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# Relation Between Basic Structural Parameters of Knitted Fur Fabrics and Their Heat Transmission Resistance

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**Abstract**
*The necessity to research and describe the heat exchange in knitted fur fabrics is presented herein together with the results of experimental research on random selected samples are. Correlations between the basic textile construction parameters (thickness, surface mass) and resistances of heat conduction, heat transmission and heat transfer were determined. The function dependences between relative resistances in relation to the surface mass of the knitted fur fabrics were defined. Analysis of the results can be implemented into the structure optimisation of the knitted fur fabric with regard to its heat insulation.*

**Key words:** *knitted fur fabrics, heat conduction, heat resistances, heat insulation.*

## Introduction

Basic protection against weather conditions are clothes, including fur. The aesthetic and practical advantages of animal fur are the reasons why this material has always been in wide use in spite of the progress in the textile industry. Due to environmental premises, textiles imitating natural fur – so-called knitted fur fabrics - have been introduced into production. The main aim of the production of such textiles is give them all the properties of natural fur – the so-called "naturalisation" of knitted fur fabrics [1, 2]. The quality features of natural and knitted furs were presented by Korliński [2]. Knitted fur fabrics are produced either as row or as column knitted. The production related issues regarding these were presented in [3, 4].

The basic parameter of the practical value of fur textile is its heat insulation. There are many works describing the connection between heat insulation and structure, as well as technological parameters such as porosity, surface mass, thickness, humidity, the heat conduction of fibers, and the finishing and conservation processes (the influence of multiple washing) of the textile [5 - 11]. There are many methods to measure the selection of parameters which describe the heat insulation of textiles, e.g., heat transfer density, the heat conduction coefficient, the heat transmission coefficient or heat resistance [5, 12, 13].

Measurement devices based on various principles, using the effect of heat exchange, both in a steady and transient state are used for measurements. Going through the available literature in this topic allows to state that the best device is one based on heat exchange in a steady state, while using a sample of small size [14 - 16].

The aim of this work is to find the dependency between the structure describing parameters and the heat insulation of knitted fur fabrics. Querying the literature proved that there is neither a way of identification of such a dependency, nor any practical methods to calculate it. Furthermore, it can be concluded that there are no solutions whatsoever concerning heat insulation related problems within this kind of fabric.

## Research methods

The subjects of this research were 11 types of weft-knitted, single level fur fabrics, made of the same material, differentiated by thickness range $d = (4.05 – 18.60)\cdot 10^{-3}$ m and surface mass range $G = (199.7 – 708.5)\cdot 10^{-3}$ kg/m$^2$.

The heat conduction and transmission coefficients had to be determined in a steady state in order to calculate the heat insulation of the samples. A precise description of the methods applied were presented by Ziegler and Kucharska-Kot [17].

### Determining the heat conduction coefficient

Heat conduction measurements were carried out on a Tilmet 75 device, which was constructed at the Department for Automation of Textile Processes of the Technical University of Łódź. The principles of this device are analogous to Haase's two-board device and Kawabata's THERMO LABO II [17], ***Figure 1***. Additionally, some distancing pieces were used in order to increase the distance between the boards up to the value which results from the textile thickness under a pressure of N = 1 cN/cm$^2$ = 10$^2$ Pa. To our knowledge, the thickness measurement of knitted fur fabrics is not regulated by any standard. That is why standard thickness gauges measure the thickness of knitted fur fabric under various, much higher values of pressure (in the range of at least several cN/cm$^2$ = 10$^2$ Pa). Hence, in this research a minimum pressure value of 1 cN/cm$^2$ = 10$^2$ Pa was applied, and the thickness was measured on a H50K-S testing machine, see e.g. Patyk, Korliński [18 - 20]. Consequently, the same pressure values were applied during the heat conduction measurements on the TILMET device.

