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Application of the Non-Contact Thermal Method for Estimation of the Thermal Parameters of Flat Materials

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Abstract
The paper presents a study on the thermal properties of flat textile products with the use of a previously elaborated method based on the simultaneous recording of temperature distribution on the opposite sides of a flat sample using IR mirrors. The method enables to determine thermal parameters in both static and dynamic conditions, which is of great importance for the study of smart textiles. In the work presented a theoretical model for determining thermal conductivity was elaborated and verified.

Key words: *thermography, temperature, thermal conductivity, nonwovens.*

Introduction

The work presented is another in a series of works [1-6] concerning the study of heat transfer in flat textile products. The research is based on the non-contact measurement of temperature distribution on the surface of a textile to which heat is delivered from an external source. The measurements are conducted with the use of a thermovision camera that records the infrared radiation emitted by the material investigated.This method of simultaneously recording the temperature distribution on the opposite sides of flat products, previously described as non-invasive, non-contact measurement, enables to observe heat flow in the longitudinal direction, to carry out experiments under dynamic conditions, to analyse the results online and to conduct an analysis for particular time periods and spatial zones. Research can be conducted for a wide range of temperatures. The possibility of conducting research under dynamic conditions can be particularly important for materials with temperature dependent thermal properties. Considering the possibilities mentioned above, the method elaborated has undisputed advantages over those generally used in the textile industry, such as those on which the Alambeta device[1)], the Permetest, the "skin model", and the Kovostov or Thermo Labo are based. These methods are described in [8].

To carry out experiments with the use of the method elaborated, one should prepare a sample of specific geometry, such as flat samples, not necessarily textile materials, with the substance or structure being of no difference. Theoretically, samples can be prepared within a wide range of thicknesses, assuming that the boundary conditions will be changed. For the geometry of a sample, as suggested in [1-4], a theoretical model [5] previously elaborated enables to determine the values of thermal parameters (conductivity coefficient), but only in stationary conditions with simplified assumptions and boundary conditions not precisely defined (concerning both the thermal power delivered and cooling mechanisms). The method modified is described in [6].

The work described in this article is a continuation of previous research with the use of the results presented in [6]. It was proved that the method described enables to determine thermal parameters in dynamic conditions. A theoretical model for a modified measuring set was elaborated.

Research material

A measuring set equipped with IR mirrors set vertically at 90° to each other and a thermovision camera set in line, which is an extension of the sample's axis in the longitudinal direction [1-5], were used in this research. The measuring set consisted of a heating element placed between the mirrors in the vertical position of the symmetry axis, which was in contact with the sample. The heating element was made of electroconductive non-woven fabric mounted on a special frame with electrical terminals. A non-woven sample divided into two parts was used in the experiments. Both the heating element and the sample were rectangular. Each part of the sample was connected to the heating layer, providing good mechanical contact and good electrical insulation with the heating element [6], the result being a three-layered measuring set: the inner layer, the heater and two outer layers – the two parts of the sample. The heating element was connected to an electrical source, whose power is recorded. The electric current flowed through the inner layer of the set, heating up both parts of the sample. The temperature distribution on the surface of both parts of the sample was recorded by a thermovision camera. The use of two identical parts of the sample provides better control of heating – heat is transferred symmetrically to both parts of the sample, which helps to define the boundary conditions when elaborating a theoretical model.

The heating layer and sample were made from isotropic non-woven fabric of surface mass m_p = 294 g/m^2 and density ρ = 208 kg/m^3, consisting of electro-conductive fibres of the Nitril-Static type. According to the assumptions made in this study, the boundary value of the sample thickness equals 5 mm.

Thermograms of the temperature distribution on the outer surface of both parts of the sample were recorded. It seemed reasonable to use double-sided recording for the results from both parts of the sample – this way one obtains averaged results. It is very important for the studies of textile materials which are in majority characterised by some irregularities.

In the experiment described in [6], after connecting the voltage (0.5 V) to the opposite narrow backsides of the heating layer, the process of heating the surface of the sample was recorded. The power of electric energy was 0.25 W. The heating process lasted 360 s, while the recording was 600 s (10 min). Next, after disconnecting the power source, the cooling process followed. Thermograms were recorded at a frequency of 1 frame/s. An example of the temperature dependence of the heating time for a particular point on the surface of the sample is presented in ***Figure 1***.

