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Analysis of the Heat Resistance of Multilayer Clothing Packages

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Abstract
Clothing fabrics are rarely used individually as the only layer protecting the body against different outer factors. Especially in cold climates, human attire is usually composed of several layers constituting together a multilayer set of textile materials. The purpose of this work was to analyse the impact of the number of layers on the thermal resistance of multi-layer clothing packages. Two-, three- and four-layer packages were made from woven fabrics of different structure. The packages were tested for thermal resistance by means of a Permetest instrument, made by Sensora (Czech Republic). The tests were carried out for individual materials forming the layers of the packages and for entire packages. Based on the research conducted and analysis of the results, it was found that the number of layers has a significant impact on the thermal resistance of multi-layer clothing packages. The thermal resistance of the multilayer textile packages measured was a little lower than the sum of the thermal resistance of the particular layers creating the packages. On the basis of the results, the thermal contact resistance and boundary effect were also discussed.

Key words: *multilayer textile packages, thermal resistance, Permetest.*

Introduction

The utility comfort of clothing usage should be considered in different aspects. Generally, researchers distinguish four categories of comfort of clothing usage [1]:

- sensorial comfort – a subjective state of satisfaction with the physical contact of human skin with fabric,
- psychological comfort – a subjective state of the emotional satisfaction of needs by clothing usage,
- physiological comfort, also called thermo-physiological comfort – a condition that provides the person with an appropriate microclimate in the skin layers during their physical activity in changing climatic conditions while maintaining a certain physical and mental efficiency,
- comfort of fitting – this regards the tightness of clothing and its weight [1].

The significance of particular categories of comfort depends on the kind of clothing and its function. However, thermo-physiological comfort is the most important category, which should be ensured while wearing each kind of clothing. Thermal comfort is considered as a basic condition for clothing usage, which is the basis of physiological comfort. The feeling of thermal comfort is influenced by all factors that shape heat exchange between the human body and the environment in order to maintain the body's thermal balance. Heat exchange in the system: human being – clothing – surroundings results from the interaction of a number of factors involved in shaping the heat balance of the human body. The heat balance aims to maintain the body's internal temperature at a constant level [2].

In cold climatic conditions, multilayer clothing is usually used, such as coats, parkas etc. In such kinds of clothing there are several layers of different functions. There are usually three main layers that play different roles:

- outer shell,
- middle layer,
- lining.

In three-layer structures, the middle layer is created from thermal insulation material providing protection against cold. Each subsequent layer affects the comfort of using and heat-insulating properties of the clothing [3].

From the point of view of human body protection against cold, thermal resistance is an important comfort-related property of textile materials and clothing. It plays a significant role in the material engineering of clothing. Thermal resistance expresses the difference in temperature across a unit area of material of unit thickness when a unit of heat energy flows through it in a unit of time.

The thermal resistance of multilayer material is usually the sum of the thermal resistance of particular layers [4]. However, the contact resistance should be taken into consideration while determining the thermal resistance of textile multilayer packages. When two materials are joined together, their surfaces do not adjoin exactly one to another. The surface of solid objects is usually rough, and due to this fact small air gaps occur between the objects (***Figure 1***). These air gaps create an additional source of thermal insulation due to the high thermal resistance of unventilated air trapped in the gaps between materials. This phenomenon is called thermal contact resistance [5].

Due to this fact, the thermal resistance of a multilayer textile package should be a little higher than the sum of the thermal resistance of the single layers creating the package, because the air spaces between the surfaces of particular layers add some thermal insulation [6, 7]. Such resistance

