation analysis was carried out in order to assess the relationships between the parameters of the woven fabric structure and thermal insulation properties of the fabrics. Values of the correlation coefficients are presented in ***Table 11***. The correlations statistically significant at a probability level of 0.05 are emphasised in bold italics.

The strongest correlation was found between the thermal resistance of the fabrics and their thickness, which is according to expectation, because for fabrics made of the same raw material (fibres), the thermal resistance depends only on their thickness. The higher the fabric thickness, the higher the thermal resistance. The results obtained confirmed the relationship above.

The strong correlation between the mass per square meter and thermal conductivity results from the fact that in woven fabrics considered as a composition of fibres, in the air between them, and in the yarns, heat transfer takes place in the fibres. Air closed inside the fabric structure plays the role of thermal insulator. The higher the amount of fibres in a volume unit of the fabric, the higher the heat transfer by conductivity.

A strong and statistically significant correlation was also noted between the average percentage filling and thermal absorptivity, as well as between the average percentage filling and thermal resistance of fabrics. The higher the average percentage filling, the higher the thermal absorptivity and the lower the thermal resistance. There is also a strong and statistically significant correlation between the integrated structure factors and the thermal properties of the woven fabrics. The highest correlation was found between the integrated structure factor φ and thermal absorptivity, as well as between the integrated structure factor φ and thermal conductivity.

The correlation between the thermal insulation properties of fabrics and the cover factors is weaker than that between the thermal properties and structural factors, which take into account the fabric weave: the filling and integrated fabric structure factor. The results above confirm that the weave of woven fabrics is very important from the point of view of the thermal insulation properties of such fabrics.

The integrated fabric structure factor calculated on the basis of the first formula of weave factor P, proposed by Milašius in 2000 [17, 18], is better correlated with the thermal insulation properties of fabrics than the integrated structure factor calculated on the basis of the new formula of weave factor P', proposed by Milašius in 2008 [19].

Both structural factors: the average percentage filling and integrated fabric structure factor φ can be used for the prediction of the thermal insulation properties of woven fabrics. Nevertheless the assessment of the relationships between the structural factors of woven fabrics and thermal properties needs further investigation based on a larger number of measured samples.

Conclusions

On the basis of the investigation carried out, the following conclusions can be drawn:

- the weave of woven fabrics influences their thermal insulation properties; the influence of the weave on the thermal insulation properties of the fabrics was observed to be significant from both a practical and statistical point of view,
- plain fabrics have a higher thermal conductivity and thermal absorptivity than twill 3/1 S, twill 2/2S, rep 2/2 (2), rep 1/1 (0,1,0) and hopsack 2/2 (0,2,0) weave fabrics with identical linear densities of warp and weft yarns as well as identical warp and weft nominal densities,
- plain fabrics are characterised by a lower thermal resistance than twill 3/1 S, twill 2/2S, rep 2/2 (2), rep 1/1 (0,1,0) and hopsack 2/2 (0,2,0) weave fabrics with the same linear densities of warp and weft yarns as well as the same warp and weft nominal densities,
- the linear density of weft yarn influences the thermal insulation properties of woven fabrics; the influence of the linear density of weft yarn on the thermal conductivity, absorptivity and resistance is statistically significant at a probability level of 0.05,
- the influence of the weave on the thermal insulation properties of woven fabric is modified by the influence of the linear density of the weft yarn,
- a strong and statistically significant correlation exists between the thickness of fabrics and their thermal resistance, as well as between the mass per square meter of fabrics and their thermal conductivity,
- a strong and statistically significant correlation exists between the thermal insulation properties of woven fabrics and their structural parameters: the average percentage filling and integrated fabric structure factor φ, both taking into account the fabric weave,
- the correlation between the thermal insulation properties of fabrics and the cover factors is weaker than that between the thermal insulation properties and structural factors calculated on the basis of the formulas, taking into consideration the weave of the fabrics, i.e. the average percentage filling and integrated fabric structure factor φ,
- an assessment of the relationships between the structural factors of woven fabrics and thermal properties needs further investigation based on a larger number of measured samples.

Acknowledgment

- *The authors would like to thank Prof. V. Milašius for his help in understanding the P factor*
- *The investigations were carried out within the framework of project No N N507 280436, funded by the Polish Ministry of Science and Higher Education in the years 2009-2011.*

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Received 09.09.2010 Reviewed 09.12.2010