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Investigation of the Thermal Insulation Properties of Multilayer Textiles

Abstract
Assuring the thermal stability of the human body is one of the most important functions of the clothing. Clothing creates a barrier between the skin surface and surroundings. This barrier influences not only the heat exchange by convection and radiation, but also the heat exchange by the evaporation of excreted sweat. The influence of clothing on the heat exchange between the human being and their surroundings is very complex. It depends on many factors connected with the environment, i.e. air temperature, air movement and humidity. No less an important role is played by the raw material, as well as the micro- and macrostructure of clothing. The aim of this work is to investigate the thermal insulation properties of the single- and multilayer textile materials. The thermal properties were measured with an Alambeta device. We investigated the relationships between the thermal insulation properties of the set of materials and the parameters of the particular components of sets, as well as the configuration of layers.

Key words: *multilayer textiles, thermal conductivity, thermal absorption, thermal diffusion, thermal insulation properties.*

Introduction

Assuring the thermal stability of the human body is one of the most important functions of clothing. Its thermal insulation properties play a crucial role for a human's heat maintenance, being especially in winter conditions [1 - 4]. Clothing can also influence work in a warm environment, and also protect against the other environmental factors such as UV or IR radiation, chemicals, etc.

To keep warm in the worst winter conditions, the human body must first of all stay dry. To do this, the clothing must transport the body moisture away from the skin, keep dry and warm air close to the body, and keep out rain and snow. In order to ensure all of these functions simultaneously the clothing for outdoor use, especially in winter conditions, is designed as a multilayer structure.

In winter clothing, a very important role is played by the middle layer, the basic function of which is to protect the human body against chilling. Different kinds of textile materials are used as the middle thermal insulating layer of multilayer clothing, such as traditional weddings or nonwovens, highly advanced thermal insulating materials like Thermore® nonwovens, or membrane systems like GoreTex®, Windstoper®, Sympatex®, Porelle®, Permatex®, Osmosis® Dry Tex, etc. These are characterised by excellent thermal insulation features combined with very good physiological properties such as moisture management and breathability. Nevertheless, such advanced thermal insulating textile materials are very expensive. This is why they are used mostly for high-performance outerwear. In the trade we can still observe the use of the traditional lining combined with the outer fabric. The thermal characteristics of these standard thermal insulation materials are not commonly known.

Experimental

The presented investigation is a part of a broader research work concerning the thermo-physiological comfort of textiles. The aim of this work was to investigate the thermal insulation properties of single- and multilayer textile materials applied in winter outdoor wear, and to analyse what shapes the thermal insulation properties of multilayer textiles in dependence on the properties and the configuration of the particular components.

Different kinds of textiles for winter outdoor clothing were investigated:
- cotton woven fabrics,
- thermal insulation textile materials,
- sets of both: cotton fabrics and thermal insulation materials.

The textile thermal insulation materials when objects of experiments are not usually used separately. Most frequently, they form the inner layer of multilayer clothing, and are used together with the fabrics as an outer layer of clothing. In these experiments the cotton fabrics were used as the outer layer of the prepared sets of materials. The choice of cotton fabrics was motivated by the following reasons:
- cotton fabrics are easy to obtain;
- cotton fabrics are commonly applied as an outer layer of outdoor clothing;
- fabrics with similar characteristics were selected in order to eliminate the influence of the fabric structure on the thermal insulation properties of the sets of materials investigated. Due to the small number of the measured samples, I tried to reduce the number of the independent factors.

Three samples of cotton woven fabrics with the same structure were measured. These were twill 2/1 fabrics made of cotton OE yarns with a linear density of 40 tex. The nominal warp density of fabrics was 25/cm, whereas the nominal weft density was 15/cm. The samples originat-

