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The impact of moisture on thermal conductivity of fabrics

Meritve vpliva vlage na toplotno prevodnost tkanin

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Abstract: The article presents the experimental results of the thermal conductivity of absorbent fabrics for increasing relative amount of water in the fabric. Measurements confirm that the effective thermal conductivity of fabrics at low moisture level is proportional to the relative amount of water absorbed in fabrics. With increasing relative amount of water in the fabric, effective thermal conductivity stabilizes around the value comparable with the thermal conductivity of water. The experimental results are compared with the theoretical linear model.

Key words: heat, heat conduction, thermal conductivity, absorbent fabrics.

Povzetek: V članku so predstavljeni rezultati meritev vpliva vlage na toplotno prevodnost vpojnih tkanin. Meritve potrjujejo, da se efektivna toplotna prevodnost tkanin z večanjem deleža vode sprva linearno povečuje. Pri večjih relativnih deležih vode v tkanini, meritve kažejo, da se efektivna toplotna prevodnost tkanin ustali okrog vrednosti primerljivi s toplotno prevodnostjo vode. Rezultati meritev primerjamo s teoretično napovedjo po linearnem modelu.

Ključne besede: toplota, toplotno prevajanje, toplotna prevodnost, vpojne tkanine.

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1. Introduction

Constant body temperature with variations not more than ± 0,2 °C is of great importance for normal activity of physiological functions in the human body [1]. The heat transfer between human body and environment takes place by conduction, radiation, evaporation of sweat and breathing. Usually, human body is covered with at least one layer of clothing. Physical properties of clothing, especially thermal properties such as thermal conductivity, specific heat, moisture and air permeability, have high impact on the heat transfer through clothing and thus they are of great interest for textile researchers. The thermal conductivity of fabric is the result of a combination of the thermal conductivities of textile fibers and of entrapped air. Absorbent fabrics absorb moisture from the environment until they are saturated [1]. The presence of water in the fabric affects its thermal properties. With increasing the relative amount of water in the fabric, air trapped between the textile fibers is squeezed out. The thermal conductivity of air is much smaller than the thermal conductivity of water and textile fabrics. Therefore, air in the fabric acts like good thermal insulator. By decreasing the amount of air, effective thermal conductivity of fabric is increasing. In the literature [2-5] many papers have studied the impact of water on thermal properties of clothing, but only few have done experimental measurements of thermal properties of moisture fabric, especially at higher relative amount of water. Measurement devices proposed for measuring thermal conductivity of fabrics are Alambeta and Permatest [2], Thermolabo [6], TheCotex [7]. Preliminary measurements have shown that the thermal conductivity of fabrics increases as relative amount of absorbed water is increased. Until now, results of the effective thermal conductivity of fabrics were not obtained for the regime, when the thermal conductivity is no longer linearly dependent on the relative amount of absorbed water.

This article presents a model of effective physical quantities, which are used to determine the thermal conductivity of wet fabrics. We focus on the measurement of thermal conductivity of cotton fabrics for increasing relative amounts of water. Experimental work is carried out with a measuring device made for measuring the thermal conductivity of solid materials [8], which we adjusted to optimize the measurement of the thermal conductivity of wet fabrics. We conclude with the comparison of experimental results and estimations of the theoretical model.

2. Heat Conduction

Heat conduction is direct transfer of heat due to the temperature gradient ∇T. Fourier law defines heat flux P through the surface S as:

$$P = -\lambda S \nabla T \quad , \tag{1}$$

where λ is the thermal conductivity of material. Thermal conductivity describes how well the material conducts the heat and determines the impact of clothing on physiological comfort. For one-dimensional heat conduction through the material of thickness d, the heat flux is conventionally expressed as:

$$P = -S\lambda \frac{\Delta T}{d} \quad , \tag{2}$$

where ΔT is temperature difference on the opposite surfaces of the material.

Several experimental studies [2,3] show that the presence of water in fabrics increases thermal conductivity and specific heat of the fabric and affects the density and fabric's thickness. There are two main factors for an increase of thermal conductivity of wet fabric: increased amount of water and decreased amount of air in the fabric. Presence of water with relatively high thermal conductivity (0,6 W/mK), which is an order of magnitude higher than the thermal conductivity of dry fabric, also reduces amounts of air that acts like good thermal insulator.