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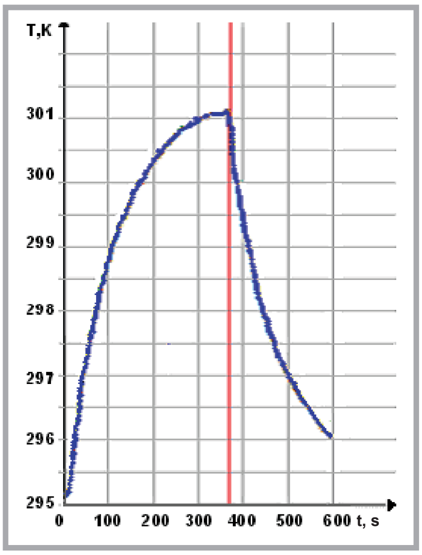

Figure 1. *Temperature dependence on the heating time for a particular point.*

On the basis of the results obtained, a theoretical model of the thermal characteristics of textiles was elaborated.

Theoretical model

A theoretical model for a three-dimensional system was elaborated on the basis of the Kirchhof-Fourier equation.

$$\frac{\partial}{\partial x}\left(\lambda_x \frac{\partial T}{\partial x}\right)+\frac{\partial}{\partial y}\left(\lambda_y \frac{\partial T}{\partial y}\right)+ + \frac{\partial}{\partial z}\left(\lambda_z \frac{\partial T}{\partial z}\right)+q_v = c\rho\frac{\partial T}{\partial t} \quad (1)$$

where:
t – time
x, y, z – coordinates of the Cartesian system,
T – absolute temperature,
λ_x – thermal conductivity in the x direction,
λ_y – thermal conductivity in the y direction,
λ_z – thermal conductivity in the z direction,
q_v – thermal efficiency of inner sources,
ρ – density,
c – specific heat.

While elaborating the model, it was assumed that the material tested was isotropic. In this case, the values of λ_x, λ_y and λ_z can be replaced with the value of λ, equal for every direction.

While constructing the model, it is assumed, as in [5], that the source of heat is outside the system considered, thus the equation takes the form:

$$\lambda\, div(grad T) = c\rho\frac{\partial T}{\partial t} \quad (2)$$

Due to the same conditions of heat exchange on the outer surfaces of the structure measured (the sample and the heating layer), it can be assumed that the temperature distribution is symmetrical to the YZ plane (***Figure 2***). Therefore, the sample was divided into two equal parts, with the dividing line running through the middle of the heating layer (***Figure 2***), as a result two symmetrical parts were obtained. For the analysis, only one of these parts was used, as described in ***Figure 2***.

Dimensions of the sample (***Figure 2***):
In the x direction – $b_x = 0{,}00145$ m,
In the y direction – $b_y = 0{,}045$ m,
In the z direction – $b_z = 0{,}09$ m.

In order to solve the equation, the boundary conditions were defined on the basis of measurement conditions. Heat delivered to the heated layer through the action of the electric current heats up the sample and is further transmitted to the environment symmetrically through both outer layers of the sample. As both layers are similar, each of them gets the same amount of thermal energy – a power equal to ½ the power of the heater, where the investigated surface is at a distance of b_x from the beginning of the coordinate system. To elaborate the model, further simplifications were assumed: the thermal inertia of the heater is low, and the electrical energy is converted into thermal energy and then transferred to the sample.

The heat from the sample is transferred from the side surfaces of the sample to the environment through free convection (marked as Q_k) and infrared radiation (Q_{IR}).

The heat transferred by free convection can be written as in [8] using formula (5).

$$Q_k = \alpha_k (T_p - T_0), \quad (3)$$

where:
α_k – convection coefficient,
T_p – temperature on the surface, transferring the heat to the environment,
T_0 – temperature of the environment.

The coefficient of free convection was determined with the use of the dimensionless Nusselt number [8], which is calculated according to:

$$Nu = c(Gr \cdot \Pr)^n \quad (4)$$

where:
Gr – Grasshof number:

$$Gr = \beta\frac{l^3 g}{\nu^2}\Delta T \quad (5)$$

Pr – Prandtl number:

$$\Pr = \frac{\mu}{a\rho} \quad (6)$$

where:
a – thermal diffusivity of the air
ρ – density,
μ – dynamic viscosity,
ν – kinematic viscosity,
g – acceleration due to gravity,
l – characteristic linear dimension, which equals b_y for the sample investigated,
ΔT – temperature increment,

c and n depend on the value of $(Gr \cdot Pr)$. The criterial numbers are calculated on the basis of the parameters of the environment for a specific temperature range. In the conditions chosen for elaborating the model i.e. with the environment temperature similar to room temperature and that of the sample, not exceeding 100°C, the Prandtl number equals 0.722 and the Grasshof number – $2{,}56 \cdot 10^5$, which gives $(Gr \cdot Pr) = 1{,}848 \cdot 10^5$. For such values of $(Gr \cdot Pr)$: $c = 0{,}54$, $n = 1/4$.