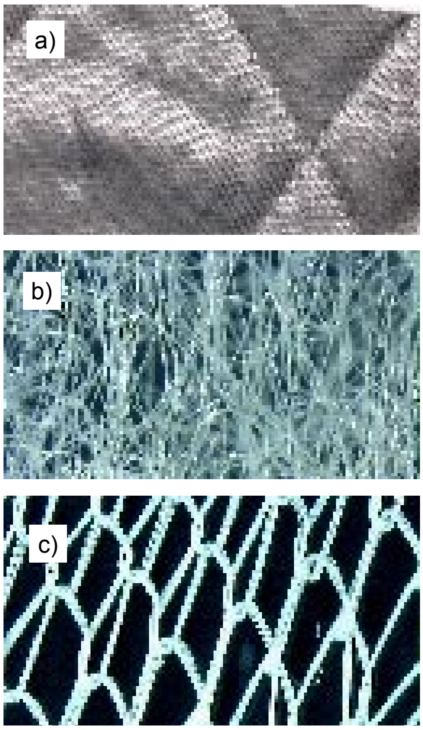

***Figure 1.** The pictures of the components of the thermal insulation material W 2; a) right side, b) middle layer, c) left side.*

ed from different finishing batches, dyed in three colours: yellow (sample A1), red (sample A2) and navy blue (sample A3). Due to the different finishings, the fabrics differed from each other in mass per square metre, as follows: sample A1 – 264.46 gm^{-2}, sample A2 – 287.41 gm^{-2} and sample A3 - 299.84 gm^{-2}.

From among the thermal insulation textiles, the following materials were selected for measurement:

- PES nonwoven fabric – sample W1,
- three-layer stitched material consisting of the viscose lining (Figure 1.a), PES nonwoven (Figure 1.b) and PES net – sample W2 (Figure 1.c).

Samples W1 and W2 are typical thermal insulation materials used as the middle layer of outdoor winter clothing. The samples were chosen from among a larger number of similar materials, both standard and advanced, domestic and imported, which were the subjects of wider investigations aimed at the creation of a database of the thermo-physiological properties of textile materials.

For the presented work, the samples were selected from among the standard thermal insulation materials originating from the Polish industry, representing 2 groups of textiles:

- synthetic nonwovens characterised by the homogenous symmetrical structure,
- multilayer thermal insulation textile materials characterised by the heterogeneous asymmetrical structure.

Next, the sets of woven fabrics and the thermal insulation materials were measured. The configuration of layers in the measured sets is given in Table 1.

The thermal properties were measured with the Alambeta device [5], which is a computer-controlled instrument for measuring the basic static and dynamic thermal characteristics of textiles [7]. This method belongs to the so-called ‘plate methods’, the acting principle of which relies on the convection of heat emitted by a hot upper plate in one direction through the sample being examined to the cold bottom plate adjoined to it.

By means of the Alambeta device, besides the classical stationary fabrics’ thermal properties such as thermal resistance r and thermal conductivity λ, we can also assess transient thermal characteristics such as thermal diffusion a and thermal absorption b [8]. It should be emphasised that 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’s thickness. This means that the device calculates the real thermal resistance (from the above-mentioned quantities) for all fabric configurations. In contrast, the other thermal parameters such as thermal conductivity, thermal absorption and the thermal diffusion are calculated on the basis of the properties measured using algorithms appropriate for unstratified (homogeneous) materials. Due to this fact, in multilayer textile structures we can consider the results calculated on the basis of the measured parameters as equivalent values, i.e. equivalent conductivity, absorption and diffusion, for comparisons valid only for similar measuring conditions and comparable layer configuration. In this context the values of λ, a, and b should be considered.

The measurements were made for the left side (the left side of the fabric sticks to the upper plate) and the right side (the right side of the fabric sticks to the upper plate) of each sample. For each side 20 measurements were made, and then the average values of the measured parameters were calculated. The following thermal parameters were assessed: thermal conductivity, thermal diffusion, thermal absorption, thermal resistance, stationary heat flow density, the ratio of the maximum and stationary heat flow density as well as the fabric thickness.

Results

The results obtained with the Alambeta device are presented in Tables 2 and 3 (see page 100). The values of the standard deviation of the results are given in brackets.

The significance of the differences between the results for the left and right sides of the measured samples was assessed using the t-Student’s test. The values of the variable t calculated on the basis of the measurement results are presented in Table 4 (see page 100). They were compared with the critical value of the variable t of the Student’s distribution at the probability level of 0.95 and the degree of freedom of 19 (t_α = 2.093). The figures in bold types indicate the statistically significant differences between the two mean values.

