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Estimation of the Overall Heat-transfer Coefficient Through a Textile Layer

Abstract
The article justifies the use of calculative determination of the heat transfer coefficient k, on the basis of immutable parameters of the textile layer such as thermal conductivity and thickness. A method of elaborating the heat transfer coefficient is described, and examples of calculations are presented for randomly selected samples of clothing woven fabrics. It was proved possible to make a calculative estimation of the influence of changes on the parameters of the textile layer, as well as the conditions of use on the value of the heat transfer coefficient. No estimation of the woven fabrics tested from the point of view of their properties was carried out. A brief description of a device for measuring the thermal conductivity coefficient and the heat transfer coefficient of flat textile products is presented.

Key words: *heat transfer, heat absorption, warmth retention, heat insulating, thermal conductivity, textile layer.*

Introduction

The warmth retention of flat textile products is not an unambiguous term. The estimation of the warmth retention has been carried out in general on the basis of measurements of various parameters such as the heat transfer coefficient, the thermal resistance, and the thermal conductivity coefficient [1 – 13]. Numerous measurement devices are used for measuring these parameters. They are based on heat exchange in stationary or transient states [1, 3, 6, 11]. The disadvantage of the majority of these devices is their relatively long measurement period. Comparing the heat-insulating ability of textile products on the basis of the heat conductivity coefficient, which of necessity is determined with the use of samples of various thicknesses, may lead to erroneous conclusions. For this reason it is better to estimate the warmth retention features of textile products by measuring the heat transfer coefficient, or the thermal resistance. The heat transfer coefficient k, which is used to estimate the warmth retention of the textile layer, is not an inherent feature of this layer, but depends on the conditions of receiving and transmitting heat. Therefore, in some cases it is more advantageous to obtain the heat transfer coefficient k by calculation. The influence of heat transmission may also be considered in this case.

The aim of this elaboration is to prove that it is possible (for some applications) to replace the measurements of the heat transfer coefficients by calculation.

The behaviour of a textile product, acting as a thermal insulator, depends on its position in relation to the human body which it covers, and which acts as the source of heat. Below, we will consider thermal calculations of the simplest case, when the textile product fits exactly onto the protected surface of the human body. In this case, in order to simplify the calculations, the thermal resistance of transmitting heat from the body to the textile layer may be omitted. The process of heat transfer from the body through the textile layer to the environment may be presented as in Figure 1, where:

q – the density of the heat stream transferred through the sample, W/m^2;
t_0 – the environmental temperature, °C;
t_1 – the temperature of the body's surface, °C;
t_2 – the temperature of the sample's surface directed to the environment, °C;
d – sample thickness, m.

The heat transfer coefficient is determined as follows:

$$k = \frac{q}{t_1 - t_0}, \frac{W}{°C} \qquad (1)$$

For a single-layer sample under heat transfer conditions as shown in Figure 1, we can determine k as below:

$$k = \frac{1}{\frac{d}{\lambda} + \frac{\lambda}{\alpha}} \qquad (2)$$

where:

λ - the thermal conductivity coefficient of the layer, W/m °C.
α - the heat transmitting coefficient to the environment (considering convection and radiation), W/m^2 °C.

The heat transfer coefficient $k = f(d, \lambda, \alpha)$ is not a constant feature of the textile layer, but depends on the conditions of the fabric's use, which influences the thermal conductivity λ, and the heat transmitting coefficient α. Even if we assume that the temperature of the textile layer and the air humidity (for small changes in these quantities) only slightly influence the thermal conductivity λ, there remains the very strong influence of the conditions of heat transmission to the environment on the value of the heat transmitting coefficient α.

In order to compare the warmth retention of the textile layer according to the heat transfer coefficient k calculated from Equation (1), it is necessary to determine it under equal conditions of heat exchange. Therefore it is more suitable for certain applications to obtain the heat transfer coefficient by calculation.

In Poland, in order to determine the density of the energy stream transferred through the textile layer, Polish Standard PN-86/P-04617 is applied [11]. The measurements should be conducted with the use of a cylindrical device of accepted shape, with samples of preset dimensions, and under conditions of preset temperatures for the heat source and the environment, as well as air blowing velocity and humidity. The standard does

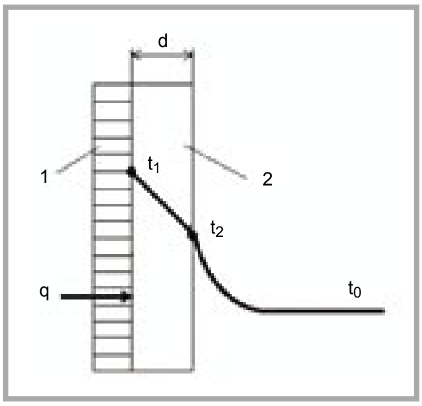

Figure 1. *Heat transfer through a flat textile sample to the environment; 1- heated plate (the human body's skin); 2 – sample.*

not prescribe the temperature of the walls surrounding the device or their distance from it, factors which influence the heat stream transmitted by radiation. The thermal resistance is determined by the ISO [2] standard. A critical estimation of this method was presented by Korliński [3].

