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Analysis of Thermal-Insulating Parameters in Two- and Three-Layer Textiles with Semi-Permeable Membranes

DOI: 10.5604/12303666.1215532

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Abstract
The main goal of paper presented was to evaluate clothing products (including products coated by semi-permeable membranes) in respect of thermal comfort. To achieve this, the thermal-insulating parameters were measured using an Alambeta measuring instrument. The research program introduced a set of diversified materials of different raw material composition, membranes applied, weave, density etc. The test results were analysed in respect of the thermal-insulating parameters of multilayer products, particularly the membrane effect as a separating and protective layer.

Key words: *membrane products, thermal-insulating parameters.*

Nomenclature

- a_b thermal absorption, $(Ws^{1/2})/(m^2K)$,
- a_d thermal diffusion, m^2/s,
- c_p specific heat of material tested, $J/(kg \cdot K)$,
- h sample thickness, m,
- k empirical coefficient correcting the transient heat transfer during measurement, -,
- q heat flux density for isotropic material, W/m^2,
- R_{ct} thermal resistance, $(m^2K)/W$,
- T temperature, K,
- T_u temperature of upper plate, K,
- T_l temperature of lower plate, K,
- ΔT temperature difference, K,
- t time, s,
- λ_m mean value of thermal conductivity coefficient, $W/(m \cdot K)$,
- ρ density of textile product, kg/m^3.

Introduction

Extended protection of the human organism against heat loss in specified climatic conditions is mainly determined by clothing created from a set of textile products. The basic parameters that determine the complete thermal insulation are the thermal insulation of each layer and the complete product, the temperature, flux velocity as well as the air humidity. The thermal insulation of the textile product is determined by its porosity, volumetric mass, thickness, thermal conductivity of fibres etc.

Some parameters of thermal insulation are of particular importance, cf. thermal absorption [1, 2]. This is a feature that allows to assess a material on the basis of feeling when touched: warm – cold, particularly when in contact with the skin.

The authors in [3] describe an investigation into protective clothing for firefighters based on the demand for radiant protective performance and heat-moisture transfer properties, which are closely associated with comfort performance. The outer shell and thermal barrier were changed to measure their effects on radiant protection and comfort performance.

The effects of textile properties on the microclimate inside caps and subjective wearing sensations were investigated in [4]. The temperature and humidity inside were influenced by the thickness, moisture retention, water absorption properties, and thermal conductivity of cap fabrics.

Sumin et. al. [5] measured the functional properties of a mass-produced nanofibre web and investigated changes in functional properties that may occur as a result of laundering. The properties include the water transfer properties of waterproofness and vapour permeability as well as the thermal transfer properties of warm/cool feeling and thermal conductivity.

The most important features of outerwear protection against precipitation are impermeability to water and vapour permeability. Impermeability to water can be defined as the resistance of water penetration through the fabric and seams, measured by the hydrostatic pressure acting on the material until droplets appear on the material surface.

Multilayer materials with membranes are designed for sportswear, tourism and protective clothing. Various possibilities of combining membranes allow a free choice of outer material, carrier material and lining according to the criterion of fashion. Two-layer laminates, where the membrane is permanently connected to the outer fabric, require an additional layer in the form of a lining. The application of an additional layer (i.e. polar) in laminates increases the heat insulation of clothing.

The thermal insulation properties of single- and multilayer textile materials were measured by Matusiak using an Alambeta device [6]. The thermal insulation properties of materials, the parameters of particular components of the sets, and the configuration of layers were investigated.

The thermal properties of different cotton and angora rabbit fibre blended fabrics are investigated in [7] to combine the excellent characteristics of these fibres and produce knitted fabrics with better comfort properties. According to the end use, the optimum ratios were analysed.

Pamuk, Öndoğan & Abreu [8] evaluate the thermal comfort properties of different fabrics that are used in the manufacture of surgical gowns. The thermal conductivity, thermal absorption and thermal resistance were measured by means of an Alambeta measuring instrument.

In study [9], the natural and forced convective heat transfer characteristics of rib knit fabric were analysed. The effect of the rib design and other fabric properties such as fabric density and air permeability on the thermal behavior were considered.

To obtain the optimal textile structure in respect of thermal comfort, some unconventional methods can also be applied, cf. for example [10, 11].

The paper presented is a continuation of previous works concerning heat flux [12 - 16]. Some theoretical aspects relating to heat transport and various forms of heat exchange as well as coupled heat and mass transport to the surroundings are discussed in [12, 13]. Heat transfer and exchange processes can be analysed and discussed within selected textile structures [14] or the particular parts of clothing [15].

Textile products are porous materials of complex porosity. "External" porosity is caused by the void spaces in-between a basic textile structure made of woven fabric, knitted fabric or non-wovens. These spaces are filled by fluid i.e. gas (for example air) or liquid (for example, rain water or sweat). The "internal" porosity is a consequence of the void's irregular spaces within the filaments, creating fibres which are also filled by fluid [16].

The thermal conductivity of textiles is strongly determined by the air content within the products in a dry state. The greater the porosity (i.e. the greater the air fraction within the textile structure), the smaller the volumetric mass. Thermal insulation grows as a directly proportional function of the air fraction. On the other hand, the greater the volumetric porosity, the smaller the thermal conductivity [17]. The additional problem is the impact of form durability on the behaviour during heat and mass transport. Some interesting problems are discussed in [18].