We theoretically determine the thermal conductivity of wet fabrics using the linear model with the assumption that fabric is moistened evenly throughout the volume. The relative amount of water r is given with the ratio between mass of absorbed water m_w and the mass of dry fabric m_f [9]:

$$r = \frac{m_w}{m_f} \quad . \tag{3}$$

When the fabric is dry the effective thermal conductivity λ_e is equal to the thermal conductivity of fabric (λ_f) itself. With increasing the relative amount of water effective thermal conductivity linearly increases towards the thermal conductivity of water (λ_w). Above the critical value of relative amount of water r_c the fabric is saturated and its effective thermal conductivity stabilizes:

$$\lambda_e = \lambda_f + r \frac{\lambda_w - \lambda_f}{r_c} \quad . \tag{4}$$

3. Experimental measurements of thermal conductivity

The measurement protocol for measuring the thermal properties of materials is defined in the European Standard UNI EN 31092 [10] and it is based on the use of the measuring device called “Skin model” [11]. Known techniques have a common disadvantage of measuring the surface temperature in a single point and then assuming uniform temperature distribution over the surface. This drawback is improved with device Thecotex [7], where the surface temperature is measured with Infrared thermo-camera [12].

3.1 Measuring device

Experimental measurements of the thermal conductivity of wet fabrics are performed by contact measuring device [8]. The measuring device consists of a cooler, through which we provide constant water flow, and an electric heater connected to a source of power supply. The entire measuring device is thermally insulated with Polyurethane foam and Styrofoam (Fig 1). We insert the fabric sample between the cooler and the heater. The sample should be square shaped with dimension 100 mm and thickness ranging from 5 mm to 10 mm. Because the thickness of the fabric is much thinner, we use multi layers of fabrics.

During the measurement, we monitor the time variation of the temperature with four surface temperature sensors Vernier that are connected via interface Vernier LabPro with computer software Logger Pro 3. Sensors provide information of temperature at two points on each surface of fabric sample. Because the fabric sample is compressed during the measurement of thermal conductivity, the thickness of the sample is measured under approximately the same conditions at several points with caliper accurate to ± 0,02 mm.

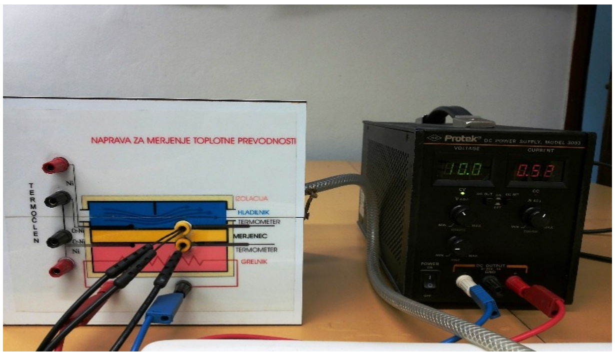

Figure 1. The measuring device for measuring the thermal conductivity of fabric. The heater is connected with constant power supply and through the cooler constant water flow is provided. The temperature is measured with four surface temperature sensors Vernier.

In this paper, we present experimental results of effective thermal conductivity for three samples from 100 % cotton with the same weaving pattern. Samples have a slightly different thickness and density (table 1).

Table 1. Thickness and estimation of density for three samples of cotton fabric labeled C1, C2, C3.

sample	thickness *d*	density
C1	0,6 mm	298 kg/m^3
C2	0,7 mm	299 kg/m^3
C3	0,9 mm	252 kg/m^3

3.2 Measurements

Before we start measuring the thermal conductivity of fabric samples, we have to provide a constant flow of water through the cooler and constant temperature of water. First, we consider only dry fabrics. We measure the mass (m_f) and thickness (d) of dry fabrics and count the number of layers. When we insert the sample, we connect the heater with power supply and monitor the electric power of heater by measuring electric voltage and electric current. After a while, system reaches steady state, where the temperature difference is constant with time.

For studying the impact of water on thermal conductivity of fabric, we moisten the sample with water vapor. Before every measurement, we have to measure the thickness and the mass of wet fabric sample. Measurement time is relatively long and water absorbed in the fabric can evaporate. Thus, we also measure the mass of wet sample after and calculate the mean value of water absorbed in the fabric.