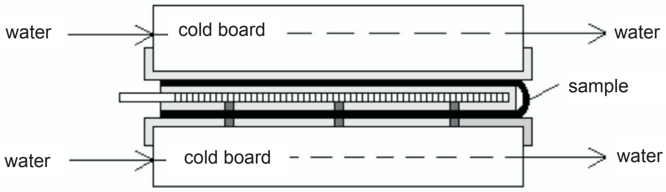

***Figure 1**. Stand scheme for the measurement of the heat conduction coefficient [16]; ▢ - knitted fur fabrics with temperature sensors, ▥ - heating board, ■ - temperature sensors.*

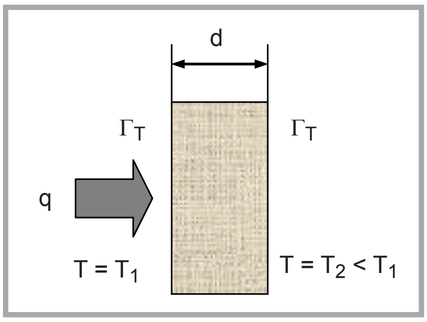

**Figure 2.** *Heat conduction through the flat wall.*

In order to model the steady heat conduction, knitted fur fabrics of complex structure (plait layer, pile layer) were homogenised to obtain a homogenous material. The following assumptions were made in the process:

- The textiles have a constant thickness d, calculated as an arithmetic mean value of the sample thickness measurements, much smaller than the other directional dimensions $(120 \times 300) \cdot 10^{-3}$ m.
- For each of the examined knitted fabrics, a constant heat conduction coefficient $\lambda$ is assumed, which means the material is considered to be isotropic.
- Constant temperatures are maintained on the outer surfaces of the textiles. The surface temperature of the sample on the side next to the heating board (pile side) is $t_1 = 32$ °C, which is higher than the surface temperature on the cold board side (fur side) $t_2$, this being: $t_1 > t_2$.
- The isothermal surfaces are parallel to the sample surface.

The assumed homogenous model of the knitted fur fabric assures that all the measured values and resulting relations apply to the whole knitted fabric, not just to its singular layers, and that they are equivalent values. The heat conduction is presented schematically in ***Figure 2***.

According to [17, 21], the phenomenon of conduction, measured on a Tilmet 75 heat conductometer, is described by the heat conduction coefficient in such an equation:

$$\lambda = \frac{qd}{\Delta t} = \frac{U^2 d}{2 \cdot F \cdot R \cdot \Delta t}, \quad \frac{W}{m\,°C} \qquad (1)$$

where λ is the heat conduction coefficient in W/(m$^2$·°C), $q$ is the heat transfer density going through the sample in W/m$^2$, $U$ is the voltage of the heater power supply in V, $d$ is the thickness of the sample in m, $F$ denotes the measurement surface on one side of the heater assumed to be $F = 0.1 \cdot 0.1$ in m$^2$, $R$ is the wire resistance, assumed to be $R$ = 884 in Ω, and $\Delta t$ the temperature difference between the two sides of the sample, $\Delta t = t_1 - t_2$ in °C.

The effects of heat convection and heat radiation play little role in the given example. That is why the heat resistance during conduction can be determined according to [21] in the following way:

$$R_\lambda = \frac{d}{\lambda}, \quad \frac{m^2\,°C}{W} \qquad (2)$$

where $R_\lambda$ is the sample heat resistance during conduction.

For each type of knitted fur fabrics, 5 measurements were carried out. The mean values of the results are presented in ***Table 1***. Additionally, the average surface mass $G$ of the samples was determined.

The results obtained are presented in ***Figures 3 – 6***. According to the literature [6, 22], the dependency between the heat conduction coefficient and the sample thickness with its surface mass can be interpolated by a linear function, see ***Figure 3*** and ***Figure 5***. By analogy, the relations for heat resistance are best interpolated by a second-order function, see ***Figure 4*** and ***Figure 6***.

## Determining the heat transmission coefficient

Research on the heat transmission coefficient $k^p$ was carried out on a measuring position, partly composed of the elements of the Tilmet 75 device. The measuring position is presented schematically in ***Figure 7*** (see page 86).

