ABOUT THE THERMAL CONDUCTIVITY OF MULTI-LAYER CLOTHING

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Abstract

Measurement of thermal conductivity of textile structures for clothing is still a big challenge. This is because the values are below or at the limits of the bottom range of existing equipment of current testing devices. On the other hand, the optimisation of the thermal comfort of clothing values is required, because there are several single layers in men´s suits or women´s costumes and only with complete information about each layer more complex computations and calculations are possible.

This work presents a part of larger experimental investigations, related to the R_{ct} values of woven and knitted structures combined into several layers. Compressibility and thickness of single and multiple layers were measured; both using standard testing equipment and analysing cross sections of the layers embedded into resin. In order to investigate the influence of the air between multiple layers, the R_{ct} values of five layers of the same structure were estimated using the PERMETEST device of the company Sensora. Some correlations were found and statistically proven between the R_{ct}, the number of layers and the volume of the air layer between the layers.

Finally, different configurations with the same layers in everyday clothing from underwear to suit were experimentally analysed and compared with the theoretically calculated values, based on a layered model of heat transfer through this clothing.

Introduction

The importance of clothing functionality has increased over the years with the development of textile technologies. Clothing should be a barrier to the outside environment and should also transport heat and moisture from the body to the surrounding environment.

The thermal exchange between the body and the environment is done through heat convection, conduction and radiation, the moisture transport occurs through perspiration [1]. Within these mechanisms, the conduction and convection are the most important ways of the heat transfer in textiles. The thermal comfort is reached when a balance between heat production and heat loss is achieved. Therefore, the human-clothing-environment system must work. These phenomena were investigated in detail in the past, but garments normally consist not just of one layer, but of several layers. An addition of the thermal resistance values of the individual layers deviates to the measurement of the multilayer garment. One reason is that the transfer of heat and moisture between the layers and between the layers to the environment is neglected. But in fact, the heat transfer was not just investigated on the textile layers, but also on the included air and the air layer on the outer surface.
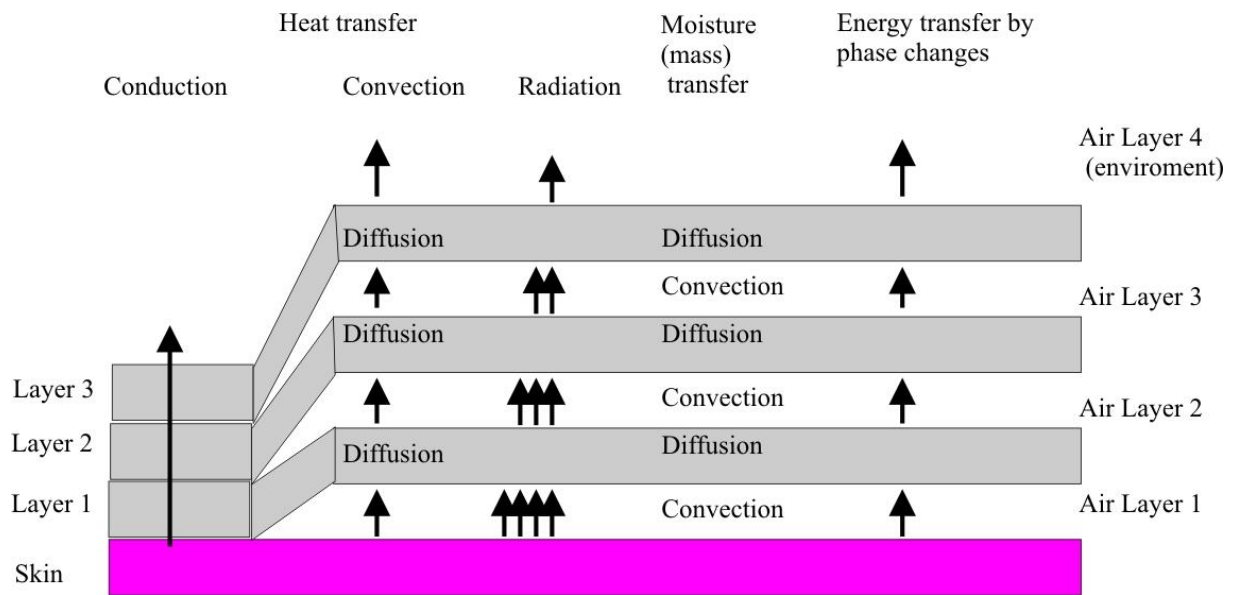
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Fig. 1: *Schematic view of the mechanisms of heat, moisture and energy transfer on a multilayer system*