Method of calculating the heat transfer coefficient k

The value of the heat transfer coefficient *k* can be obtained by calculation. The density of the heat stream, which is transmitted outwards to the environment at stationary state, equals:

$$q = q_k + q_r \quad (3)$$

where:

q_k – the density of the heat stream transmitted by convection,

q_r – the density of the heat stream transmitted by radiation.

The density of the heat stream q_k is determined by the Newtonian equation:

$$q_k = \alpha_k(t_2 - t_1) \quad (4)$$

where α_k is the coefficient of heat transmission by convection.

According to the theory of similarity used in thermodynamics, it is possible by considering particular conditions of shape, dimensions, temperature range, and type of airflow at the proximity of the wall, to calculate the value of the heat transmission coefficient α_k. Using the Michieyev procedure cited by Staniszewski [12], we can obtain the following dependency for a vertical plate, under conditions of natural convection:

$$Nu = C\,(Gr\,Pr)^n$$

where:

Nu – the Nusselt number,

Pr – the Prandtl number,

Gr – the Grashof number (free convection number),

C, n – constants dependent on the value product of $Gr\,Pr$.

The values of the similarity numbers (criteria of similarity) were calculated for parameters determined at temperatures t_2 and t_0, the sample dimensions, and the conditions of free convection. The value of α_k was calculated from the Nusselt number:

$$Nu = \alpha_k\, l / \lambda_0$$

where:

l – the sample length in direction of the air flow (l is the vertical dimension of the sample for a sample placed as shown in Figure 3, and under conditions of free convection),

λ_0 – the thermal conductivity of air.

The density of the stream q_r is determined by the Stefan-Boltzman equation, in the following form:

$$q_r = \varepsilon\, C_0 \left[\left(\frac{273+t_2}{100}\right)^4 - \left(\frac{273+t_0}{100}\right)^4\right] \quad (5)$$

where:

C_0 – the technical radiation constant of the black body (perfect radiator), $C_0 = 5.67\ \mathrm{W/m^2K^4}$.

ε – the emissivity of the outer surface of clothing; the value of $\varepsilon = 0.9$ according to Michalski [16] was taken for calculations.

Based on the principle of heat stream continuity, the heat stream $q = k(t_1 - t_0)$ calculated from Equation (1) is transmitted to the environment with a density equal to the density of the stream conducted through the sample:

$$q = (t_1 - t_2)/\mathrm{d} \quad (6)$$

The system of Equations (3), (4), (5), and (6) allows us to determine the density of the stream q and the temperature t_2. From Equation (1) we calculate the heat transfer coefficient k.

Measurement methods

The heat transfer coefficient was also measured using the Tilmet 75 thermal conductivity meter. This device was designed and built at the Department for Automation of Textile Processes of the Technical University of Łódź, and its function is to measure the thermal conductivity coefficient of flat textile products. Using one of its parts, it is also possible to measure the heat transfer coefficient *k*.

Tilmet 75 as a device for measuring the thermal conductivity coefficient λ

Tilmet 75 is a device of a relatively small time constant, in the range of some minutes, to test samples with dimensions of 100 mm × 200 mm and a thickness greater than 0.57 mm. The temperature of the heated plate equals 37 °C, whereas the 'cold' plate is cooled with tap water. The heat stream and the surface temperature of the product tested are measured electrically. The device is a thermal conductivity meter of the Poensgen type [13]. While designing this device, the designers also considered the idea of Haase [1], and the Japanese Thermo Labo device, which is a part of the KESFB-Auto-A system [14].

The design principle is presented in Figure 2. The power of the electric heater and the temperature on both sides of the sample tested are measured under stationary conditions. The thermal conductivity coefficient is calculated from the following dependency:

$$\lambda = q / (t_1 - t_2)$$

As the result of the analysis [6] carried out on the basis of Spearman's rank correlation coefficient, it could be stated that a correlation exists between the values of the measurement results obtained with the use of the Tilmet 75 device, and those obtained with the Tecosy device, made in Hungary. An analysis of the uncertainty of the results obtained by the Tilmet 75 device is presented in the work of Kucharska-Kot & Kuśmierek [15].