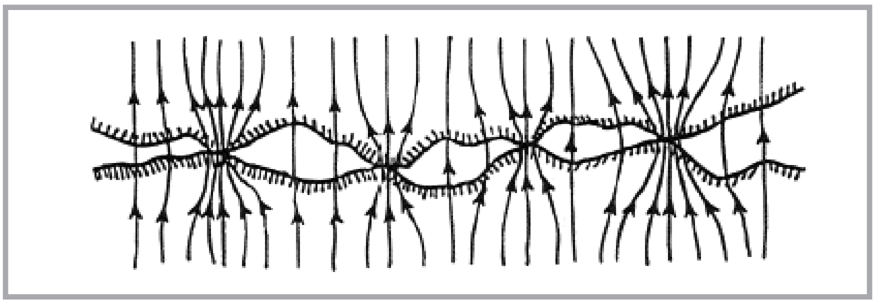

Figure 1. *Visualisation of air gaps between two surfaces of solid materials [5].*

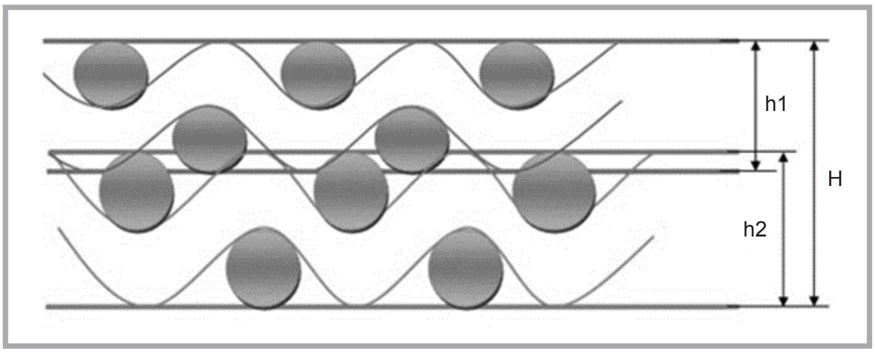

***Figure 2.** Scheme of two textile layers adhering [8].*

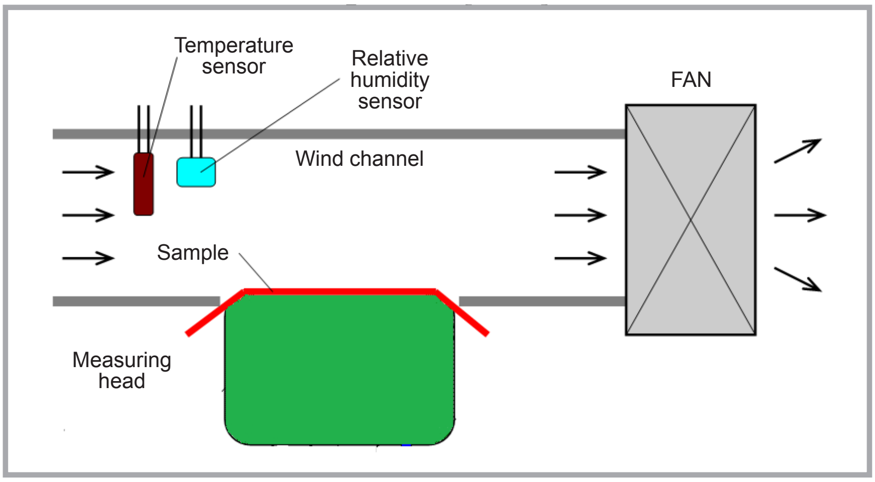

***Figure 3.** Scheme of the Permetest device [14].*

occurs when two surfaces of solid materials are adjacent. In the case of flexible materials, such as textiles, the situation is different. Previous studies have shown that the thermal resistance of multilayer textile sets is usually lower than the sum of the thermal resistance of the single textile materials creating the multilayer set [4, 8]. This was explained by the fact that the flexibility and structure of textile materials, especially their texture, different directions of fibres and open pores, in particular of those materials creating the layers, cause that two phenomena can occur:

- an increased number of contact points,
- the filling of pores in one layer by elements of an adjacent layer (***Figure 2***).

These phenomena need further investigation, especially in the aspect of the relationship between the thermal resistance of multilayer textile materials and the surface characteristics of adjacent layers. The results presented in the publications mentioned above are based on results from an Alambeta device [4, 8], which is a computer-controlled portable instrument for the fast and non-destructive measurement of transient and steady-state thermo-physical properties of textile materials. On the Alambeta device the fabric being measured is placed between the two plates of the device: hot (upper) and cold (lower).