The thermal conductivity is the exchange of kinetic energy of particles through a stationary boundary between two systems. The heat conduction is measured by using the Fourier's law of heat conduction [2].

$$q = kA\frac{\Delta T}{d} \text{ (W)} \tag{1}$$

where q = rate of conduction heat transfer in Watt, k= the specific thermal conductivity of the fiber material in W/mK, A= Area perpendicular to heat flow in m², $\Delta T = (T_1-T_2)$ temperature difference between the areas in °K, d = the thickness of the fabric in m.

The total thermal resistance Rct is given by

$$R_{ct} = \frac{T_S - T_E}{q_{dry}} \tag{2}$$

where q_{dry} is the total heat flux through the layers. The fabric thermal resistance R_{cf} is given by

$$Rcf = Rct - Rct0 \tag{3}$$

where R_{ct0} is the thermal resistance without the fabric layer.

To calculate the effective thermal resistance, the clothing system should have reached a steady state and there should be no mass transfer, so it can be referred as the dry condition, and the fabric system is modulated in a multilayer structure.
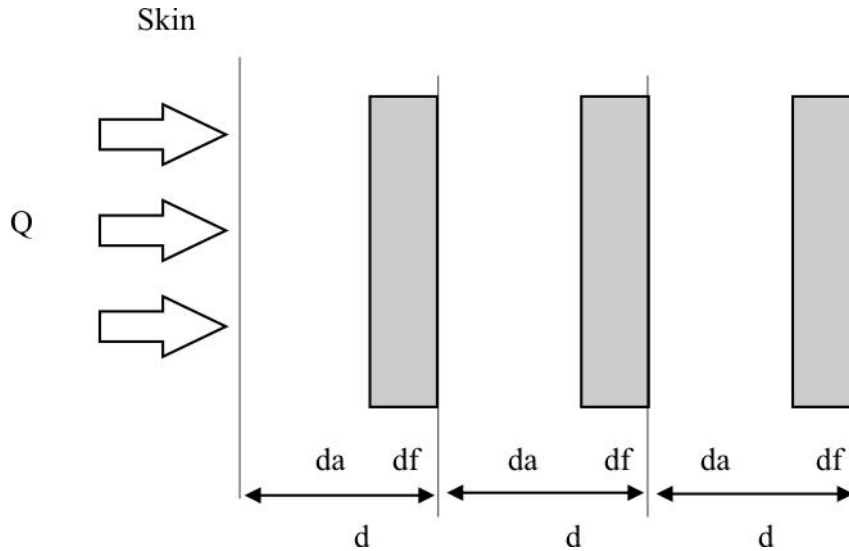
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Fig. 2: *Modulated simple fabric structure*

Where df and da are the thickness values of the fabrics and the air gaps in the fabric structure, whereas kf and ka are the thermal conductivity values for the fibers and still air.

Accordingly the thermal resistance can be simplified and calculated as follows [3]:

$$Rct = \frac{df}{kf} + \frac{da}{ka} \text{ (m}^2\text{K/W)} \tag{4}$$

where $df = df_1 + df_2 + \cdots + df_n$ and $da = da_1 + da_2 + \cdots + da_n.$

for the simple layers 1 to n. This equation only actually considers the conductivity.

A difference between the calculated and measured results is expected. The reason is that it is not possible to determine the microclimate between skin and garment, which is important for the heat transfer.

1   Experimental

The aim of this work is to investigate these transitions from heat between the textile layers and intermediate air layers and also the transitions between the textile layer and the ambient air. The main focus is on the question of whether it is possible to predict the behaviour of the multilayer structure, based on the measurement of the single layers and the information about the air between them.

The key points of this study are to analyze dependencies and interrelationships between test parameters. Therefore, two different cotton samples were measured from one to five layers; the values were analyzed to find out correlations between expected and calculated values with the measured multilayer samples. In addition, typical combinations of menswear clothing items were compiled and physical properties measured. The relationships between individual layers and multi-layered fabrics were checked.