Hence we obtain:

$$Nu = 0{,}54(Gr \cdot Pr)^{1/4} = = 0{,}54(1{,}848 \cdot 10^5)^{1/4} = 11{,}196 \approx 11{,}2.$$

From the definition, the Nusselt number takes the form:

$$Nu = \frac{\alpha_k l}{\lambda_p} \quad (7)$$

where:
l – characteristic linear dimension for the sample considered $l = b_y$
λ_p – specific thermal conductivity of the air

After transformation we obtain:

$$\alpha_k = Nu\,\frac{\lambda_p}{b_y} = 11{,}2\,\frac{\lambda_p}{b_y}$$

Substituting the value of the Nusselt number, the sample size (taking into consideration the actual position of the sample in the area measured [6]) and the coefficient of thermal conductivity of

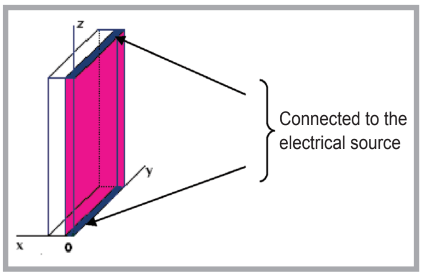

Figure 2. *Sample used for elaborating the theoretical model.*

the air, we obtain the value of the coefficient of convection $\alpha_k = 5{,}5\frac{W}{m^2K}$. The dependence of the ther*m*al conductivity of the air on its temperature, which affects the value of a_k, is not considered. With an increase in temperature from 20ºC to 30°C (experimental range), the coefficient of thermal conductivity of the air increases by 2% [8]. Taking into consideration small variations in this parameter, we can assume that the value of the coefficient of convection is constant. Calculations concerning temperature dependent parameters will be the subject of further studies.

The heat emitted can be calculated from the following formula [8]:

$$Q_R = C\left[\left(\frac{T_p}{100}\right)^4 - \left(\frac{T_o}{100}\right)^4\right] \qquad (8)$$

$$C = \varepsilon\, C_0$$

where:
C – emission constant,
ε – emissivity of the sample,
C_0 – emission constant of the absolutely black body.

Because of the fact that the XY surfaces (top and bottom in ***Figure 2***) are narrow, they take up only a small part of the total surface of the sample and are in the contiguity of electrical connections; it is also assumed that there is no heat exchange with the environment.

While the heat transferred to the heating layer is marked as $\boldsymbol{Q_e}$, the boundary conditions can be defined as:

for $z = 0;\ 0 \le x \le b_x;\ 0 \le y \le b_y\ \ \boldsymbol{Q = 0}$.
for $z = b_z;\ 0 \le x \le b_x;\ 0 \le y \le b_y\ \ \boldsymbol{Q = 0}$.
for $x = 0;\ 0 \le y \le b_y;\ 0 \le z \le b_z\ \ \boldsymbol{Q = Q_e}$
for
$x = b_x;\ 0 \le y \le b_y;\ 0 \le z \le b_z\ \boldsymbol{Q = -(Q_k + Q_{IR})}$
for
$y = 0;\ 0 \le x \le b_x;\ 0 \le z \le b_z\ \boldsymbol{Q = -(Q_k + Q_{IR})}$
for
$y = b_y;\ 0 \le x \le b_x;\ 0 \le z \le b_z\ \boldsymbol{Q = -(Q_k + Q_{IR})}$
(9)

The initial condition is the initial temperature of the sample, which is assumed to be equal to that of the environment – T_0.

To solve the equation, FlexPDE 6 software was used. The program transforms a system of partial differential equations into a system of finite elements, solves the equations and presents the results in a graphic or numerical form. The program includes all functions necessary to solve partial differential equations, an editor of the solution's description, a generator to create a finite elements net, a software package for equation solving and a system for graphic interpretation of the results.