The aim of the work presented was to analyse the thermal resistance of multilayer textile packages and the influence of the number of layers on the thermal resistance of the packages. Measurements were made using a Permetest device. In the Permetest the measurement procedure is different from that used on an Alambeta device. It is described in the next section. Due to this fact the heat flow through the sample measured is different from that while measuring by means of an Alambeta device.

***Table 1.** Basic structural parameters of the woven fabrics investigated.*

Parameter	Method	Unit	WL 11	WL 12	WL 13
Raw material	–	–	WO100	WO80/PES20	WO70/PES30
Weave	–	–	crepe	crepe	plain
Mass per square metre	PN-ISO 3801:1993	gm^{-2}	360.0	376.9	198.6
Number of ends	PN-EN 1049-2:2000	cm^{-1}	14.8	16.8	12.7
Number of picks		cm^{-1}	12.4	14.0	10.0
Thickness	PN-EN ISO 5084:1999	mm	2.43	1.85	0.73

Materials and methods

Measurement was performed on the basis of three kinds of woven fabrics made of wool and polyester. The basic properties of the fabrics applied in the experiment are presented in ***Table 1***.

From the woven fabrics multilayer packages were created: two- three- and four-layer textile packages. From each fabric laboratory samples of 18 x 18 cm dimensions were cut. Individual fabrics and multilayer sets were measured in the range of the thermal resistance using a Permetest device, made by Sensora (Czech Republic) [9].

The Permetest device is a fast response measuring instrument for non-destructive determination of the thermal resistance, water-vapour resistance and water-vapour relative permeability of textile materials, foils and paper sheets. It is considered as a portable "skin model". The instrument provides all kinds of measurements very similar to the ISO 11092 standard, and the results are evaluated by a procedure identical to that required in the standard [10]. The Permetest device utilises the one-plate principle of measurement (***Figure 3***). The sample measured is placed in the wind channel on the hot plate of the measuring head. Heat transport is performed by heat conduction through the sample measured and by heat diffusion forced by air movement in the measuring channel [11-13].

Measurement was made twice: with and without the sample. The thermal resistance R_{ct} according to the Permetest is calculated by ***Equation (1)*** [15]:

$$R_{ct} = (t_m - t_a)\,(Q_v^{-1} - Q_0^{-1}),\ \text{mK m}^2\text{W}^{-1} \qquad (1)$$

where:
t_m – temperature of the measuring head surface,
t_a – temperature of air in the wind channel,
Q_o – density of heat flow through the sample measured,