Textile products with semi-permeable membranes enable to create functional clothing which protects against wind and rain, and ensure the the transport of water vapour (sweat) form the skin to the surroundings. Depending on the destination of clothing, products with semi-permeable membranes are diversified in respect of the structure; two- and three-layer structures are usually applied. The external layer is typically made of woven fabric, knitted fabric and non-wovens, with the intermediate layer being a semi-permeable foil (i.e. membrane), whereas the internal layer is made of woven (i.e. lining) or knitted fabric.

Depending on the final destination, different two- and three-layer laminates are applied. Two-layer laminates can be characterised by (i) the membrane connected directly to the outer material and lining arranged separately and (ii) the membrane connected to the lining, whereas the outer material is separate. Three-layer laminates are a combination of covering material as the outer layer, membrane and lining or polar knitted fabric as the inner layer. The polar knitted fabric applied as an insulating layer leads to the improved thermal insulation of complex clothing.

The main goal of the paper was to determine the basic thermal-insulating parameters of multilayer textiles with semi-permeable membranes. These parameters can be used to assess the textile product comprehensively.

The novelty elements are the following: (i) Heat transport through the multilayer structures was analysed with simplifications introduced that are typical for the equipment used during the tests. (ii) A wide selection of two- and three-layer laminates with different material characteristics and diverse structures was investigated. (iii) The results are estimated in respect of the suitability to start work on an assessment system for textile materials due to their complex optimisation of thermal protection.

Materials tested

During the tests, the materials of the company Optex were used. The test program was planned in such a way that the materials were diversified in respect of the raw material composition, the membrane used and the weave.

The textiles tested are waterproof, semi-permeable clothing materials with membranes. Tests were conducted on specimens of new material, whose impermeability to water is at a level from 8 to 10 m of water.

Code symbols and material characteristics are given in ***Tables 1, 2*** & ***3*** (see page 82).

Test methodology

Determination of thermal-insulating parameters

Thermal-insulating parameters are determined by means of an Alambeta measuring instrument of the Sensora company [20]. The following parameters were selected to measure: the thermal conductivity coefficient, thermal diffusion, thermal absorption, thermal resistance, ratio of maximal and stationary heat flux densities, and the maximal heat flux density. Each clothing material was tested 20 times on both the outer as well as inner sides.

Membrane laminates are tested according to the following principles [21].

- Outer side. The outer woven fabric is located next to the upper heater.
- Inner side. The woven fabric is located on the lower head of the measuring instrument.

The samples were tested in a normal climate i.e. air temperature 293 K and relative humidity of air 65%.

Determination of thickness

Thickness can be determined according to Standard PN-EN ISO 5084:1999, Textiles. Determination of thickness of textiles and textile products. The measurement area of the pressure foot is $20 \cdot 10^{-4}$ m^2, the applied pressure: 1000 Pa for the flat products, and 100 Pa for the convex products [19].

Principle of operation of Alambeta measuring device

The principle of operation of the Alambeta measuring device is based on mathematical analysis of the heat flux density transported through the material tested,which is the result of the tempera-

Table 1. Characteristics of clothing materials.

Code	Characteristics	Surface mass, g/m²	Thick-ness, ·10⁻³ m	Number of threads per decimeter (woven fabrics)		Weave (outer woven fabric)
				warp	weft	
2L1	Two-layer laminate: PES woven fabric 100% membrane PES100%	145 ± 6	0.29 ± 0,02	503 ± 10	494 ± 15	
2L2	Two-layer laminate: PES woven fabric 30% + CO 70% membrane PU 100%	220 ± 9	0.54 ± 0,02	276 ± 6	250 ± 8	
2L3	Two-layer laminate: PES woven fabric 100% membrane PU 100%	160 ± 6	0.47 ± 0,02	323 ± 6	260 ± 8	twill
2L4	Two-layer laminate: PES woven fabric 100% membrane PES 100%	165 ± 7	0.40 ± 0,02	386 ± 8	283 ± 6	
2L5	Two-layer laminate: PES woven fabric 100% membrane PU 100%	180 ± 7	0.40 ± 0,02	418 ± 17	365 ± 22	
2L6	Two-layer laminate: PES woven fabric 100% membrane PU 100%	140 ± 6	0.28 ± 0,02	571 ± 23	565 ± 34	plain
2L7	Two-layer laminate: PES woven fabric 100% membrane PES 100%	290 ± 12	0.73 ± 0,02	470 ± 19	312 ± 19	twill
3L1	Three-layer laminate: PES woven fabric 100% membrane PU 100% polar knitted fabric (K1): PES 100%	370 ± 15	2.43 ± 0,02	618 ± 25	460 ± 28	
3L2	Three-layer laminate: PES woven fabric 70%,CV 30% membrane PU 100% polar knitted fabric (K2): PES 100%	394 ± 16	2.21 ± 0,02	214 ± 9	192 ± 12	plain
3L3	Three-layer laminate: PES woven fabric 100% membrane PTFE 100% polar knitted fabric (K2): PES 100%	330 ± 13	2.04 ± 0,02	271 ± 5	260 ± 8	
3L4	Three-layer laminate: PES woven fabric 100% membrane PU 100% polar knitted fabric (K2): PES 100%	330 ± 14	2.17 ± 0,04	271 ± 5	260 ± 8	
3L5	Three-layer laminate: PES woven fabric 100% membrane PES 100% polar knitted fabric (K2): PES 100%	285 ± 12	2,20 ± 0,03	503 ± 10	494 ± 15	twill
3L6	Three-layer laminate: PES woven fabric 100% membrane PTFE 100% polar knitted fabric (K2): PES 100%	310 ± 12	2.09 ± 0,05	271 ± 5	260 ± 8	plain
3L7	Three-layer laminate: PES woven fabric 100% membrane PES 100% PES knitted fabric 100%	193 ± 8	0.53 ± 0,02	503 ± 10	494 ± 15	twill

Table 2. Characteristics of the tested knitted fabrics.