Tilmet 75 as a device for measuring the heat transfer coefficient k

Only the specially fixed heated plate is used to measure the heat transfer coeff-icient *k*. The heat stream and the temperature of the heated plate are measured, which allows the coefficient *k* at a known temperature of the environment to be calculated. The plan of the stand is presented in Figure 3. In order to compare the calculative method with those based on measurements, we ad-

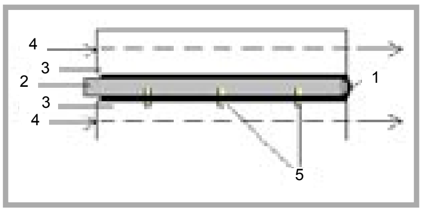

__Figure 2.__ A simplified scheme of the stand for measuring the heat transfer coefficient; 1 – sample tested, 2 – heated plate, 3 – 'cold' plate, 4 – cooling water, 5 – temperature sensors.

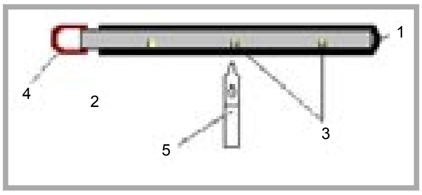

__Figure 3.__ Simplified plan of the stand for measuring the heat transfer coefficient – upper view; 1 – sample tested, 2 – heated plate, 3 – temperature sensors, 4 – stand holder, 5 – pyrometer.

Table 1. *Parameters of the woven fabrics tested.*

Wowen fibric denotation	Weawe	Thickness, mm	Apparent density, kg/m^3	Densiy of warp, dm^{-1}	Density of weft, dm^{-1}
1	twill	0.95	184	60	50
2	plain	1.57	260	129	126
3	plain	2,12	165	148	144

ditionally measured the surface temperature t_2 of the sample with a radiation pyrometer [16 - 18]. It should be stressed that in all the measurements we carried out, the woven fabric's density was sufficiently high (with a cover factor of practically 100%), and the danger of additional influence from the ground temperature was eliminated. Thus, the temperature t_2 was determined in two ways, by calculation and by measurement. In the thermal stationary state of the stand, the heat stream q was determined as in the case of thermal conductivity measurements, and next the heat transfer coefficient k was calculated from dependency (1). In our tests, the heat stream density was determined under the condition of natural convection, which is different than that prescribed in standard PN-86/P-04617, according to which the measurement is conducted under conditions of forced convection.

Results of calculations and measurements

Three randomly selected woollen woven fabrics were selected for analysing the proposed method of estimating the heat transfer coefficient *k*. Their properties are listed in Table 1, whereas the results of measurements and calculations are given in Table 2.

The authors' approach to the topic considered should be additionally emphasised at this point. We did not want to verify the measurement results by calculation, or vice versa. The calculations, which are based on dependencies resulting from the similarity theory and dimension analysis, are based on experiments with the use of models, which also means that they are based on measurements. The authors only wish to demonstrate the coincidence of measurement results and the results of the calculative method of estimating one of the heat insulating properties, i.e. the heat transfer coefficient, which in turn may have considerable importance in usage.

Measuring instruments and apparatus used; accuracy of measurements and calculations

A radiation pyrometer with accuracy of ± 1 °C was used for measuring the outer surface temperature t_2 of the sample.

A laboratory liquid thermometer with 0.1 °C elementary division was used for measuring the environmental temperature t_0.

A thickness meter produced by Shoper with a readout error of 0.01 mm was used for measuring the woven fabrics thickness *d*.

The area of the heated plate was measured with a graduated rule to an accuracy of ± 1 mm.

The electrical power was measured to an accuracy of 0.1 W.

The thermal conductivity λ and the heat transfer coefficient *k* were determined on the basis of measurements made with the Tilmet 75 device. An estimation of the accuracy of this instrument was carried out by Kot & Drużbiak [6]. As an example, it may be stated that for the woven fabric sample number 2 in Table 2, the expanded standard uncertainty *U* of the measurement, at a significance level of 0.05, equals $U = 0.0017$ W/m °C.

Five measurements were carried out for each woven fabric, and average values were calculated. The measurements were conducted at relative air humidity of 40 - 50%. The heat transfer coefficient was calculated. Additional, to demonstrate the influence of the heat transmitting conditions on the heat transmitting coefficient, the thermal resistance of conduction $R_\lambda = d/\lambda$ and the thermal resistance of heat transmitting $R_\alpha = 1/\alpha$ were calculated.

The calculative method of estimating the heat transfer coefficient yields results similar to the values measured. The differences in values of the coefficients calculated and those obtained by measurements fell within the range of 0.8% to 5% of the values obtained by measurements. The accuracy of the calculation method is additionally proved by the convergence of those values of the outer surface temperature which were calculated and measured by a pyrometer. The discrepancy of the results calculated and measured was within the range of 1.9% to 6.2% of the differences between the surface and the environmental temperature.

