DESIGNING OF SPECIAL CLOTHING BASED ON EXPERIMENTAL RESEARCHES OF MATERIAL PROPERTIES

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Abstract: *The article presents the results of experimental researches on determination of thermal and physical characteristics of thermal insulating materials using the principle of spatial three-dimensional presentation of the study object with distributed parameters. The proposed method of research and obtained experimental results provide an opportunity to determine thermal and physical properties of materials with high accuracy, which creates the conditions for improvement of the quality of special clothes designing.*

Key words: *high temperature environment, thermal insulating materials, temperature conductivity coefficient.*

1 INTRODUCTION

The performance of works in unfavorable conditions always requires the use of special clothes. Integrated design approach consists in the development of special clothes with increased operational, hygienic and aesthetic indicators, as well as in the development of design and technological solution that would provide the highest possible level of worker`s protection and at the same time meet the ergonomic requirements for this product.

Scientific developments in the field of special clothes designing, and the growing consumers` demands on the quality of products and their appearance, all the above set more and more complicated tasks for the designers of the clothes. Development and creation of new sets of specials clothes require integrated design and technological solution for its components, taking into account protective properties, ergonomic and aesthetic indicators [1].

Materials used in the manufacturing of heat-protective clothing protect against radiation and convection heat, as well as against open flame impact [2]. Generalized classification of materials is provided in Figure 1: for the intended purpose they are divided into thermal flame proof materials (for outer layers), thermal insulating materials (for inner layers) and lining materials.

It is known [2-6] that thermal insulating layer (non-woven textile material) plays a significant role in increase of the protective properties of the products aimed to protect against the influence of high temperature environment. Non-woven textile material is a textile fabric, obtained from one or several layers of textile materials, as well as their combination with non-textile materials, fastened together in different ways. The following materials can serve as the basis for non-woven textile materials, namely: fibrous covering, system of threads, fabrics, knitted fabrics, tapes and other framework structures. Threads, fibers and various adhesive components can be used as base fasteners.

By the way of production, non-woven materials can be divided into covering-stitched, thread-stitched, framework-stitched, needle-punched, glued and composite materials. Formation of covering is made in different ways: using the sew-knitted and needle-punched technologies. The sew-knitted technology is used in the production of non-woven fabrics, made by knitting with threads (yarn) or fibers of the most fibrous covering (covering-stitched), threads (thread-stitched), textile fabrics, tapes, nets, etc. (framework-stitched), with the formation of loops of threads or fibers (needle-punched). Therefore, covering-stitched, thread-stitched and framework-stitched methods of production are distinguished.

Needle-punched non-woven fabrics are made by piercing the fibrous covering with special needles, entangling and sealing of fibers on needle-punched machines [2].

Considering raw material composition, non-woven materials are subdivided depending on the type of fibers, from which they are made. A wide range of non-woven thermal insulating materials includes half-wool, cotton, synthetic wadding pads of heat-resistant fibers, knitted half-wool wadding pads, needle-punched half-wool and synthetic fabrics.

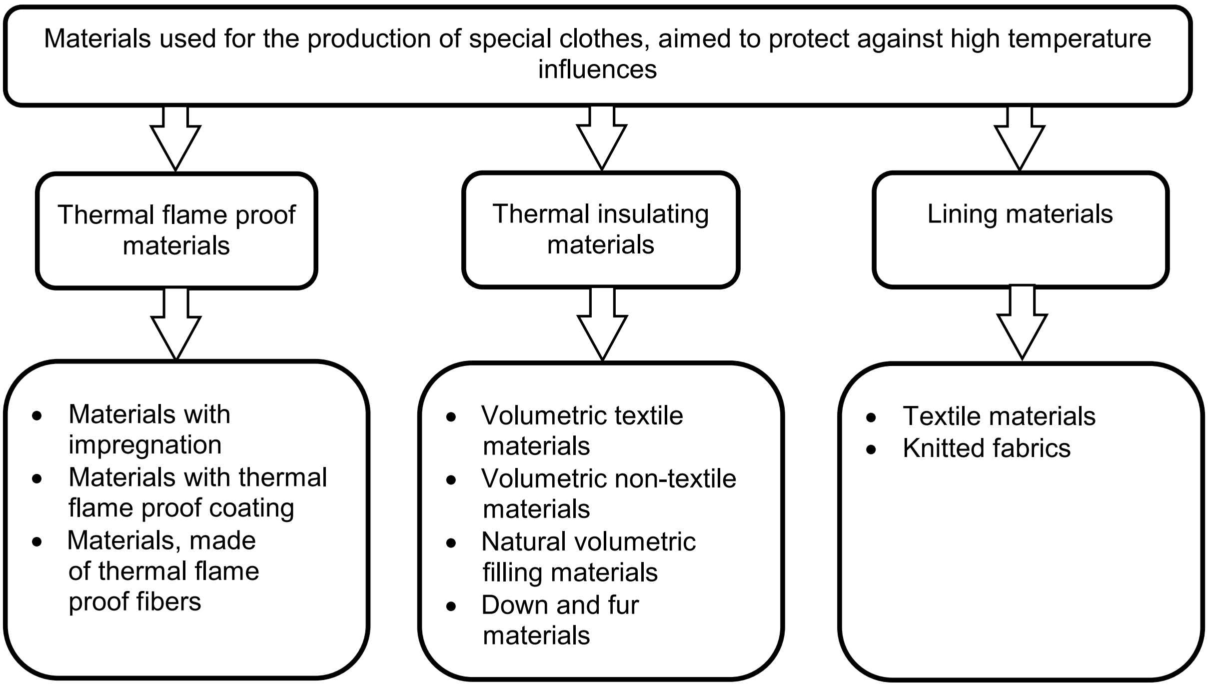


Figure 1 General classification of materials used for production of means of hands protection against high temperature influences