Code	Characteristics	Surface mass, g/m²	Thickness, ·10⁻³ m
K1	Polar knitted fabric: PES – 100%	180 ± 9	2.19 ± 0.03
K2		120 ± 6	1.95 ± 0.03

Table 3. Characteristics of membranes.

Code	Characteristics	Thickness, ·10⁻³ m
M1	Membrane: PU – 100%	0.02
M2	Membrane: PES – 100%	0.02
M3	Membrane: PTFE – 100%	0.02

ture difference between the heater (i.e. the upper head) and lower plate. Thus semi-empirical equations should be determined in order to correctly describe the heat transfer phenomena.

The measurement starts when the heating device (i.e. the heating head) comes into contact with the sample tested. Thus the heat is transported through both surfaces of the sample and the values of heat flux density are equal to $q_1(t)$, $q_2(t)$, Respectively. When the heat fluxs are established, the thickness of sample h is measured as the distance between two contact surfaces. The heating head is then raised automatically, which means that the flux densities $q_1(t)$, $q_2(t)$ are equalised, and the measurement has been completed.

The maximal heat flux density at the contact surface $q_{\max}$ [20, 21] is described as follows:

$$q_{\max} = \frac{a_b \, \Delta T}{\sqrt{\pi \, t}} \tag{1}$$

The components are the thermal absorption a_b, gain in temperature ΔT and time t.

Some thermal parameters such as thermal conductivity, thermal absorption and thermal diffusion can be calculated on the basis of the properties measured directly for homogeneous materials using an Alambeta instrument [6]. The other parameters, are the heat flux density, temperatures of both the upper and lower surfaces as well as the thickness of the material tested. The results obtained allow to determine the thermal resistance of t textiles for their different configurations. The two- and three-layer structures are consistently characterised by means of the so-called equivalent values, i.e. equivalent conductivity, absorption and diffusion [6]. These measurements are comparable on condition that the measuring conditions are repeatable and the layer configuration is similar.

The thermal conductivity coefficient can be determined by means of heat flux density in the surrounding q_∞. The equation below gives the mean value of measurements within two different locations in the surrounding $q_{1\infty}$ and $q_{2\infty}$.

$$\lambda_m = \frac{q_\infty h}{(T_u - T_l) + k q_\infty} \tag{2}$$

The additional parameters are the thickness h, empirical coefficient of heat transfer correction k and temperatures of upper T_u and lower sides T_l.

Thermal resistance is determined using the ***Equation 3*** in the reverse form.

$$R_{ct} = \frac{(T_u - T_l) + kq_\infty}{q_\infty h} \quad (3)$$

Thermal diffusion is a special parameter that describes the thermal insulation of clothing. Now the heat does not diffuse from the solid surface but from the surfaces of particular fibres, which defines the diffusion as a volume phenomenon. Therefore measurements of this parameter are quite difficult. However, we can determine the equation:

$$a_d = \frac{\lambda_m}{\rho\, c_p} \quad (4)$$

The left-hand side is a function of the mean thermal conduction coefficient λ_m, density ρ and specific heat of the textile material c_p.

Finally the thermal absorption is described mathematically as follows.

$$a_d = \sqrt{\lambda_m\, \rho\, c_p} \quad (5)$$

Test results and statistical analysis

The significance of differences between the arithmetic mean values was estimated using variance analysis. Statistical analysis was determined by means of Statistica software [22].

The following definitions are introduced in order to analyse the results obtained.

- Independent factor: type of laminate.
- Dependent factors: parameters determined by the means of the Alembeta measuring instrument i.e. thermal conductivity coefficient, thermal diffusion, thermal absorption, thermal resistance, ratio of maximal and stationary heat flux densities, and maximal heat flux density.
- Assessment of the significance of the impact factor: the factor influences the parameter of thermal insulation prescribed for the statistical significance $p < 0.05$, but it does not influence the parameter for $p > 0.05$.