4. Results and Analysis

4.1 Thermal conductivity of cotton fabrics at different relative amounts of water

We have confirmed that the effective thermal conductivity of fabrics increases by increasing the amount of water. A comparison of the thermal conductivity of the fabric samples C1, C2 and C3 is shown in Figure 2. As expected linear trend of thermal conductivity at smaller relative amounts of water is observed for all three samples. The measurements also show that the effective thermal conductivity of all three samples stabilizes around the same value.

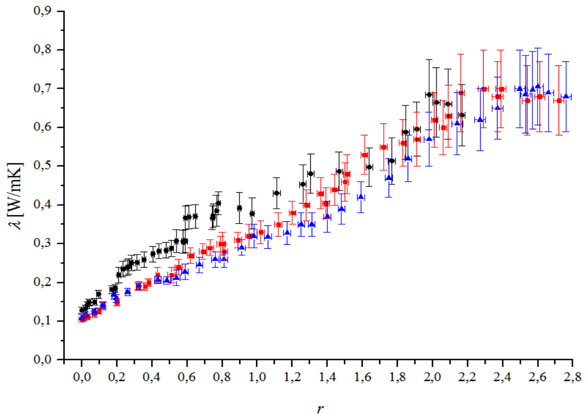

Figure 2. Thermal conductivity dependence of three fabric samples C1 (red squares), C2 (black circles) and C3 (blue triangles). Initially the thermal conductivity linearly increases with relative amounts of water and then stabilize at higher *r*.

4.2 Analysis

The effective thermal conductivity of fabrics at small relative amounts of water shows approximately linear dependence. Our measurements expand the range of current results in the literature. The relative amount of water is gradually increased up to r = 2,8, as the samples are saturated. Our experimental results at higher relative amounts of water in the fabric show that effective thermal conductivity for all three samples stabilizes at approximately same value $r = 2{,}4$. The effective thermal conductivity at this value and higher is ranged between 0,65 W/mK and 0,70 W/mK, which is comparable with the thermal conductivity of water itself. As expected, samples with same weaving pattern and from same textile fibers share the same characteristic.

4.3 Comparison of experimental results with theoretical model

The effective thermal conductivity of wet fabric is calculated by the equation (4) for different relative amounts of water. Figure 3 shows the comparison of the experimental result of effective thermal conductivity of fabrics with the theoretical estimation.

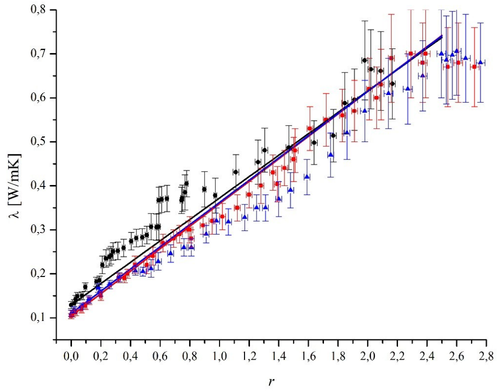

Figure 3. Experimental results of measurements of effective thermal conductivity of wet fabric samples compared with theoretical estimation represented by red curve for C1, black curve for C2 and blue curve for C3.

The theoretical model fits well with the experimental results, especially at lower relative amounts of water in the fabric. This is also the range in which previous measurements of effective thermal conductivity were made. The matching between the theoretical model estimation and actual experimental results at higher relative amounts of water is smaller.

5. Conclusion

Experimental results have confirmed previous measurements and theoretical forecast that absorbed water increases the effective thermal conductivity of fabrics. For small relative amounts of water in the fabric, effective thermal conductivity shows linear dependence.

Measurements were performed also for higher relative amounts of water absorbed in fabric up to saturation. Close to the saturation point, the mass of water absorbed in the fabric is up to three times higher than the mass of the dry fabric. At higher relative amounts of water, effective thermal conductivity is asymptotically approaching thermal conductivity of water itself.

Comparison between experimental and theoretical results of effective thermal conductivity for relative amounts of water under $r < 0{,}8$ shows a good match. At higher relative amounts of water absorbed in fabric, there are some deviations between experimental and theoretical results, especially near the saturation. Further research should focus on upgrading the theoretical model, where the impact of air should be taken into account.

Experimental results have wide applicative value in the design of special textile materials for clothing intended for use at higher physical activity, in particular in situations where people are exposed to rapid temperature changes. At higher temperature, human body dissipates heat by sweating, sweat is absorbed by fabric and therefore thermal conductivity increases. When the temperature suddenly lowers, wet clothing no longer provides sufficient thermal insulation.

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