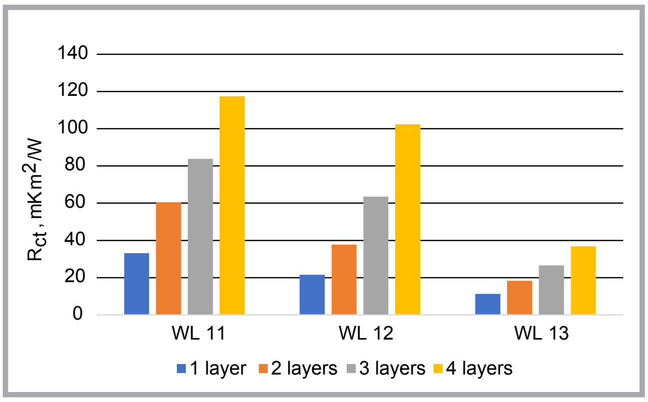

***Figure 4.** Thermal resistance of the single fabrics and multilayer packages made thereof.*

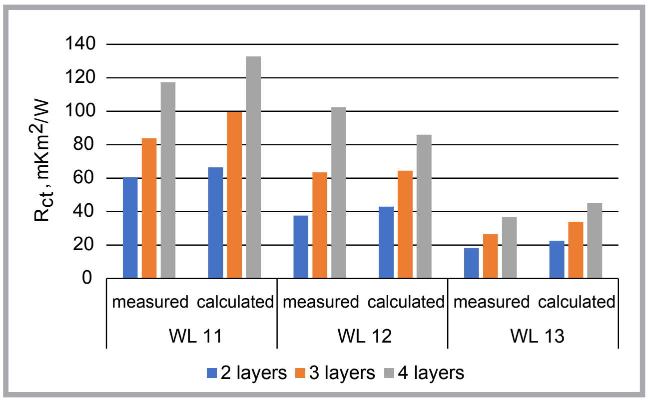

***Figure 5.** Comparison of the measured and calculated thermal resistance according to **Equation (1)**.*

Q_v – density of heat flow from the measuring head surface (without sample).

According to the standard, for each material (single and multilayer) three repetitions of measurement were performed. The measurement was made at an air velocity of 1 m/s in standard climatic conditions.

Results and discussion

Results from the Permetest device are presented in ***Table 2***.

The highest thermal resistance was stated for the WL 11 fabric variant, and the lowest – for the W 13 fabric variant. The same relationship was stated for the multilayer packages. For the textile packages of the same number of layers, the highest thermal resistance was stated for packages made of the WL 11 fabric, whereas the lowest – for the packages made of the WL 13 woven fabric. According to expectations, the thermal resistance of multilayer textile packages increases with an increase in the number of layers (***Figure 4***).

According to theory, the total thermal resistance of the multilayer textile package is the sum of the thermal resistance of particular layers, according to ***Equation (2)***:

$$R_T = R_{L1} + R_{L2} + ... + R_{Ln} \qquad (2)$$

where:
R_T – total thermal resistance of multilayer assembly,
R_{L1} – thermal resistance of 1st layer,
R_{L2} – thermal resistance of 2nd layer,
n – number of layers.

Taking the above into account, we calculated the theoretical thermal resistance of the multilayer sets of textile materials as the sum of the thermal resistance of individual materials creating the sets. A comparison of the measured and calculated thermal resistance according to ***Equation (1)*** is presented in ***Figure 5***.

The results presented are in agreement with those stated in previous publications [4, 8]. In almost all of cases, the thermal resistance of the multilayer textile sets measured by means of the Permetest device is lower than that calculated using ***Equation (1)***. The exception is the thermal resistance of the four-layer set made of the WL 12 woven fabric. This result should be considered as an outlier.

Taking into account the results presented, we can assume that the above-mentioned two phenomena [4,8]:

- increased number of contact points,
- fulfill of pores in one layer by elements of an adjacent layer (***Figure 2)***,

also occurred in the current experiment. Especially, the second factor mentioned above can cause a compaction of the structure of package in the zone of layer adhesion (***Figure 2***) and, at the same time, higher thermal conductivity in this zone. In the case of the multilayer textile packages created, the thermal contact resistance is not visible in the results. At the same time, there is agreement between the results from both instruments: Alambeta and Permetest. However, while measuring by means of the Alambeta device, the material measured is placed between two plates: hot and cold. both of which adhere to the sample at a constant pressure of 200 Pa [11-13]. Measurement is performed without air movement above the sample measured.

In the Permetest measurement there are also other factors which can influence the results. According to Hes [12, 14], there is an additional factor influencing the results. It is the so-called boundary effect. The effect is based on the disruption of air movement in the immediate vicinity of the sample surface due to surface unevenness. Air movement turbulences near the fabric surface influence the heat flow through the sample and, at the same time, the results from the Permetest device. Hes suggests a new procedure which can be used to determine the thermal resistance of fabric using a Permetest device and “skin model”. The procedure involves measuring one layer and next two layers of the material being assessed. Finally, the thermal resistance of the fabric R_f investigated should be calculated as the difference between the thermal resistance of two layers and one layer, according to ***Equation (3)***:

$$R_f = R_{L2} - R_{L1} \qquad (3)$$

Based on the ***Equation (3)*** and results from the Permetest device (***Table 2***), the