The heat transfer coefficient *k* only allows the determination of the warmth retention of the given textile layer in comparison with another layer considered, in other words, for arrange heat of the layers compared according to their warmth retention..

Considering the value heat transfer coefficient of a thin textile layer, the thermal resistance of heat transmission R_α has a dominant influence (the environmental temperature, the air movement), which the resistance of heat conduction R_λ (the heat conductivity of the layer) does not have. In the cases which we tested, for thicknesses from 0.95 to 2.12 mm this influence was over three times greater (look for R_α/R_λ in Table 2). The thermal resist-

Table 2. *Average values of the calculation and measurement results; d – sample thickness, λ -heat transmitting coefficient of the layer,* t_1 *– body surface temperature,* t_0 *– environment temperature,* t_{2p} *– sample surface temperature measured by pyrometer,* t_{2cal} *– sample surface temperature calculated,* q_{meas} *- heat stream density measured,* q_{cal} *- heat stream density calculated,* k_{meas} *– heat transfer coefficient measured,* k_{cal} *- heat transfer coefficient measured,* R_λ *- thermal resistance of heat conduction,* R_α *- thermal resistance of heat convection.*

Woven. Fabrik denotation	Quantities measured							Quantities calculated					
	d	λ	t_1	t_o	t_{2p}	q_{pom}	k_{pom}	t_{2obl}	k_{obl}	q_{obl}	$\Delta k=k_{pom}-k_{obl}$	$\Delta k\%=\Delta k/k_{pom}\cdot 100\%$	R_α/R_λ
	mm	W/m ^{o}C	^{o}C	^{o}C	^{o}C	W/m^2	W/m^2 ^{o}C	^{o}C	W/m^2 ^{o}C	W/m^2	W/m^2 ^{o}C	%	-
1	0,95	0,0446	37,0	27,5	34,9	73,30	7,71	35,0	7,78	74,0	-0,065	-0,84	4,03
2	1,57	0,0436	37,0	27,5	34,7	65,38	6,88	34,5	7,21	68,5	-o,33	-4,79	6,33
3	2,12	0,0470	37,0	27,5	34,5	62,72	6,60	34,1	6,78	64,5	-0,178	-2,62	3,35

ance of heat conduction is proportional to the layer thickness. If the thickness layer increases, the drop in temperature on the clothing's surface also increases. For thick clothing fabrics (over 6 mm, in the case considered), or under conditions of more intensive cooling, the relation of R_α/R_λ may invert.

The estimated value of the coefficient k may be obtained by the calculation method. In order to obtain this value, it is enough to know the immutable product's (the fabric's) features: the thickness d and the thermal conductivity λ, as well as the product's conditions of usage such as body temperature I_1, environmental temperature t_0, and the air velocity v. By the calculation method, it is easy to estimate the sensitivity of the function:

$$K = f(\lambda, d, t_1, t_0, v)$$

on the change of the function parameters. Three examples are presented below:

- The influence of fabric thickness on the value of the heat transfer coefficient for woollen woven fabrics of thickness d = 1.57 mm and d = 2.13 mm, under conditions of natural convection, and at a temperature of 20 °C, equals:
  $\partial k/\partial d = -0.74\ (\mathrm{Wm^{-2}\ °C}) / \mathrm{mm}$
- The influence of a change in temperature from t_0 = 20 °C to t_0 = 27.5 °C, under conditions of natural convection for a woollen woven fabric of thickness d = 1.57, equals:
  $\partial k/\partial t_0 = 0.0186\ (\mathrm{Wm^{-2}\ °C}) / °\mathrm{C}$
- The influence of a change from natural to forced convection at a temperature of 20 °C, for a woollen woven fabric of thickness d = 1.57, equals:
  $\partial k/\partial v = 2.28\ (\mathrm{Wm^{-2}\ °C}) / \mathrm{m\ s^{-1}}$.

Conclusions

The heat transfer coefficient k is useful for clothing fabric producers to arrange the fabrics according to their warmth retention.

For clothing designers and producers, it is enough to know the estimated value of the heat transfer coefficient obtained by calculation on the basis of immutable textile parameters, namely the product's thickness and its thermal conductivity, without the need to carry out measurements. The calculation method of estimating the heat transfer coefficient does not require repeatable measurement conditions. The proposed method is simpler and easier to realise, compared with the measuring method, and is useful in some applications.

The calculation method of the heat transfer coefficient may be also used for clothing packets, which consists of layers, and to those which have a cylindrical shape.

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