1.1   Thickness of woven and knitted structures

Two methods for testing the thickness were applied – the standard one, using the pressure, and the other using analysis of the layer. The standard testing method eliminates the air between the layers, which is very important for thermal comfort. Because of this, the fabrics were embedded in resin in a relaxed state. So, more realistic information about the air gap between them can be obtained. The results between both methods are presented.
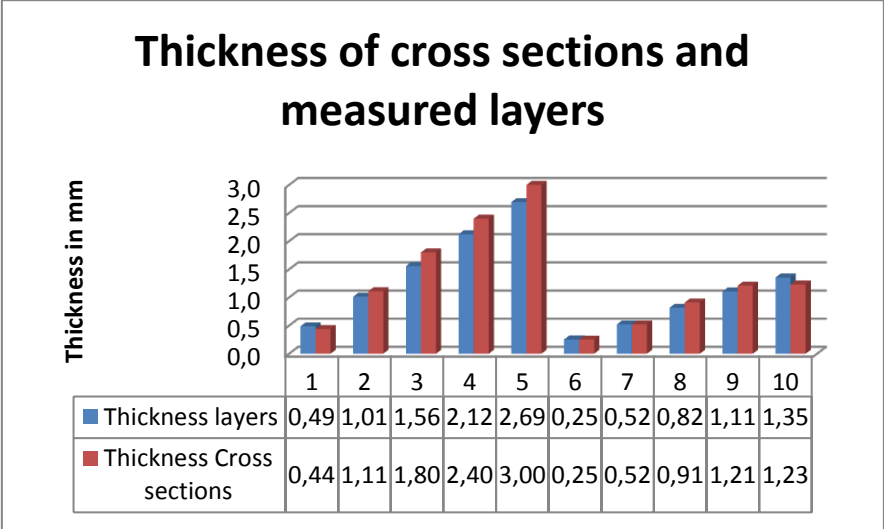
The first part of the measurement involves a comparison of two different textile samples tested for their properties on one to five layers. For a visual representation of the multi-layered textiles being tested, the layers were embedded in resin, polished and photographed at a 200-fold microscopic magnification. Except for the visual representation of the number of layers it also serves the measured differences in porosity to be visually presented.
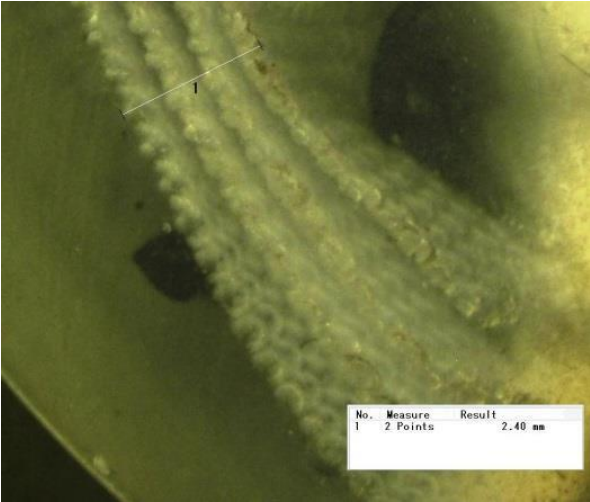
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Fig. 3: *Example of cross section of multilayered structures*

These are clearly visible in direct comparison of when using knitted and woven fabrics. In addition, the dimensions of the textile layer thicknesses were recorded, in order to show that such measurements give a good indication of the dimensions.


	1	2	3	4	5	6	7	8	9	10
Thickness layers	0,49	1,01	1,56	2,12	2,69	0,25	0,52	0,82	1,11	1,35
Thickness Cross sections	0,44	1,11	1,80	2,40	3,00	0,25	0,52	0,91	1,21	1,23

Source: Own
Fig. 4: *Cross-sections vs. measured thickness*

Figure 4 shows the connection between the cross-sectional thickness and measured thicknesses of the textiles. By pouring the resin over the samples there may be differences, since the samples were previously fixed and thus partially squeezed. Nevertheless, such samples are a good indication of the dimensions of textile samples, even if they have not been tested according to standards. But it is also quite clear that the air gap is higher and the "standard" testing method for thickness is underestimated.