A radiation pyrometer with an accuracy of ±1 ºC was used for the measurement of

***Table 1.*** *Mean values of heat conduction and heat resistance during the conduction.*

| Samples description | $d \cdot 10^3$, m | $G \cdot 10^3$, kg/m$^2$ | λ, W/(m·°C) | $R_\lambda$, (m$^2$·°C)/W |
|---|---|---|---|---|
| A | 4.05 | 199.7 | 0.06 | 0.07 |
| B | 5.48 | 224.3 | 0.07 | 0.08 |
| C | 7.13 | 355.2 | 0.06 | 0.12 |
| D | 8.54 | 425.6 | 0.08 | 0.11 |
| E | 9.56 | 374.7 | 0.08 | 0.12 |
| F | 10.92 | 526.9 | 0.07 | 0.16 |
| G | 12.76 | 545.3 | 0.08 | 0.16 |
| H | 14.15 | 633.6 | 0.08 | 0.18 |
| I | 16.02 | 705.1 | 0.08 | 0.15 |
| J | 17.16 | 708.5 | 0.09 | 0.20 |
| K | 18.60 | 703.2 | 0.09 | 0.21 |

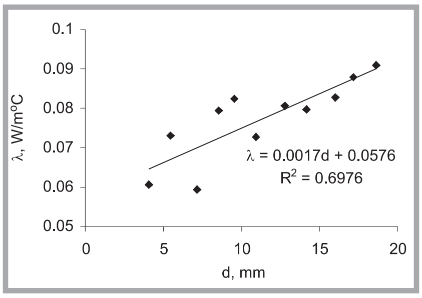

**Figure 3.** *Dependence diagram λ = f(d).*

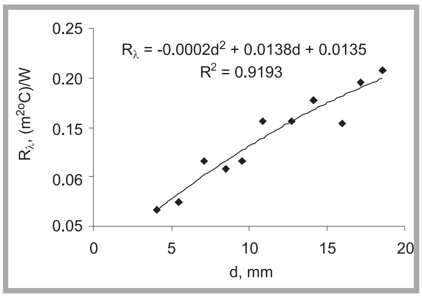

**Figure 4.** *Dependence diagram $R_\lambda = f(d)$.*

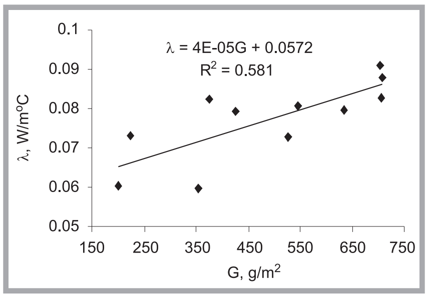

**Figure 5.** *Dependence diagram λ = f(G).*

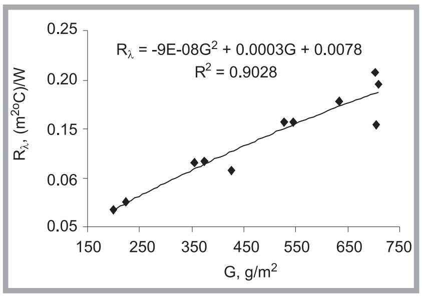

**Figure 6.** *Dependence diagram $R_\lambda = f(G)$.*

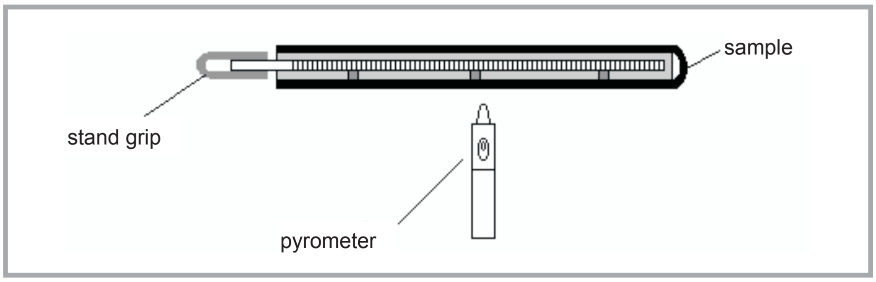

***Figure 7.** Stand scheme for the measurement of the heat transmission coefficient (overview); ▒ - knitted fur fabrics with temperature sensors, ▥ - heating board, ■ - temperature sensors.*