***Table 2.** Thermal resistance of woven fabrics and multilayer sets made thereof, mK m²/W.*

Fabric variant	Number of layers							
	1 layer		2 layers		3 layers		4 layers	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
WL 11	33.2	1.8	60.5	4.7	83.8	3.1	117.4	8.4
WL 12	215	2.7	37.7	1.8	63.5	3.2	102.4	4.8
WL 13	11.3	0.7	18.3	1.8	26.6	4.5	36.8	0.7

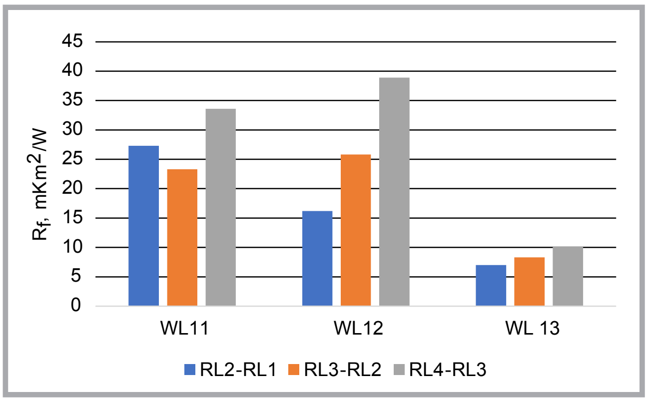

Figure 6. *Thermal resistance of measured fabric R_f calculated on the basis of **Equations (3), (4)** and **(5)**.*

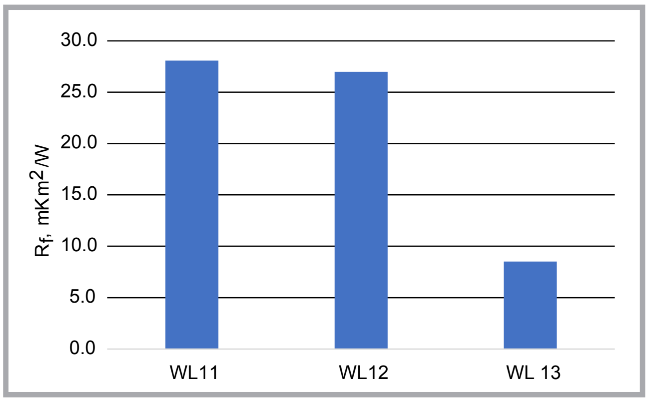

Figure 7. *Mean thermal resistance R_f of fabrics measured.*

thermal resistance of the fabrics investigated is as follows:

- WL 11 – 27.3 mK m^2/W,
- WL 12 – 16.2 mK m^2/W,
- WL 13 – 7.0 mK m^2/W.

And, in consequence, the thermal resistance resulting from the boundary effect is appropriately 5.9 mK m^2/W for the WL 11, 5.3 mK m^2/W for the WL 12, and 4.3 mK m^2/W for the WL 13. Differences between the values of thermal resistance presented caused by the boundary effect result from the different surface characteristics of the fabrics measured.

It should be taken into consideration that the boundary effect also occurs while measuring the heat flow without a sample. In this case, the size of the boundary effect depends on the surface characteristics of the measuring head. Finally, the thermal resistance caused by boundary effects both connected with the surface of the measuring head and that of the sample measured is a result of both values.

Following Hes's suggestion, the thermal resistance of the fabrics investigated can also be calculated as the difference between the thermal resistance of the three-layer set and two-layer set according to ***Equation (4)***:

$$R_f = R_{L3} - R_{L2} \tag{4}$$

or as the difference between the thermal resistance of the four-layer set and three-layer set according to ***Equation (5)***:

$$R_f = R_{L4} - R_{L3} \tag{5}$$

Values of the thermal resistance of the fabrics investigated calculated of the basis of ***Equations (4)*** and ***(5)*** are different than those calculated using ***Equation (3)*** (***Figure 6***).