1.2 Analysis of the interdependence of separately measured and calculated textile layers

The fabrics were contrasted, the layers were measured and the sum of the individual layers was calculated. It is noteworthy that in both series of measurements, a linear increase is observed, but the added values are lower than with the tested layers. Figure 5 shows the respective increases in thermal resistances of the multilayer samples measured and the added values of the individual measurements. Since the single measurement is a pure addition of the textile layers, without the intervening air-layers being taken into account, it can be assumed that this is the reason for the lower values. Nor should it be forgotten that almost all measurements are below the measurement accuracy of the PERMETEST device. That is why inaccuracies are expected.

Rct in m² mK/W

	1	2	3	4	5
Rct measured	4,40	10,80	20,70	31,10	46,10
Rct added	4,40	8,80	13,20	17,60	22,00
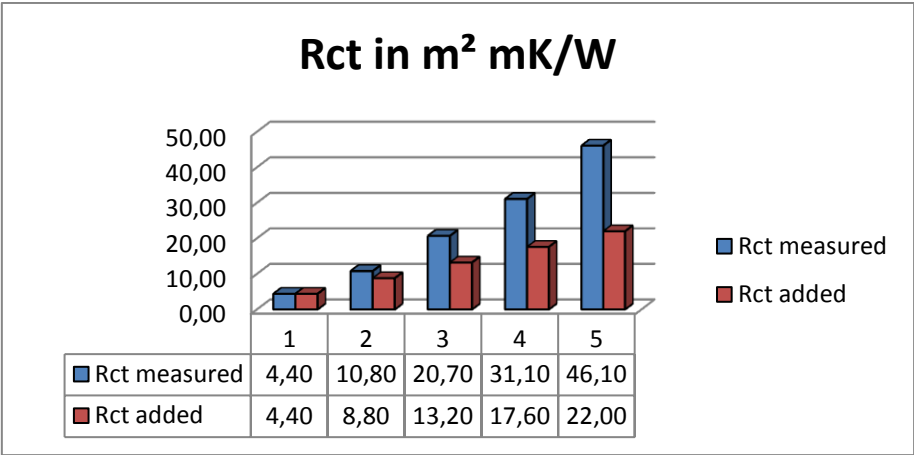
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Fig. 5: *Thermal resistance of measured and calculated multilayer knitting*

Based on the regression line of the heat transfer measurements in Figure 6 a linear relationship between individual measurements and multilayer measurement is shown. This is very strong, which is why we can say that the insulation values of the air layers conclusions of the single measurement are to be considered in the case of a multilayer textile.

$$y = 2,3568x - 8,49$$
$$R^2 = 0,9789$$
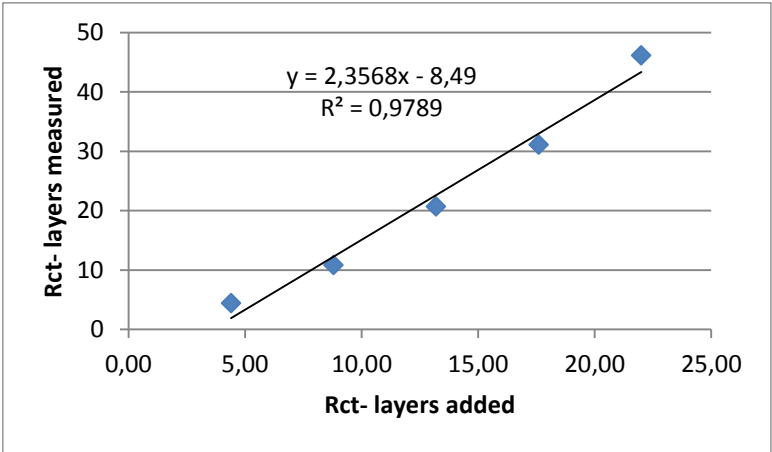
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Fig. 6: *Comparison between measured and calculated knitted structures*

The heat transfer resistance increases linearly with more layers. As was already stated, the multilayered textiles tested always show higher values in the thermal resistance than the added values. This is because the values of the air layers are completely ignored or not

correctly measured when calculating the value of the multilayered structure based on the single layer values.