***Table 2.** Specification of mean values of heat transmission coefficients k and $k^p$. heat transfer coefficients α and heat resistances during the heat transmission $R_k$ and $R_k^p$ for different knitted fur fabrics.*

| Tested knitted fabric | $d \cdot 10^3$. m | $G \cdot 10^3$. kg/m$^2$ | k. W/(m$^2$·°C) | $k^p$. W/(m$^2$·°C) | α. W/(m$^2$·°C) | $R_\alpha$. (m$^2$·°C)/W | $R_k$. (m$^2$·°C)/W | $R_k^p$. (m$^2$·°C)/W |
|---|---|---|---|---|---|---|---|---|
| A | 4.05 | 199.7 | 5.31 | 5.89 | 9.72 | 0.10 | 0.19 | 0.17 |
| B | 5.48 | 224.3 | 3.51 | 4.55 | 6.90 | 0.10 | 0.29 | 0.22 |
| C | 7.13 | 355.2 | 4.05 | 4.30 | 8.86 | 0.11 | 0.28 | 0.23 |
| D | 8.54 | 425.6 | 3.54 | 4.02 | 7.08 | 0.14 | 0.28 | 0.25 |
| E | 9.56 | 374.7 | 3.58 | 4.72 | 10.46 | 0.10 | 0.28 | 0.21 |
| F | 10.92 | 526.9 | 3.22 | 4.20 | 11.33 | 0.09 | 0.32 | 0.24 |
| G | 12.76 | 545.3 | 3.50 | 4.62 | 17.12 | 0.06 | 0.29 | 0.22 |
| H | 14.15 | 633.6 | 3.49 | 4.42 | 20.42 | 0.05 | 0.29 | 0.23 |
| I | 16.02 | 705.1 | 2.68 | 2.96 | 6.91 | 0.14 | 0.38 | 0.34 |
| J | 17.16 | 708.5 | 2.59 | 2.89 | 6.63 | 0.15 | 0.39 | 0.35 |
| K | 18.60 | 703.2 | 3.33 | 3.84 | 17.76 | 0.06 | 0.30 | 0.27 |

