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.
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 \[2\].

\[
q = kA \frac{\Delta T}{d} \text{ (W)}
\]  

(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 m\(^2\), \(\Delta T = (T_1 - T_2)\) temperature difference between the areas in °K, \(d\) = the thickness of the fabric in m.

The total thermal resistance \(R_{ct}\) is given by

\[
R_{ct} = \frac{T_S - T_E}{q_{dry}}
\]  

(2)

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

\[
R_{cf} = R_{ct} - R_{ct0}
\]  

(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.
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]:

\[
R_{ct} = \frac{df}{kf} + \frac{da}{ka} \text{ (m}^2\text{K/W)}
\]  

(4)

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

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 multilayered 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.

**Source:** Own

**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.

**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.

![Graph showing thermal resistance of measured and calculated multilayer knitting](image)

Source: Own

**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.

![Graph showing comparison between measured and calculated knitted structures](image)

Source: Own

**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 affect 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**


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 tkani m 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


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.

Ninnejsze opracowanie przedstawia część bardziej obszarowych 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.