1.3   Measurement of garment combinations for men

Usual combinations of menswear clothing items were chosen and tested as a single layer, as well as multilayered combinations. By using one to three-layer coatings it should have been proved that further layers effect the thermal insulation. A comparison between the measured single layers and the combinations of garments shows that there are no statistical proven interdependences between them. To check the accuracy of the measurements the results were compared to the results found in the ISO 9920. The clothing combinations that are included in the standard are between 0.15 to 0.30 m² K / W. Measured combinations are between 0.011 m² K / W, which consists of a T-shirt, a long sleeved T-shirt and a jacket, and 0,043 m² K / W for the combination of a T-shirt, a long sleeved T-shirt and a fleece pullover. These are the values, which define the standard and have an approximately ten times higher insulation than the examined items of clothing. A comparison of the individual layers, such as the T-shirt according to standard should have had a value of 0.012 m² K / W, but the measurement yielded a result of 0.0044 m² K / W, it means just over a third of the given data. The shirt could not be measured and showed a value of zero, while a value of 0.045 m² K / W is given in the standard. Since the samples were tested with the PERMETEST device, and most measurements were outside the measurement range of the instrument, an exact comparison is not possible at this point.

Conclusion

The collection of physiological data is very complex. The measurement with the skin model or the PERMETEST device according to DIN EN 31092 [2013] can only make very limited statements about the overall comfort of clothing. Although it provides information about the stationary heat and water vapor transmission of materials, and therefore brings some evidence to select specific textiles, the comparison with the insulation values of the standard DIN EN ISO 9920 [2009] shows that the results do not match. In addition, the two measures of heat and water vapor resistance are determined in separate experiments and therefore do not allow assessment of the interaction between these two parameters.

The measuring range of PERMETEST device starts at 0.02 m² K / W, most clothing textiles were substantially lower than this value, so the results are inaccurate. In addition, these steady-state measurements provide meaningful results only if the clothing does not store heat or moisture and it does not lead to condensation in the textile. Since this is different but usual in practice, these measurements are well comparable.

In order to evaluate the comfort, the clothing combination must always be measured, as it is worn. Measurements on single-layer fabrics can be very inaccurate compared to the heat transfer of a multilayer combination. With several layers of the same fabric we see a linear relationship in the measurement of the thermal resistance, even if the results increase with the number of layers. The water vapor resistance coincides very well. For clothing combinations of different materials, these correlations, however, confirmed to be less significant. It could also be shown that the statements on the addition of the results of the thermal resistance of multilayer fabrics are incorrect.

The measurements according to DIN EN 31092 [2013] give the overall thermal resistance, but not the kind of heat transfer and not the heat passes through each layer. The knowledge of these phenomena in the textile must be deepened to make a modeling of the various processes possible. For this, the processes of heat and moisture transport should be identified and

analyzed separately. For example, moisture can evaporate and condense from one layer into or onto another. These processes release energy, which in turn affects the temperature of the body. A quantification of these processes is not possible; this is why these processes should be given more attention to in the future.

Literature

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TEPELNÁ VODIVOST TEXTILNÍCH STRUKTUR NĚKOLIKAVRSTEVNATÉHO OBLEČENÍ

Měření tepelné vodivosti textilních struktur pro oblečení je stále velkou výzvou. Důvodem je, že tyto hodnoty jsou na hranici spodního rozsahu stávajícího vybavení současných zkušebních zařízení, nebo i nižší. Na druhé straně je ale vyžadována optimalizace tepelného komfortu oděvů. Pánské i dámské oděvy jsou vytvářeny z několika vrstev, a pouze s kompletními informacemi o každé vrstvě jsou možné složitější výpočty a kalkulace.

Tato práce prezentuje část rozsáhlejších experimentálních studií, týkajících se R_{ct} hodnot tkaných a pletených struktur sestávajících z několika vrstev. Byla změřena stlačitelnost a tloušťka jednotlivých vrstev i vícevrstvých struktur. V obou případech byla použita standardní testovací zařízení a provedena analýza příčného řezu vrstev zalitých do pryskyřice. Za účelem zkoumání vlivu vzduchu mezi několika vrstvami byly R_{ct} hodnoty pěti vrstev se stejnou strukturou odhadnuty pomocí zařízení PERMETEST společnosti Sensora. Byly zjištěny a statisticky prokázány jisté korelace mezi hodnotami R_{ct}, počtem vrstev a objemem vzduchové vrstvy mezi jednotlivými vrstvami.