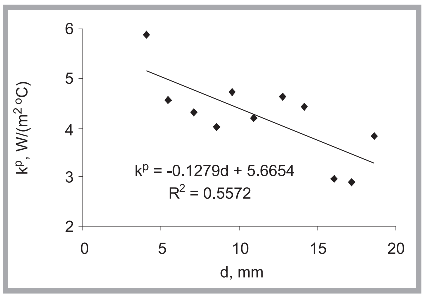

***Figure 9.** Dependence diagram $k^p$ = f(d).*

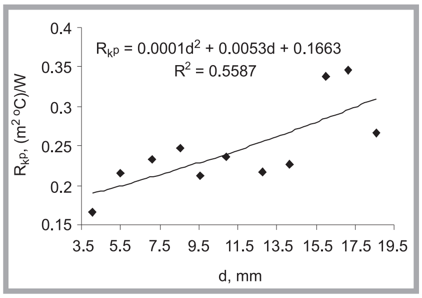

***Figure 10.** Dependence diagram $R_{kp}$ = f(d).*

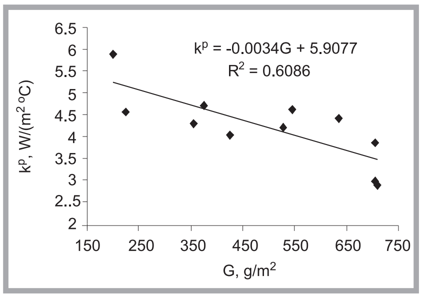

***Figure 11.** Dependence diagram $k^p$ = f(G).*

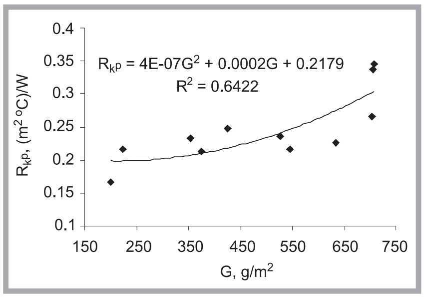

***Figure 12.** Dependence diagram $R_{kp}$ = f(G).*

the outer temperature of the knitted fabric $t_2$. For the measurement of the ambient temperature $t$, a liquid lab-thermometer with an accuracy of 0.1 ºC was used. According to [17], the accuracy of measurement using a Tilmet 75 heating board is ±1 mm, while the power measurement accuracy is 0.1 W.

The following assumptions were made for the description of heat transmission through the knitted fur fabrics:

- The knitted fabrics have a constant thickness $d$.
- The surface temperature of the sample from the heating board side (pile side) is $t_1$ = 32 °C, which is higher than the ambient temperature $t_0$ and the textile temperature on the fur side $t_2$, meaning: $t_1 > t_2 > t_0$.
- The samples come into contact with the heating board, which is why the heat resistance by heat transfer between the heater surface and the knitted fabric layer is negligible.

As a result of the temperature difference between the heating board and the surrounding environment, heat is transferred through convection, radiation and conduction. The heat from the heating board goes through the sample and is emitted to the environment (***Figure 8***).

According to the above- mentioned assumptions, the observed effect can be described by means of the following Equation [17]:

$$k = \frac{1}{\frac{d}{\lambda} + \frac{1}{\alpha}} = \frac{1}{\frac{d}{\lambda} + \frac{t_2 - t_o}{q}}, \quad \frac{W}{m^2\ °C} \qquad (3)$$

where $k$ is the heat transfer coefficient in W/(m$^2$·°C), λ is the heat conduction coefficient, measured previously on Tilmet 75 device in W/(m·°C), $d$ is the sample thickness in m], α is a heat transfer coefficient comprising the convection and radiation in W/(m$^2$·°C). The total heat transfer resistance is determined as follows:

$$R_k = 1/k \qquad (4)$$

while the heat transfer resistance is given by the equation:

$$R_\alpha = 1/\alpha \qquad (5)$$

For each of the knitted fabrics 11, measurements were made. During the research, the fur direction was assumed to be downwards, as that is the normal way knitted fur fabrics are used. On the basis of the results obtained, the following parameters, presented in ***Table 2***, were calculated:

- $k^p$ – heat transmission coefficient for temperature $t_2$ ,measured with a pyrometer in W/(m$^2$·°C),
- $k$ – heat transmission coefficient for temperature $t_2$, calculated mathematically in W/(m$^2$·°C), where the following relation was assumed:
  $t_2 = t_{2obl} = t_1 - g \cdot d/\lambda \cdot 10^{-3}$ in °C,
- α – heat transfer coefficient to the surrounding environment in W/(m$^2$·°C),
- $R_k^p$ – heat resistance of the heat trans-

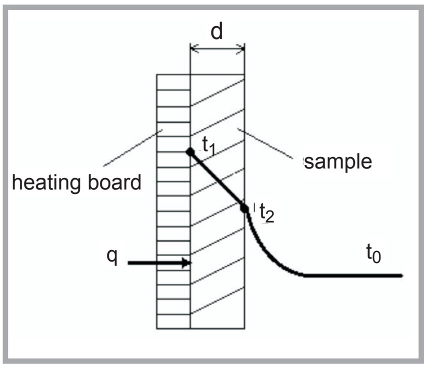

*Figure 8. Heat transmission through the sample during the heat transmission coefficient measurements; q – heat flux density going through the sample in W/m$^2$, d – sample thickness in m, $t_1$ – heating board temperature determined by the temperature sensor in °C, $t_2$ – temperature on the sample surface in °C, $t_0$ – ambient temperature in °C.*

mission calculated from the heat transmission coefficient $k^p$ in (m$^2$·°C)/W,

- $R_k$ – heat resistance of the heat transmission calculated from the heat transmission coefficient $k$ in (m$^2$·°C)/W,
- $R_\alpha$ – heat transfer resistance, (m$^2$·°C)/W.