Analysis of test results of thermal conductivity

Mean values of the thermal conductivity coefficient determined for both material sides are shown in ***Figure 1***. The analysis of variance shows that the type of laminate considerably influences the values of the thermal conductivity coefficient ($F = 696.5$; $p < 0.05$) because the thicknesses and structure are now different. Furthermore the values of the thermal conductivity coefficient are close irrespective of the laminate side, which can be the consequence of heat flux transfer through all material layers. A membrane can be incorporated into the external layer and the thermal conductivity is determined using the arithmetic average of the following coefficients: (i) combination of the fabric and membrane as outer layer, (ii) knitted fabric as the inner layer. In the case of a separate membrane, we calculate the mean value of the coefficients for (i) the fabric as the outer layer, (ii) the membrane, (iii) the knitted fabric as the inner layer. Thus the choice of the laminate side is insignificant for the value of the ther-

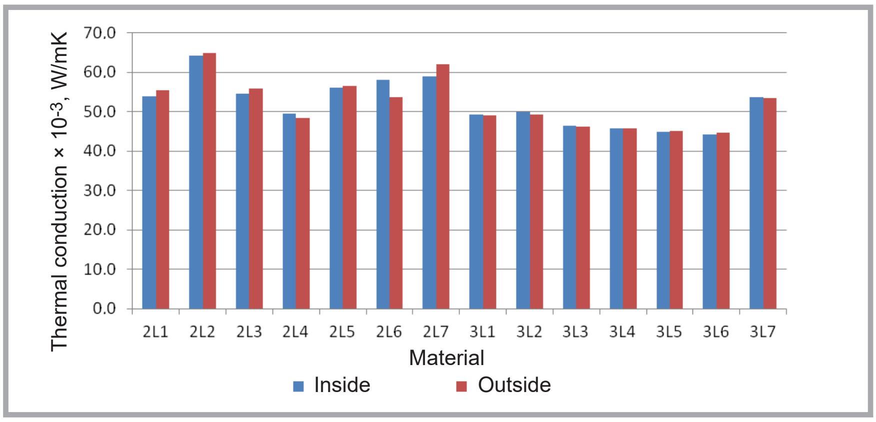

Figure 1. *Mean values of thermal conductivity coefficient for both material sides.*

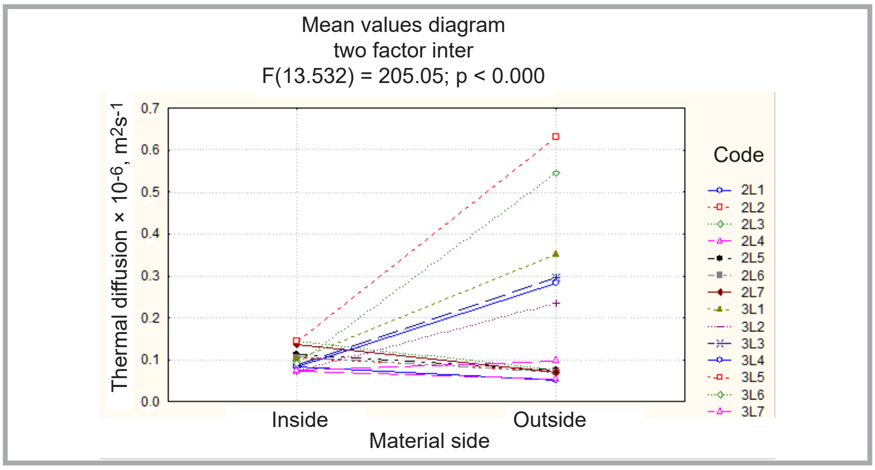

Figure 2. *Mean values of two factor analysis of variance for thermal diffusion.*