Různé kombinace vrstev materiálů používaných na běžné ošacení, od spodního prádla po vrchní vrstvy oděvů, byly experimentálně analyzovány a porovnány s teoreticky vypočtenými hodnotami.

LEITFÄHIGKEIT VON WÄRMER TEXTILER STRUKTUREN VON MEHRSCHICTIGER KLEIDUNG

Die Messung der Wärmeleitfähigkeit textiler Strukturen für Kleidung stellt unverändert eine große Herausforderung dar. Der Grund dafür besteht darin, dass diese Werte sich an der unteren Grenze der bestehenden Ausstattung der gegenwärtigen Versuchseinrichtungen oder sogar noch darunter bewegen. Auf der anderen Seite wird eine Optimierung des Wärmekomforts der Bekleidung angestrebt. Damen- und Herrenkleidung besteht aus mehreren Schichten, und nur mit vollständigen Informationen über jede Schicht sind kompliziertere Berechnungen und Kalkulationen möglich. Diese Arbeit präsentiert einen Teil umfangreicher experimenteller Studien, welche die R_{ct}-Werte gewobener und gestrickter Strukturen betreffen, die sich aus mehreren Schichten zusammensetzen. Es wurden die Kompressibilität und die Dicke der einzelnen Schichten und auch der mehrschichtigen Strukturen gemessen. In beiden Fällen wurde von einer Standardtesteinrichtung Gebrauch gemacht und eine Analyse des Querschnitts von in Harz eingegossenen Schichten durchgeführt. Zur Untersuchung der Wirkung der Luft zwischen mehreren Schichten wurden die R_{ct}-Werte von fünf Schichten mit der gleichen Struktur mit Hilfe der Eirichtung PERMETEST der Gesellschaft Sensora geschätzt. Es wurden dabei bestimmte Korrelationen zwischen den R_{ct}-Werten, der Anzahl der Schichten und dem Umfang der Luftschichten zwischen den einzelnen Schichten festgestellt und auch statistisch bewiesen. Verschiedene Kombinationen von Schichten aus Materialien, die für gewöhnliche Kleidung – von Unterwäsche bis zu Oberbekleidung – verwendet werden, wurden experimentell analysiert und mit den theoretisch berechneten Werten verglichen.

PRZEWODNOŚĆ CIEPLNA STRUKTUR TEKSTYLNYCH UBRAŃ KILKUWARSTWOWYCH

Pomiar przewodności cieplnej struktur tekstylnych stosowanych do ubrań pozostaje wciąż dużym wyzwaniem. Wynika to z tego, że wartości te są na granicy dolnego zakresu istniejącego wyposażenia obecnych urządzeń testujących, a nawet niższe. Z drugiej strony

wymagana jest jednak optymalizacja komfortu cieplnego ubrań. Ubrania męskie i damskie są produkowane z kilku warstw a bardziej zaawansowane obliczenia i kalkulacje są możliwe tylko wówczas, gdy posiadamy kompleksowe informacje na temat każdej warstwy.

Niniejsze opracowanie przedstawia część bardziej obszernych badań eksperymentalnych, dotyczących wartości R_{ct}- struktur tkanych i plecionych składających się z kilku warstw. Dokonano pomiaru ściśliwości i grubości poszczególnych warstw i struktur kilkuwarstwowych. W obu przypadkach wykorzystano standardowe urządzenia testujące i wykonano analizę przekroju poprzecznego warstw zalanych żywicą. W celu zbadania wpływu powietrza pomiędzy kilkoma warstwami, wartości R_{ct} pięciu warstw o takiej samej strukturze oszacowano przy pomocy urządzenia PERMETEST firmy Sensora. Stwierdzono i statystycznie udowodniono pewne korelacje między wartościami R_{ct}, liczbą warstw a pojemnością warstwy powietrza pomiędzy poszczególnymi warstwami.

W sposób eksperymentalny przeanalizowano różne połączenia warstw materiałów stosowanych do zwykłych ubrań, od bielizny po wierzchnie okrycia, i porównano je z teoretycznie obliczonymi wartościami.