Thermal conductivity

Thermal conductivity is the quantity of heat transmitted through a unit thickness in a direction normal to a surface of unit area, due to a unit temperature gradient under steady state conditions, and when the heat transfer is dependent only on the temperature [6].

The thermal conductivity of homogenous materials is defined by the following formula [6, 9]:

$$\lambda = \frac{Q}{A \cdot \frac{\Delta t}{h}}, \text{ in W m}^{-1}\text{ K}^{-1} \qquad (1)$$

where:

λ – the thermal conductivity,
Q – the heat transmitted,
A – the area,
Δt – the temperature gradient,
h – the sample thickness.

The mean thermal conductivity of the woven fabrics A1, A2 and A3 is at a similar level (Figure 2).

The differences observed result from the differences of the fabric mass per square metre. The differences also occur between the right and left sides of the measured samples; it is difficult to explain them. For each side of the fabrics, the measurement was repeated 20 times for randomly chosen places of fabrics. The differences of the results for the left and right sides are probably caused by the irregularity of the fabric structure.

***Table 1.** Configuration of layers in sets of the textile materials.*

Symbol of sample	Configuration of layers
A1W1	woven fabric A 1 + PES nonwoven W 1
A2W1	woven fabric A 2 + PES nonwoven W 1
A3W1	woven fabric A 3 + PES nonwoven W 1
A1W2	woven fabric A 1 + multilayer material W 2
A2W2	woven fabric A 2 + multilayer material W 2
A3W2	woven fabric A 3 + multilayer material W 2

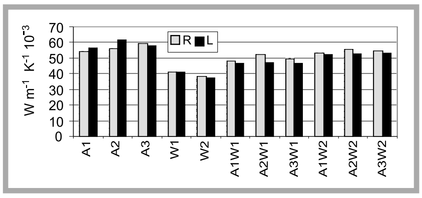

***Figure 2.** The thermal conductivity of the textile materials.*

Table 2. Results of the thermal insulation properties of woven fabrics and thermal insulation materials; the values of standard deviations are presented in brackets.

Parameter	W1		W2		A1		A2		A3	
	R	L	R	L	R	L	R	L	R	L
Thermal conductivity - λ, W m^{-1} K^{-1} x 10 $^{-3}$	41.2 (1.52)	41.1 (1.58)	38.3 (1.23)	37.2 (1.01)	54.1 (1.26)	56.5 (1.63)	55.9 (2.14)	61.4 (1.72)	59.1 (1.48)	57.7 (3.56)
Thermal diffusion - a, m^2 s^{-1} x 10^{-6}	-	-	0.278 (0.030)	0.582 (0.110)	0.099 (0.020)	0,120 (0.029)	0.085 (0.020)	0.103 (0.016)	0.072 (0.012)	0.080 (0.015)
Thermal absorption - b, W m^{-2} $s^{1/2}$ K^{-1}	25.5 (2.23)	26.7 (2.27)	72,8 (3.09)	49.3 (3.06)	175.3 (20.21)	166.9 (22.60)	194.7 (20.43)	193.0 (13.00)	221.55 (17.66)	206.2 (20.60)
Thermal resistance - R, K m^2 W^{-1} x 10^{-3}	92.00 (6.46)	90.90 (6.77)	52.10 (2.96)	55.40 (3.61)	12.68 (0.59)	12.89 (0.70)	13.14 (0.86)	13.28 (0.55)	12.34 (0.68)	13.33 (1.15)
Thickness - h, mm	3.80 -	3.74 (0.41)	2.00 (0.13)	2.06 (0.16)	0.68 (0.02)	0.73 (0.03)	0.73 (0.03)	0.82 (0.02)	0.73 (0.03)	0.77 (0.04)
Ratio of the max and stationary heat flow - p	2.23 (0.24)	2.36 (0.26)	5.70 (0.89)	3.00 (0.29)	1.35 (0.08)	1.35 (0.05)	1.50 (0.08)	1.52 (0.10)	1.59 (0.06)	1.54 (0.09)
Stationary heat flow density - q_s, K W m^2	0.166 (0.011)	0.178 (0.009)	0.832 (0.121)	0.407 (0.040)	0.773 (0.043)	0.744 (0.036)	0.847 (0.058)	0.848 (0.043)	0.939 (0.050)	0.852 (0.065)

Table 3. Results of the thermal insulation properties of the sets of materials; the values of standard deviations are presented in brackets.