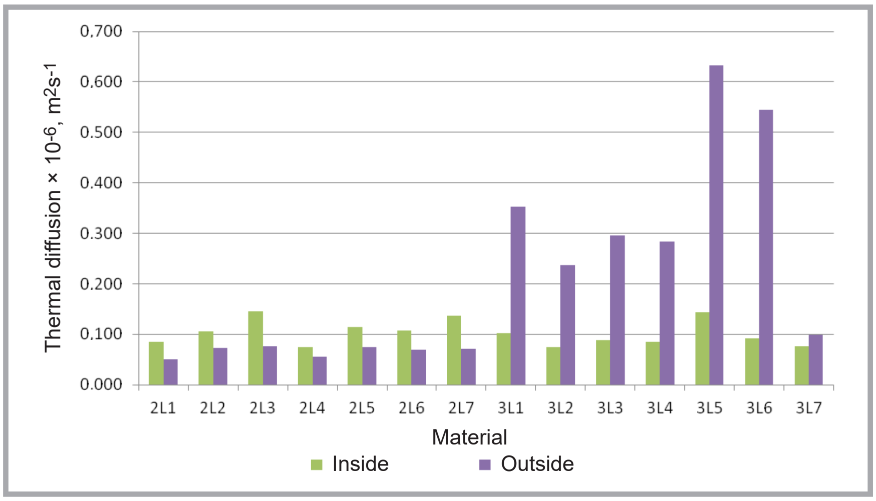

Figure 3. *Mean values of thermal diffusion for both material sides.*

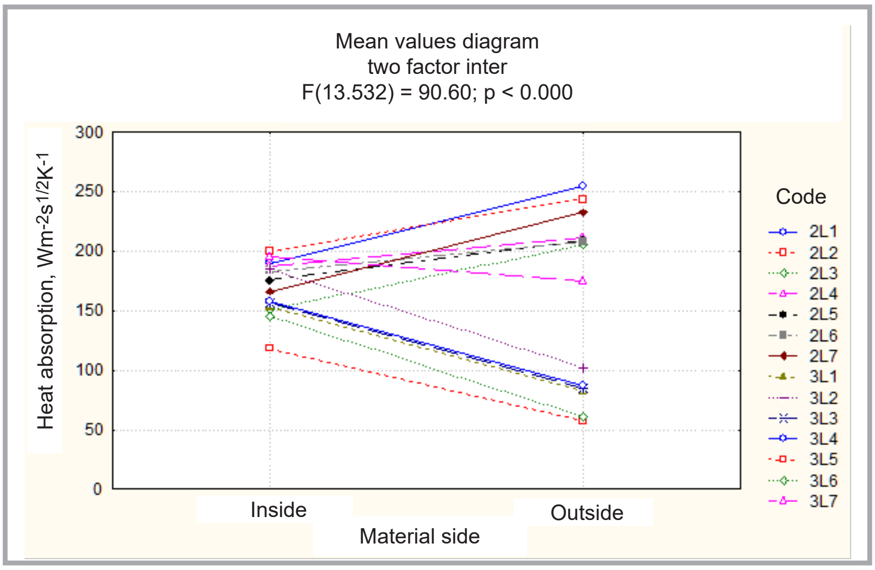

***Figure 4.** Mean values of two factor analysis of variance for thermal absorption.*

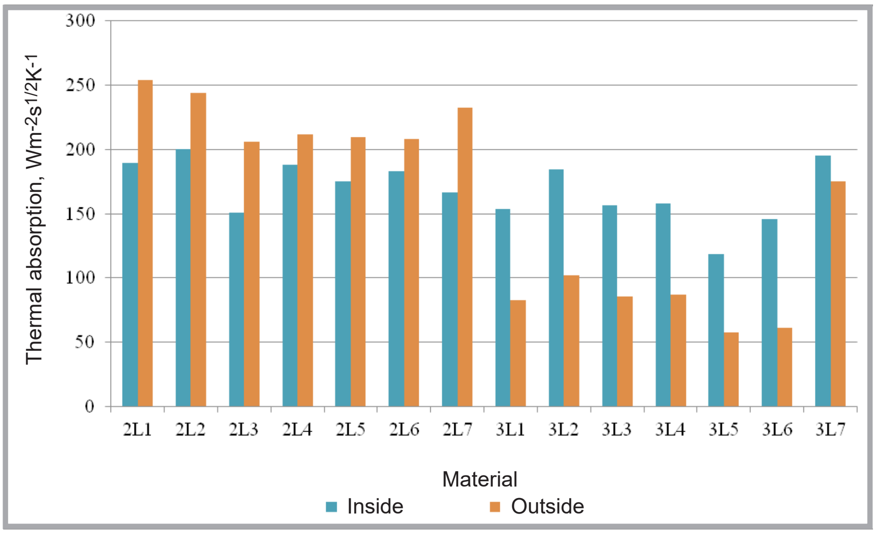

***Figure 5.** Mean values of thermal absorption for both material sides.*

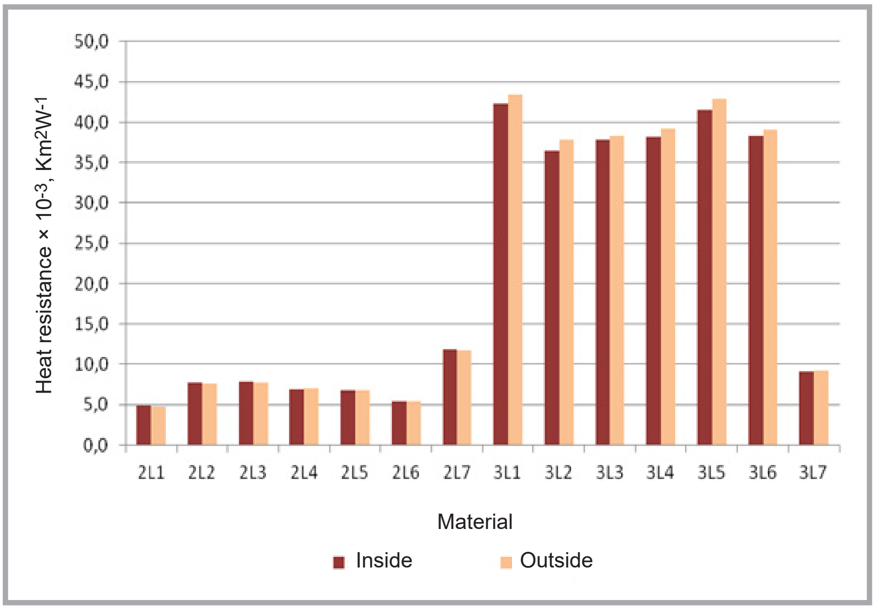

***Figure 6.** Mean values of thermal resistance for both material sides.*

mal conductivity coefficient, although the structure and raw material composition are different for both the outer and inner sides.

Analysis of test results of thermal diffusion

From ***Figure 2*** it follows that the type and side of laminate considerably influence the values of thermal diffusion ($p < 0.05$). Thus the diffusion strongly depends on the structure of the product and the different size of micropores within laminates. The smaller the pore dimensions, the lower the thermal diffusion.

It should be emphasised that all the graphs presented in ***Figures 2, 4*** and ***9*** are ot functions and show only the trends of changing values between both sides of the fabric.

Differences in thermal diffusion for two-layer laminates (***Figure 3***) follow from the diversified structure and surface of each layer (the outer side is the external woven fabric i.e. textile material of discrete structure, and the inner side is the membrane i.e. material of continuous structure). It is evident that the heat transport is different in both cases because the diffusion depends on the density as well as specific heat of the material. The external fabric has a discrete structure of specified porosity, whereas the membrane pores are of insignificant diameter.