Especially, the values calculated for the WL 12 fabric differ from each other significantly, which is difficult to explain. First of all, the precision of measurement by means of the Permetest device can cause differences. The unevenness of the fabric structure should also be considered as a reason for the differences stated for the WL 12 fabric.

It was decided to calculate the thermal resistance of the fabrics investigated as the arithmetic mean of thermal resistance calculated on the basis of ***Equations (3), (4)*** and ***(5)***. Results are presented in ***Figure 7***.

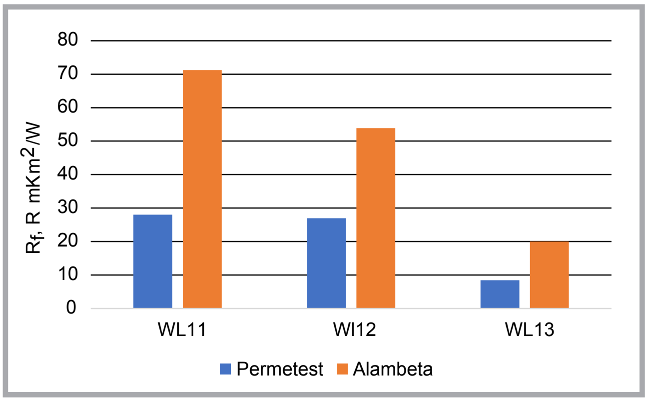

Figure 8. *Comparison of mean values of thermal resistance R_f calculated on the basis of the results from the Permetest device and thermal resistance R from the Alambeta device.*

Figure 8 presents a comparison of the mean values of thermal resistance R_f calculated on the basis of the results from the Permetest device and thermal resistance *R* from the Alambeta device. The absolute values of thermal resistance from both instruments are different, which is obvious because the principle of measurement using both instruments is different. In contrast to the Permetest device, while measuring using an Alambeta device there is not any air movement above the fabric surface. Due to this fact no forced diffusion occurs. There is a too low number of cases to calculate the correlation coefficient between the results from the Alambeta and Permetest devices. However, it is clearly seen that there is agreement between both instruments in the aspect of relationships between the thermal resistance of the fabrics measured. According to both instruments, the highest thermal resistance was stated for the WL 11 woven fabric, whereas the lowest – for the WL 13 woven fabric (***Figure 9***).

There is also another factor which should be taken into consideration while discussing the results from the Permetest device. It is the change in the cross-section of the wind channel resulting from adding another layer to the multilayer packages measured, which causes a diminishing of the cross-section of the wind channel in the space above the material measured. At the same time, the wind velocity is a little higher above the sample being measured, which influences heat flow in the channel of the device due to the change in the forced heat diffusion.

There are many unknowns that do not allow to solve the problem unequivocally. Among others, the surface geometry characteristic of the fabrics being investigated plays an important role. Due to this fact it is predicted to continue the investigations in this direction. Surface roughness and other parameters characterising the surface geometry of fabrics influence the boundary effect and, at the same time, the final results from the Permetest device. The surface characteristic also influences the contact thermal resistance while measuring multilayer sets. All factors mentioned should be the objects of further investigations. The surface geometry of textile materials can be assessed using optical methods, for instance 3D laser scanning and a profilometer. Such investigations published till now [16, 17] have confirmed that it is possible to quantify the surface geometry of fabrics and next to connect the surface parameters with the thermal properties.

Summing up

In the work presented, measurements of multilayer packages of textile materials were performed by means of a Permetest device. The results obtained confirmed that the thermal resistance of multilayer sets of textile materials increases with an increase in the number of layers. It was also stated that the thermal contact resistance is not visible in the results for multilayer textile packages. Results from the Permetset device are in agreement with previously published results based on measurement by means of an Alambeta device. The boundary effect suggested by Hes was also the object of analysis. For both the thermal contact resistance and boundary effect it is necessary to know the surface geometry characteristic of the fabrics measured, which can be done using advanced optical methods. This will be analysed in further steps of the investigation of multilayer textile packages.

Acknowledgment

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