Graphic illustrations of the research results are presented in ***Figures 9 – 12***. The results in ***Figures 9*** and ***11*** can be interpolated by a linear function according to [6, 22]. The dependences between the heat resistance and thickness, as well as surface mass, is best approximated by a second-order function, see ***Figures 10*** and ***12***.

In order to determine the dependences between the thermal properties and the surface mass of the knitted fabrics a parameter W was introduced, which is described by the following equations for each of the heat resistance types:

$$W_{R_{kp}} = R_{kp}/G \cdot 10^3 \text{ in } (m^2 \cdot °C/W) \cdot (m^2/kg) \quad (6)$$

$$W_{R_\lambda} = R_\lambda/G \cdot 10^3 \text{ in } (m^2 \cdot °C/W) \cdot (m^2/kg) \quad (7)$$

$$W_{R_{\alpha_2}} = R_{\alpha_2}/G \cdot 10^3 \text{ in } (m^2 \cdot °C/W) \cdot (m^2/kg) \quad (8)$$

where $G$ is the surface mass of the samples, $R_{kp}$, $R_\lambda$, $R_{\alpha_2}$ are the resistances of heat transmission, heat conduction and heat emission, $W_{R_{kp}}$, $W_{R_\lambda}$, $W_{R_{\alpha_2}}$ are the respective values of the $W$ parameter (***Table 3***). Because the following relation exists between the resistance types:

$$R_k = R_\lambda + R_{\alpha_2} \quad (9)$$

for the $W$ parameters an analogous equation is true:

$$W_{R_{kp}}' = W_{R_\lambda} + W_{R_{\alpha_2}} \quad (10)$$

The values of the $W$ parameters are given in ***Table 3***.

Small and medium deviations 0.04% – 13.29% can be observed between the $W_{R_{kp}}$' parameter, calculated according to Equation (10), and the $W_{R_{kp}}$ parameter, determined by the measurements, with the exception of sample B, for which the difference is greater or equal to 20.35%. Due to this, the $W_{R_{kp}}$' parameter can be used to describe the heat insulation.

The graphic interpretation of the relations between the various $W$ parameters and the corresponding values of surface mass for the examined knitted fabrics (without type I and J) are depicted in ***Figure 13***.

The results obtained were arbitrary interpolated by second-order functions. The following dependences between the $W$ parameters and the surface mass $G$ were determined:

$$W_{R\lambda} = 4 \cdot 10^{-7}G^2 - 0.0005G + 0.42; \quad R^2 = 0.5948 \quad (11)$$

$$W_{R\alpha} = 9 \cdot 10^{-7}G^2 - 0.0017G + 0.8183; \quad R^2 = 0.9460 \quad (12)$$

$$W_{Rk^p} = 2 \cdot 10^{-6}G^2 - 0.0029G + 1.094; \quad R^2 = 0.9382 \quad (14)$$

$$W_{Rk^{p'}} = 1 \cdot 10^{-6}G^2 - 0.0022G + 1.383; \quad R^2 = 0.9753 \quad (15)$$

## Results analisis

- The heat conduction coefficients of the examined knitted fur fabrics were within the range of (0.0595 – 0.0910) W/(m·°C), where thinner knitted fabrics had a lower heat conduction than thicker ones. Itwas also observed that the heat conduction coefficient rises simultaneously with the surface mass of the fabric. The values obtained are over the range determined by Robakowski [7] (0.032 – 0.044) W/(m·°C), and also higher than the theoretical range of heat conduction coefficient