Thus the choice of side is also significant for the thermal diffusion. Two-layer laminates have the increased diffusion on the outer side compared to the inner side, which is a consequence of different physical properties of both laminate sides. The reduced diffusion on the the inner side is advantageous during use because this material portion is closer to the skin.

Different results are obtained for three-layer laminates because the thermal diffusion is higher on the outer side and lower on the inner side.

Analysis of test results of thermal absorption

From ***Figure 4*** it follows that the type of laminate considerably influences the values of thermal absorption ($p < 0.05$). The differences in absorption are caused by the different feeling of fabric on the outer side in relation to the inner surface.

Similarly the side of the laminate considerably influences the values of thermal absorption. The majority of two-layer laminates have t considerably lower thermal absorption of the outer side than the inner side, cf. ***Figure 5***. The inner side is equipped with a membrane which creates a subjective cold feeling of the layer. The higher the absorption, the cooler the feeling of the laminate side, which is disadvantageous during use because the inner side of the laminate comes into contact with the skin. The user of clothing made from this laminate may feel uncomfortably cold. It follows easily that the skin surface is subjectively cooled, although there is no significant temperature difference between the laminate and the skin. Three-layer laminates behave differently when the inner side is made of knitted fabric. Thus the outer layer now has higher thermal absorption than the inner layer, which is favorable during use, because the skin touches a surface of warmer feeling.

Analysis of test results of thermal resistance

The analysis showed that the type of laminate has a significant impact on the value of thermal resistance. The results (***Figure 6***) for the two-layer laminates are in the range of 4.7 to 11.8 Km^2W^{-1}, while for the three-layer laminates it is from 9.1 to 43.4 Km^2W^{-1}. Large variations in the values result from the various thicknesses of layers and their conduction coefficients. Consequently for a prescribed thickness of the laminate applied it can be simply concluded that the greater the thickness (the highest thickness of the laminate 3L1), the higher the values of thermal resistance, hence better protection against the cold.

Analysis of test results of the ratio of maximal and stationary heat flux densities

The ratio of the maximal heat flux density q_{max} to the stationary heat flux density q_s is one of the parameters characterising the thermal insulation of a product and is a surface property like thermal absorption. The analysis showed that both types of laminate and their sides have a significant impact on the value of the ratio. The laminates tested have different values of the parameter (***Figure 7***) due to differences in the thickness, structure of the external fabric or the type of membrane.

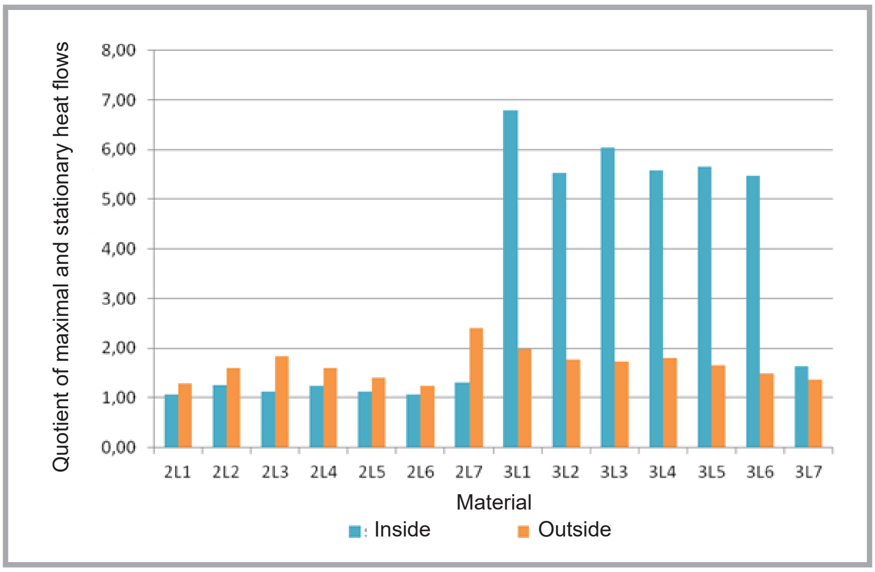

Figure 7. *Mean values of quotient of maximal and stationary heat flux densities for both material sides.*