Parameter	A1 W1		A2 W1		A3 W1		A1 W2		A2 W2		A3 W2	
	R	L	R	L	R	L	R	L	R	L	R	L
Thermal conductivity - λ, W m^{-1} K^{-1} x 10 $^{-3}$	48.2 (1.27)	46.6 (0.97)	52.3 (3.15)	47.2 (1.22)	49.3 (2.04)	46.5 (1.09)	53.0 (2.60)	52.4 (3.10)	55.4 (3.09)	52.6 (2.99)	54.6 (3.88)	53.3 (2.52)
Thermal diffusion - a, m^2 s^{-1} x 10^{-6}	0.205 (0.027)	0.738 (0.120)	0.206 (0.020)	-	0.200 (0.020)	0.910 0.030)	0.158 (0.020)	0.294 (0.062)	0.159 (0.030)	0.288 (0.051)	0.154 (0.023)	0.286 (0.041)
Thermal absorption - b, W m^{-2} $s^{1/2}$ K^{-1}	107.1 (6.34)	42.1 (6.56)	115.6 (4.90)	26.8 (8.59)	110.5 (4.98)	42.7 (4.83)	134.2 (6.72)	97.6 (6.59)	140.4 (8.78)	98.6 (5.54)	139.8 (7.52)	99.9 (4.47)
Thermal resistance - R, K m^2 W^{-1} x 10^{-3}	82.88 (3.78)	93.90 (6.33)	81.47 (4.17)	94.71 (3.56)	81.72 (4.10)	93.00 (5.73)	52.56 (2.58)	53,86 (2.99)	51.76 (3.09)	56.50 (3.21)	52.38 (3.65)	54.95 (3.56)
Thickness - h, mm	3.99 (0.21)	4.38 (0.33)	4.26 (0.31)	4.48 (0.25)	4,03 (0.28)	4.33 (0.34)	2.78 (0.16)	2,81 (0.15)	2.86 (0.15)	2.97 (0.17)	2.85 (0.20)	2.92 (0.15)
Ratio of the max and stationary heat flow - p	8.42 0.73)	2.41 (0.78)	8.63 (0.92)	1.98 (0.25)	8.15 (0.85)	2.41 (0.20)	5.41 (0.52)	5.71 (0.74)	5.10 (0.67)	6.19 (0.79)	5.23 (0.45)	6.14 (1.16)
Stationary heat flow density - q_s, K W m^2	0.729 (0.069)	0.178 (0.013)	0.762 (0.067)	0.144 (0.011)	0.722 (0.063)	0,178 (0.012)	0.785 (0.060)	0.796 (0.012)	0.756 (0.077)	0.813 (0.117)	0.764 (0.071)	0.320 (0.154)

This is confirmed by the results of the fabric thickness measured at both sides of the fabrics (Figure 3).

According to expectations, the thermal insulating materials W1 and W2 are characterised by lower values of the thermal conductivity than the woven fabrics. Moreover, the thermal conductivity of the PES nonwoven W1 is higher than that of W2. The thermal conductivity of the sets of fabrics is at a similar level to the arithmetical mean values from those of the thermal conductivity of the particular fabrics creating the measured set of materials.

Thermal diffusion

Thermal diffusion is an ability related to the heat flow through the air in the fabric structure. The thermal diffusion of the textile materials is the transient thermal characteristic of textiles. It is defined by the equation (for homogenous materials):

$$a = \frac{\lambda}{\rho \cdot c}, \text{ in } m^2 s^{-1} \qquad (2)$$

where:
a – the thermal diffusion,
λ – the thermal conductivity,
ρ – the material density,
c – the specific heat capacity.