On the basis of a program written for the case mentioned above, using the geometry of the sample presented in ***Figure 2***, calculations were made (with the given parameters of the material tested). The value of the coefficient of emissivity ($\varepsilon = 0.9$) was determined by comparative measurement of a standard sample.

$$c = 1000\frac{J}{kgK}$$

$$\rho = 208\frac{kg}{m^3} \qquad (10)$$

$$C = \varepsilon\, C_0 = 0.9 \cdot 5.67\frac{W}{m^2K^4} = 5.1\frac{W}{m^2K^4}$$

The value of c was chosen using literature data for different materials, while r was determined in the experiments. The boundary values were the following: $Q_e = 60$ W/m^2 and $T_0 = 295$ K. The value of Q_e results from the conversion of the electrical power per unit area of the sample. The solution was started with the given value of the coefficient of thermal conductivity $\lambda = 0{,}05\frac{W}{mK}$, next the values of λ were revised in order to obtain the

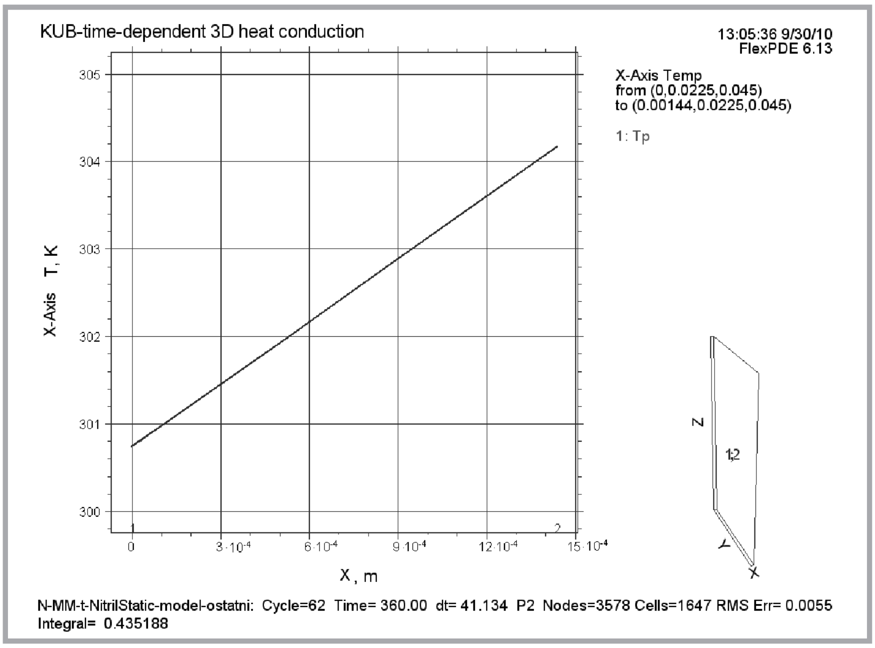

Figure 3. *Temperature distribution along the x axis, drawn through the centre of YZ plane in the last second of heating.*

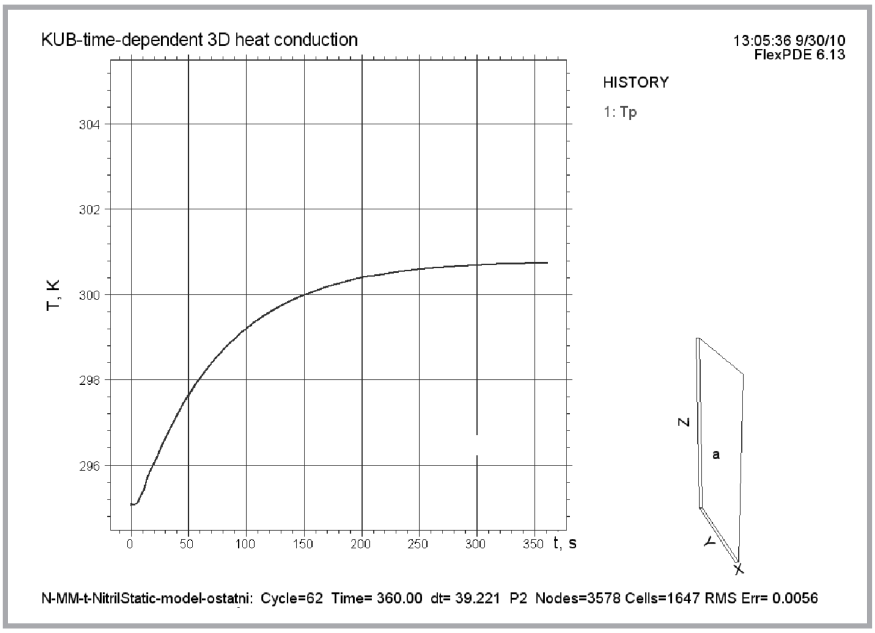

Figure 4. *Time course of the temperature in the YZ plane, with x = b_x at the point analysed.*