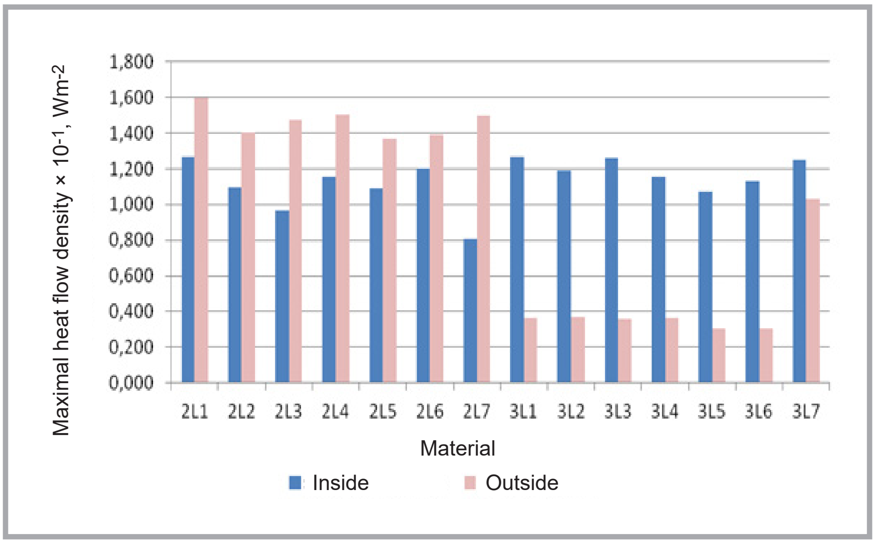

Figure 8. *Mean values of maximal heat flux density for both material sides.*

In the case of two-layer laminates, the outer side has smaller values of the ratio q_{max}/q_s than the inner side, which is disadvantageous during use because the inner side is positioned closer to the skin. Then the heat flux density penetrating the structure from the user to the surroundings increases. Moreover the feeling of the surface becomes colder and unpleasant for the user.

Other results more favorable to the user are determined for the three-layer laminates. Values of the ratio are higher for the outer than for inner side.

Analysis of test results of maximal heat flux density

The type of laminate affects the maximal heat flux density because the results are significantly different (***Figure 8***). From the viewpoint of thermal-insulating properties, the maximal heat flux density should be characterised by low values. Then the heated air layer between the human body and product tested has greater thermal insulation than the laminate, which minimises heat loss. For the two-layer laminate, the density of the stationary heat flux is higher for the upper than inner side (***Figure 9,*** see page 86), which reduces the thermal insulation of the laminate, being uncomfortable for the user. The inner side is closer to the skin surface than the outer one.

For the three-layer laminate there is a reverse relationship, which is favorable during use as the intensive heat transfer does not have a considerable bearing on

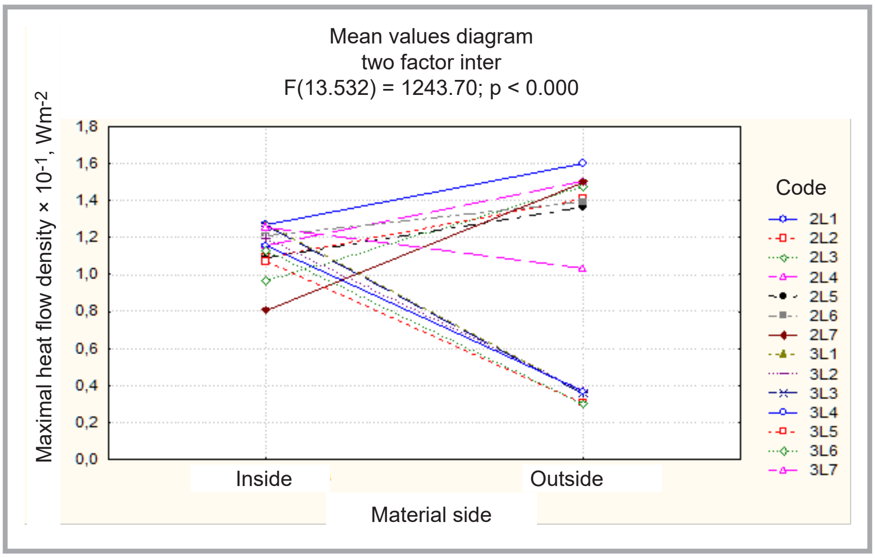

***Figure 9.** Mean values of two factor analysis of variance for maximal heat flux density.*

the cooling of skin because it exists in the distant laminate layer.

Conclusions

Analysis of the results obtained related to several important parameters of thermal insulation allow to draw conclusions regarding clothing materials with semi-permeable membranes.

Studies on the thermal resistance of clothing materials with semi-permeable membranes demonstrated that the results obtained are considerably different, caused by the variable thickness of laminates. A laminate of the greatest thickness (among the two-layer laminates it that signified as code 2L7, and among the three-layer laminates – 3L1) has the highest value of thermal resistance i.e. better protection against cold.

Another important parameter is thermal absorption. According to the results, the heat absorption depends strongly on the side of the laminate. The higher the absorption, the colder and the less comfortable the feeling of the surface. For the two-layer laminate, values of thermal absorption measured on the inner side are much higher than on the outer side. The inner side is made of a membrane or foil of smooth surface, which gives a cold feeling. In the case of three-layer laminates, lower values are obtained on the inner side, which was polar knitted fabric. The user of ready-made clothing has a feeling of warmth, which results from the feeling of knitted fabric. Clothes made from this material do not require additional insulation or ta protective layer to secure the membrane against damage.

The analysis of thermal diffusivity showed that there are differences between the values of diffusion between the upper and inner side, with some laminates (3L1, 3L2, 3L3, 3L4, 3L5, 3L6) having considerable differences. Generally the thermal diffusion in the case of two-layer laminates is at a low level, which indicates the slight ability of these products to transfer heat through pores. In the case of three-layer laminates, higher values of thermal diffusion are on the inner side. Diffusion depends on the material density, specific heat and porosity.

Values of the ratio of maximal and stationary heat flux densities vary greatly depending on the arrangement of the material sample during measurements. Values of the ratio for the laminates tested indicate that the two-layer laminates are characterised by unfavorable surface properties (cold feeling).