***Table 3.*** *Specification of mean values of parameters $W_{R_{kp}}$. $W_{R_\lambda}$. $W_{R_{\alpha_2}}$ for different knitted fur fabrics.*

| Tested knitted fabrics | G·10$^3$. kg/m$^2$ | $W_{R_\lambda}$. (m$^2$·°C/W)·(m$^2$/kg) | $W_{R_\alpha}$. (m$^2$·°C/W)·(m$^2$/kg) | $W_{R_{kp}}$. (m$^2$·°C/W)·(m$^2$/kg) | $W_{R_{kp}}$'. (m$^2$·°C/W)·(m$^2$/kg) |
|---|---|---|---|---|---|
| A | 199.7 | 0.34 | 0.52 | 0.83 | 0.85 |
| B | 224.3 | 0.33 | 0.46 | 0.96 | 0.80 |
| C | 355.2 | 0.33 | 0.32 | 0.65 | 0.64 |
| D | 425.6 | 0.25 | 0.33 | 0.58 | 0.58 |
| E | 374.7 | 0.31 | 0.26 | 0.57 | 0.57 |
| F | 526.9 | 0.30 | 0.17 | 0.45 | 0.46 |
| G | 545.3 | 0.29 | 0.11 | 0.40 | 0.39 |
| H | 633.6 | 0.28 | 0.08 | 0.36 | 0.36 |
| I | 705.1 | 0.22 | 0.21 | 0.48 | 0.42 |
| J | 708.5 | 0.28 | 0.21 | 0.49 | 0.49 |
| K | 703.2 | 0.29 | 0.08 | 0.38 | 0.38 |

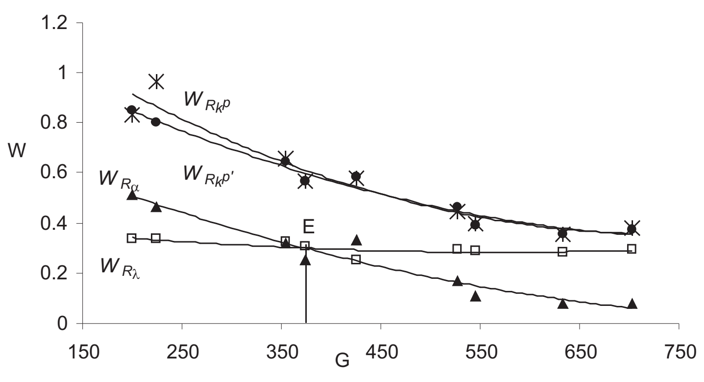

***Figure 13.*** *Dependence diagram W = f(G).*

for the fibers (0.045 – 0.055 W/(m·°C). Moreover, the values are higher than any other results of experiments presented in scientific literature. During other research using a Tilmet 75 device, the λ values obtained were no greater than 0.0600 W/(m·°C). In those measurements the heating board temperature was assumed to be $t_1$ = 37 °C, which is considerably higher than in the research presented here. According to [3], it can be assumed that high values of the heat conduction coefficient are the result of the structure of knitted fur fabrics, that is the direction of fibers, which is perpendicular to the product surface. In the examined fabrics the inclination angle to the middle products surface was greater in thinner samples than in thicker ones. It indicates that thinner samples should be characterised by a higher heat conduction coefficient. A reversed relation can be the result of the significant influence of a sample's thickness on the coefficient value, see Equation (1).