The results obtained are presented in Figure 4.

The highest value of the thermal diffusion was observed for the PES nonwoven W1. Unfortunately, the thermal diffusion for sample W 1 was higher than the scale range of the Alambeta device. Sample W1 is a nonwoven structure of high porosity, and in the same way a large amount of air in the structure. This facilitates the thermal diffusion, which, as was mentioned earlier, occurs in gases, and justifies the very high thermal diffusion of the material W1.

The high value of thermal diffusion was also noted for the sample of multilayer material W2. Moreover, in the case of sample W2 we can observe a significant difference between the right and left sides of the material. The lining fabric on the side of the warm plate of the Alambeta device (measurement on the right side of the material) impedes the air movement, and in the same way limits the thermal diffusion.

The values of the thermal diffusion of the material sets A1 W1, A2 W1 and A3 W1 are high, due to the very high diffusion from the nonwoven component W1. A significant difference is also observed be-

Table 4. The calculated values of the t variable.

Specimen	t - Student variable values						
	λ	a	b	r	h	p	Q_s
A1	**5.336**	**2.471**	1.233	1.027	**5.257**	1.936	**2.330**
A2	**8.961**	**3.519**	0.314	0.639	**11.566**	0.779	0.059
A3	1.644	1.938	**2.530**	**3.317**	**3.325**	**2.165**	**4.776**
W1	0.174	-	1.631	0.542	0.431	1.637	**3.902**
W2	**2.949**	**12.137**	**22.064**	**3.106**	1.446	**12.904**	**14.940**
A1 W1	**4.435**	**18.69**	**31.848**	**6.688**	**4.445**	**35.656**	**34.997**
A2 W1	**6.676**	-	**40.150**	**10.803**	**2.472**	**31.636**	**40.834**
A3 W1	**5.498**	**87.38**	**43.743**	**7.154**	**2.996**	**29.351**	**38.022**
A1 W2	0.703	**9.489**	**17.414**	1.473	0.656	1.462	0.377
A2 W2	**2.904**	**10.447**	**18.014**	**4.776**	2.041	**4.703**	1.824
A3 W2	1.211	**13.707**	**20.379**	**2.249**	1.337	**3.298**	1.793

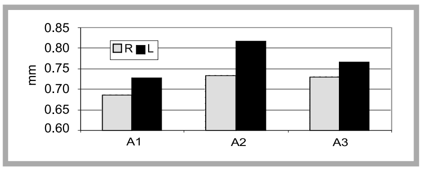

Figure 3. *The thickness of the cotton woven fabrics.*

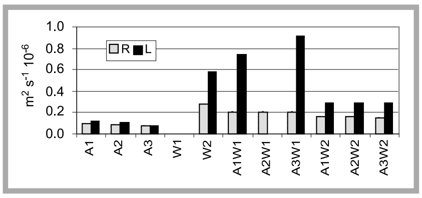

Figure 4. *The thermal diffusion of the textile materials.*

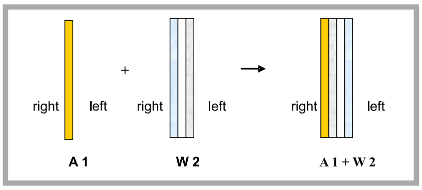

Figure 5. *Configuration of particular layers in the multilayer material.*

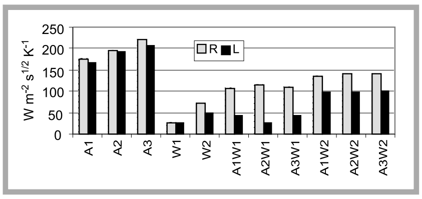

Figure 6. *The thermal absorption of the textile materials.*

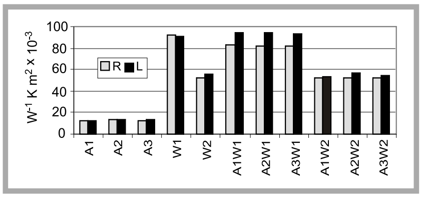

Figure 7. *The thermal resistance of the textile materials.*

tween the left and right sides of the material sets. The higher thermal diffusion is observed on the left side, where the PES nonwoven W1 is situated.