Clothing of very good heat-insulating properties is characterized by a low coefficient of thermal conductivity, low heat flux density, and thermal diffusion at a level which ensures low heat loss and simultaneous warm feeling resulting from the low thermal absorption. The studies concerning the heat-insulating properties of membrane laminates proved that better thermal insulation is provided by the three-layer laminates. Their good heat insulating characteristics result from the low thermal conductivity, the feeling of warmth, the low heat flux density as well as the high thermal resistance.

A good example is the comparison of two textiles of similar thickness, i.e. the two-layer laminate 2L2 (0.54 mm) as well as the three-layer laminate 3L7 (0.53 mm), which is characterised by better thermal insulation properties.

The results obtained can be implemented into a comprehensive assessment system of textiles in respect of their thermal insulation. The partial results can be used to formulate a complex assessment function and next to determine the optimisation criterion. Therefore our next goal is to create a complex assessment system concerning the thermal insulation of textile products, using the thermal insulating parameters obtained and global optimisation theory.

References

1. Jasińska I, Frydrych I and Sybilska W. Parameters of the thermal insulation of products type Gore-tex – Part I (in Polish). *Przegląd Włókienniczy* 2005; 6: 32-34.
2. Jasińska I, Frydrych I and Sybilska W. Parameters of the thermal insulation of products type Gore-tex – Part II (in Polish). *Przegląd Włókienniczy* 2005; 7: 34-37.
3. Fanglong Z, Weiyuan Z and Minzhi C. Investigation of Material Combinations for Fire-fighter's Protective Clothing on Radiant Protective and Heat-Moisture Transfer Performance. *Fibres and Textiles in Eastern Europe* 2007; 15, 1(60): 72-75.
4. Jun Y, Park Ch H, Shim H and Kang T J. Thermal Comfort Properties of Wearing Caps from Various Textiles. *Textile Research Journal* 2009; 79(2): 179-189.
5. Lee Sumin D Kimura, Keun Hyung Lee, J C Park and Ick Soo Kim The Effect of Laundering on the Thermal and Water Transfer Properties of Mass-produced Laminated Nanofiber Web for Use in Wear. *Textile Research Journal* 2010; 80(2): 99-105.
6. Matusiak M. Investigation of the thermal insulation properties of multilayer textiles. *Fibres and Textiles in Eastern Europe* 2006;14, 5(59): 98-102.
7. Nida Oglakcioglu, Pinar Celik, Tuba Bedez Ute, Arzu Marmarali and Huseyin Kadoglu. Thermal Comfort Properties of Angora Rabbit/Cotton Fiber Blended Knitted Fabrics. *Textile Research Journal* 2009; 79(10): 888-894.
8. Pamuk O, Öndoğan Z and Abreu M J. The Thermal Comfort Properties of Re-

usable and Disposable Surgical Gown Fabrics. *Slovene Journal For Textile and Clothing Technology, Design and Marketing* 2009; 52: 1−72, 1−3.
9. Uçar N and Yılmaz T. Thermal Properties of 1 x 1, 2 x 2, 3 x 3 Rib Knit Fabrics, *Fibres and Textiles in Eastern Europe* 2004; 3(47): 34-38.
10. Dems K, Radaszewska E and Turant J. Modeling of fiber-reinforced composite material subjected to thermal load. *Journal of Thermal Stresses*, 2012; 35, 7: 579-595.
11. Sztajnowski S, Krucińska I, Sulak K, Puchalski M, Wrzosek H and Bilska J. Effects of the artificial weathering of biodegradable spun-bonded PLA nonwovens in respect to their application in agriculture. *Fibres and Textiles in Eastern Europe* 2012; 96(6): 89-95.
12. Korycki R. Method of thickness optimization of textile structures during coupled heat and mass transport. *Fibres and Textiles in Eastern Europe* 2009; 17, 1(72): 33-38.
13. Korycki R and Szafranska H. Optimisation of pad thicknesses in ironing machines during coupled heat and mass transport. *Fibres and Textiles in Eastern Europe* 2016; 24, 1(115): 120-135.
14. Korycki R and Więzowska A. Modelling of the temperature field within knitted fur fabrics. *Fibres and Textiles in Eastern Europe* 2011; 84, 1: 55 – 59.
15. Korycki R. Modeling of transient heat transfer within bounded seams. *Fibres and Textiles in Eastern Europe* 2011;19, 5(88): 112 – 116.
16. Sybilska W and Korycki R. Analysis of coupled heat and water vapor transfer in textile laminates with membrane. *Fibres and Textiles in Eastern Europe* 2010; 18, 3(80): 65-69.
17. Multi-author work, Texile metrology, Vol. IV, Scientific and Technical Publishing House (WNT), Warsaw 1973.
18. Pawłowa M and Szafranska H. Form durability of clothing laminates from the standpoint of maintenance procedures. *Fibres and Textiles in Eastern Europe* 2007; 15, 3(62): 97-101.
19. PN-EN ISO 5084:1999. Textiles. Determination of thickness of textiles and textile products.
20. Manual of device Alambeta.
21. Frydrych I, Sybilska W and Wajszczyk M. Analysis of Selected Physical Properties of Membrane Fabrics Influencing the Utility Comfort of Clothing. *Fibres andTextiles in Eastern Europe* 2009; 17, 6(77): 50-55.
22. Manual of Stat Soft. Inc. Statistica for Windows.

Received 10.11.2015 Reviewed 12.03.2016