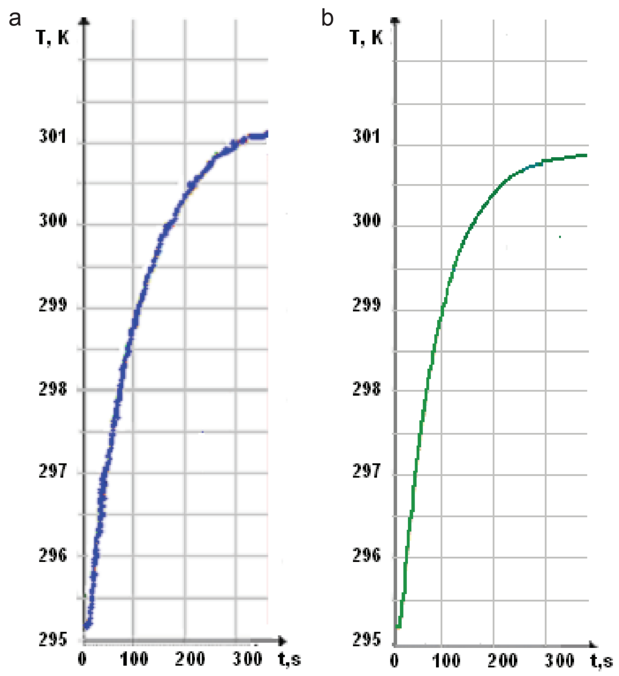

Figure 5. Time course of the temperature on the YZ plane, with $x = b_x$ at the point analysed; a – experimental (from Figure 1) b – theoretical (from Figure 4).

greatest convergence of the theoretical and experimental results.

The graphs below (***Figures 3-5***) present the results obtained after further approximations for $\lambda = 0{,}025\frac{W}{mK}$.

Figure 3 presents the temperature distribution along the X axis (see ***Figure 2***) drawn through the centre of the YZ plane in the last second of heating.

The temperature is the highest for a distance of $x = 0$ and decreases to a value of 301 K with $x = b_x$.

Figure 4 presents the temperature dependence on the heating time for a point (displayed in the Figure) located on the YZ plane, with $x = b_x$, $y = b_y/2$.

According to ***Figure 4***, the theoretical time course of the temperature is largely convergent with the experimental course, presented in ***Figure 1.***

For comparison, the experimental results and calculations are presented below in ***Figures 5a*** and ***5b***, according to the model elaborated in the same scale.

According to the comparison of the time course of the temperature, the theoretical and experimental results are convergent. However, the results of the research conducted on an Alambeta* device showed a different value of the coefficient of thermal conductivity for this material $-\lambda = 0{,}039\frac{W}{mK}$. The value of thermal diffusivity taken from the device equals $5\cdot10^{-7}\frac{m^2}{s}$, giving a value of $c\rho = 7{,}8\cdot10^4\frac{J^S}{m^3K}$. With thedensity of the material determined in the experiments as $c = 375\frac{J}{kgK}$, we obtain a value of the specific heat of, which is very low compared to that of the specific heat of copper. It seems that with such large divergences of the basic parameters of the material, comparison of the results obtained with the use of an Alambeta device and those from the method presented is pointless.

It should be emphasised that calculations were made with constant values of the thermal parameters of the material. At present, tests are being carried out on materials of temperature dependent parameters, such as phase-change materials. The specific heat will be determined in another experiment, in which a theoretical model of such material will be elaborated, where the temperature dependence of the convection coefficient will be taken into account.

Conclusions

The experimental results obtained using FlexPDE 6 on the basis of the theoretical model proposed, with assumed boundary conditions and parameters of the sample, enabled to determine the coefficient of thermal conductivity and indicated convergence with the experimental results of the heating process.

It would be advantageous to carry out further studies on the cooling process of a sample as well as on materials that change their thermal properties after the delivery of thermal energy.

Editorial note

1) The Alambeta device, produced by the Czech company SENSORA, is widely used for textile measurements.

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