In the case of the sets A1 W2, A2 W2 and A3 W2, the thermal diffusion of the left side is not as high than for the material W2. This is because in the investigated sets of materials, the thermal insulation material W2 is situated in such a way that the lining is on the left side of the sets. In the same way, the right side of W2 creates the left side of the measured set (Figure 5). The structure of the material sets is closed on both sides, and this limits the thermal diffusion.

Thermal absorption

Thermal absorption for homogenous materials can be expressed by the following equation:

$$b = \sqrt{\lambda \cdot \rho \cdot c}\text{, in W m}^{-2}\text{ s}^{1/2}\text{ K}^{-1} \qquad (3)$$

where:
λ – the thermal conductivity,
ρ – the fabric density,
c – the the specific heat of the fabric.

Thermal absorption is a surface property which allows the fabric's character to be assessed with regard to its 'cool/warm' feeling, i.e. the feeling obtained when the human skin briefly touches any object, such as the textile material [8]. Fabrics with a low value of thermal absorption give a 'warm' feeling, whereas those with a high value of the thermal absorption give a 'cool' feeling. Thermal absorption is a transient parameter which depends neither on the temperature gradient between the fabric and skin, nor on the measurement time. It is not an instrument parameter, but a real textile characteristic. The validity of thermal absorption was confirmed by several tests, where the results of subjective feeling of nearly 100 persons were compared with the objective values measured by the Alambeta device [8].

The results of the thermal absorption measurement are presented in Figure 6.

The cotton fabrics are characterised by much higher values of the thermal absorption than the thermal insulation materials W1 and W2. In the frame of the cotton woven fabrics, the influence of the colour on the value of the thermal absorption was noted. The lowest value of the thermal absorption is for the yellow fabric, whereas the highest was for the blue one. For the woven fabrics, the thermal absorption of the right side is higher in all cases than the thermal absorption of the left side. This can be explained by the greater smoothness of the right side in comparison to the left side of the material.

The thermal absorption of the multilayer material W2 is significantly higher than that of the nonwoven W1. Moreover, there is the difference between the value of the thermal absorption of the right and left sides of the sample W2. The right side of the material W2 is created by the lining fabric of the very smooth surface. It is characterised by a cool feeling, due to the high value of its thermal absorption.

The woven fabrics A1, A2 and A3 are characterised by a cooler feeling than the thermal insulation materials W1 and W2. This is also confirmed by the results for the set of the materials. In all cases, the right side of the set of materials created by the woven fabric has a higher value of the thermal absorption, and at the same time a cooler feeling than the left side created by the thermal insulation material W1 or W2.

Thermal resistance

The thermal resistance expresses the difference of the temperature across a unit area of the material of unit thickness when a unit of heat energy flows through it in a unit of time. It can be defined by the following formula [6]:

$$r = \frac{h}{\lambda}\text{, in K m}^{2}\text{ W}^{-1} \qquad (4)$$

where:
r – the thermal resistance,
h – the sample thickness,
λ – the thermal conductivity.

The results of the thermal resistance are presented in Figure 7.

The thermal resistance of all woven fabrics is at the same level for each sample, A1, A2 and A3. Moreover, it is much lower than that of the thermal insulation materials W1 and W2.

The thermal resistance of the right side of the sets of woven fabrics with nonwoven W1 is lower than that of the left side. This may be because the PES nonwoven W1 in this case adjoins the heating plate of the Alambeta device. Nonwoven W1 has the highest thermal resistance, which limits the quantity of heat transmitted through the measured sample.

A strong correlation relationship is observed between the value of the thermal resistance of materials and their thickness (Figure 8).