- The above described heat conduction measurements allow to state that a simultaneous increase in the thickness and surface mass of knitted fur fabrics significantly improves heat insulation. Heat resistance is greater for fabrics of greater thickness and surface mass. The values of heat conduction resistance were within the range of (0.0669 – 0.2074) (m$^2$·°C)/W.
- The value of heat transmission coefficient $k^p$ measured with a pyrometer in temperature $t_2^p$ differs from the value of heat transmission coefficient $k$ calculated for temperature $t_2$ from the conduction coefficient equation. The mean difference is equal to 1.14.
- The examined knitted textiles were characterized by heat transmission coefficient $k^p$ in the range of (2.89 – 5.89) W/(m$^2$·°C). The heat transmission coefficient measurements showed that coefficient value $k^p$ is highest for the knitted fabrics of lowest thickness and surface mass; however, it decreases for thick knitted fabrics of high surface mass. The heat transmission coefficient corresponds to the amount of heat flux going through a sample in a unit of time in the given conditions, which is why its results characterise the knitted fabrics correctly.
- The increase in thickness and surface mass causes the increase in heat resistance during heat transmission. It proves knitted fur fabrics with greater surface mass and thickness have better insulation properties.
- The increase in surface mass causes a decrease in the $W_{R_\lambda}$ parameter and it is a linear function. The $W_{R\alpha_2}$ parameter has higher values for the samples with smaller surface mass. For the samples of surface mass in the range G = (199.7 – 708.5)·10$^{-3}$ kg/m$^2$, the $W_{Rk}p'$ parameter values are within the range (0.3579 – 0.8503) (m$^2$·°C/W)·(m$^2$/kg). The increase in surface mass causes a decrease in the $W_{Rk}p'$ parameter, but for a surface mass greater than $G_1$=675·10$^{-3}$ kg/m$^2$, it can be assumed that this parameter value remains constant. That is why it is advisable to design knitted fur fabrics of surface mass lower than $G_1$. Mass $G_1$ had the lowest value of the $W_{Rk}p'$ parameter, and thus the best heat insulation was obtained.
- The basic problem which designers face is the creation of a knitted fur fabric that allows to achieve the best heat insulation from a unit of thread. To achieve user comfort, , the material should be characterised by a minimum mass. Therefore, the achievement of high heat insulation with the lowest possible surface mass is an important issue from the point of view of both the producer and user, due to reduced material consumption. When the heat insulation of the material is the design criterion, the $W_{Rk}p'$ parameter should be used as it describes these textile properties in the best way.

## Conclusions

1. The thickness $d$ and surface mass $G$ have a linear dependence on the heat conduction coefficient and increase by a correlation coefficient R$^2$ = (0.6–0.7), see ***Table 1, Figures 3*** and ***5***. The results obtained are similar to those in scientific literature.
2. In relation to the heat conduction resistance $R_\lambda = d/\lambda$ in (m$^2$·°C)/W, for a correlation coefficient R$^2$ = (0.91 – 0.92), the resistance $R_\lambda$ is an ingredient of the transmission resistance and also has a growth characteristic.
3. The heat transmission coefficient $k$ decreases, while the transmission resistance $R_k$ increases when the thickness d and surface mass G grows within the range of R$^2$ = (0.55 – 0.65).
4. The relative resistances of heat conduction $W_{R_\lambda}$, heat transfer $W_{R\alpha}$ and heat transmission $W_{Rk}$ (see Equations (6), (7), (8) and ***Table 2***) in the function of surface mass $G$ are constant for $W_{R_\lambda}$ (R$^2$ = 0.60) and decrease by $W_{R_\alpha}$ and $W_{Rk}$ (for R$^2$ = 0.94 – 0.98), see ***Figure 12***. The "relative resistances" presented here allow to design the structure of knitted fur fabrics in a more economical way due to lower consumption of raw material.
5. The above presented results show the necessity and possibility of analysing the dependencies between the structure parameters of knitted fur fabrics and heat transfer resistances.
6. The current model does not support a theoretical description of all effects, e.g. variable conditions caused by transient heat conduction, shape identification and optimization, the existence of heat bridges etc. That is why the results obtained undoubtedly indicate the necessity to create a new, more developed physical and mathematical model to describe the heat conduction of knitted fur fabric. This will be the topic of our next publication.

## Acknowledgment

*This research work was conducted by the 1st Author within the frame of project No N 501 06032/39/58 granted by the Department for Scientific Research of the Polish Government*

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❑ ***Received 28.11.2005 Reviewed 15.01.2006***

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