The ratio of the maximum and stationary heat flow density

The maximum heat flow density q_{max} appears at the moment that the cold fabric contacts the hot plate of the Alambeta de-

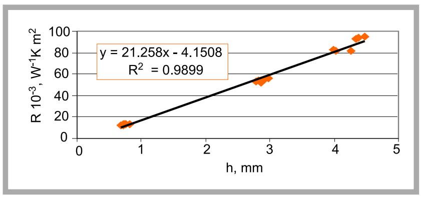

Figure 8. *Relationship between the thickness of the textile materials and their thermal resistance.*

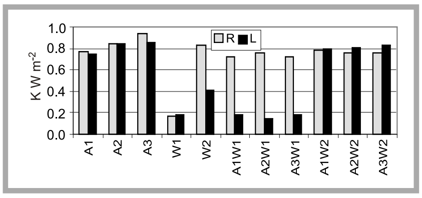

Figure 9. *The stationary heat flow density.*

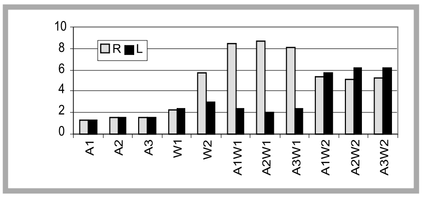

Figure 10. *The ratio of the maximum and stationary heat flow density.*

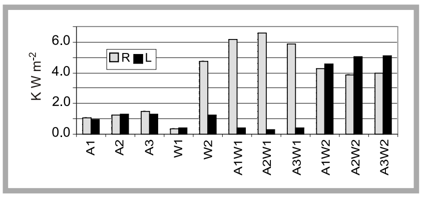

Figure 11. *The maximum heat flow density.*

vice. Over time, the heat flow stabilises itself at a specific level q_s, which is called the stationary heat flow density. The ratio of the maximum and stationary heat flow density p is one of the parameters which characterises the thermal insulation of fabric, and similarly to thermal absorption, it is a surface property.

The results of measurement of the stationary heat flow density are presented in Figure 9.

The stationary heat flow density of the cotton woven fabrics is higher than the stationary heat flow density of the thermal insulation nonwovens W1. In the case of the materials A1, A2, A3 and W1, the stationary heat flow density is on a similar level for both sides of the sample, due to their homogeneous structure. For the multilayer material W2 a significant difference is observed between the right and left sides of the material. Differences between the left and the right sides were also noted for the sets of woven fabrics with the PES nonwoven W1. The higher value of the stationary heat flow density occurs on the right side of the sets where the cotton woven fabric is placed.

The values of the ratio of the maximum and stationary heat flow density for measured materials are presented in Figure 10.

On the basis of the presented results, very high values of the ratio of the maximum and stationary heat flow density were noted for the right side of the sets of woven fabrics with the PES nonwoven W1. Taking into consideration the high values of the stationary heat flow density (Figure 9), which is in the denominator of the formula expressing the ratio of the maximum and stationary heat flow density:

$$p = \frac{q_{max}}{q_s} \qquad (5)$$

we can conclude that the maximum heat flow density q_{max} for these cases is also high (Figure 11).

Moreover, it was noted that for the heterogeneous materials, a higher ratio of the maximum and stationary heat flow density occurs on the cooler side of the material.

Conclusions

Due to the small number of samples measured, it is difficult unambiguously to assess the relationships between the values of the thermal parameters of particular fabrics and the final values of these parameters for the multilayer material consisting of these fabrics. It stands to reason that our measurements confirmed that the thermal insulation properties of a set of textile materials depending on the properties and on the configuration of the components. Nevertheless, on the basis of the investigation carried out, the following conclusions can be drawn:

- the equivalent thermal conductivity of a set of fabrics is at the similar level to the arithmetical mean values from the thermal conductivity of the components;
- the porous nonwoven structures are characterised by extremely high thermal diffusion;
- the fabric of the highest tightness, placed at the side of the higher temperature, limits the equivalent thermal diffusivity of the multilayer textile structure;
- higher thermal absorption occurs on this side of the fabric, which is characterised by greater smoothness;
- the equivalent thermal diffusion, the stationary heat flow density and the maximum heat flow density of the multilayer materials consisted of components characterised by different thermal characteristics depend on the configuration of layers;
- the stationary heat flow density for woven fabrics of a tight structure is much higher than the stationary heat flow density of the porous nonwovens;
- great significant differences occur between the values of stationary and maximum heat flow density for both sides of the heterogeneous material sets.

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