When designing special clothes, in order to get the predicted properties, it is necessary to know basic thermal and physical indicators of the materials, from which the package of the clothes is made. Therefore, the object of the research is thermal insulating materials, used in the production of special protective clothes, with unknown thermal and physical characteristics. Selection of appropriate materials in the process of designing new types of special clothes necessitates experimental researches on their thermal and physical properties using the methods and devices that provide high accuracy of measurements. The research method is proposed, based on the simulation of dynamic processes in the objects with distributed parameters. Thermal insulating materials, namely volumetric non-woven materials, are selected for the further research. The main criterion in the selection of thermal insulating materials for special clothes against high temperature influences is the determination of materials thermal characteristics because only the knowledge of these properties provides an opportunity to design the means with the maximum degree of protection. However, when designing and developing special clothes, physical and mechanical characteristics of thermal insulating material cannot be neglected. Thus, the material with shallow thickness and density and with a small coefficient of thermal conductivity can be considered as the best thermal insulating material [3-7].

2 EXPERIMENT PLANNING

The velocity of propagation of heat transfer in the process of heating of the fabric, and the gradients of fixed temperature of the layers of clothes, designed to work in high temperature conditions, both are completely determined by temperature conductivity of the fabrics. The development of the method of experimental determination of temperature conductivity of various materials, which provides the opportunity to make grounded decisions during the special clothes designing and to predict its properties, is an important task at the design of special clothes.

The aim is achieved by the fact that the package of materials with unknown thermal and physical characteristics is researched as a three-dimensional object with distributed parameters. In spatial objects with distributed parameters, the coordinates of the state gradually change over time along certain spatial coordinates. The modeling of technological objects with such parameters is possible considering the directions of change of the state coordinates. Mathematical modeling of objects with distributed parameters is related to certain spatial systems of coordinates, in which the object of modeling is located in accordance with the directions of key parameter changes [7-9].

In different layers of the package of fabrics, the temperature is a function of not only time, but also geometric coordinates of the considered layer. In this regard, it should be taken into account that the boundary conditions are the necessary elements of the models of objects with spatial distribution of influencing parameters.

The mathematical model of such an object in dynamics is a differential equation in partial derivatives. Material mathematical modeling of this category of objects with the use of electronic computing machines is associated with significant programming complexities [7-10]. That is why an approximate replacement of objects with distributed parameters by a certain set of objects with lumped parameters, which can be described using the scheme of ordinary differential equations, is widely used.

The velocity of propagation of heat transfer in a three-dimensional environment, the temperature conductivity coefficient of which is a, in time t in coordinates $X, Y, Z,$ is described by the Fourier equation, which in the three-dimensional environment is as follows:

$$\frac{\partial T(t,X,Y,Z)}{\partial t}=\alpha\left(\frac{\partial^2 T(t,X,Y,Z)}{\partial X^2}+\right.$$
$$\left.+\frac{\partial^2 T(t,X,Y,Z)}{\partial Y^2}+\frac{\partial^2 T(t,X,Y,Z)}{\partial Z^2}\right) \tag{1}$$

For the experimental studies of thermal and physical properties of fabrics, the samples of fabrics are used, the length and width of which are considerably larger than their thickness, because the transfer of the heat in real conditions takes place through the thickness of the package. As a result, we can consider:

$$Z=\infty;\ X=\infty \tag{2}$$

If we study the temperature change in the separate layers of the package of fabrics, then the Y_i coordinate may take the value $Y_i = ih$, that is:

$$Y_1 = h;\ Y_2 = 2h;\ Y_3 = 3h;\ \text{etc.} \tag{3}$$

If the Y spatial coordinate is fixed, then the Fourier equation for each layer of the package of fabrics has the form of ordinary derivatives:

$$\frac{dT_i(t)}{dt}=\alpha\frac{d^2T_i(t)}{dY^2},\ i = 1\ldots N-1 \tag{4}$$

where, i - serial number of the package layer; N - number of layers of the investigated fabric; $T_i(t)$ - change of the temperature of i layer of the package in time.

Distribution of temperature in separate layers of fabric causes the transformation of mathematical description of temperature field as a continuous function into a lattice function, the value of which exists only for fixed values of Y coordinate. This causes the need to replace ordinary derivatives by finite differences.

During the experiments, when forming the required volume (array) of data, determination of the results of experiment is possible only for fixed moments of time, so the nature of temperature change as a continuous time function should be replaced by the function of discrete time t_n with a constant step of quantization τ_κ:

$$\tau_\kappa = t_n - t_{n-1}. \tag{5}$$

where, n = 0; 1; 2…; τ_κ - step of quantization of time; t_n and t_{n-1} - the values of t_n and t_{n-1} discrete moments of time.

The left side of the Fourier equation can be replaced by finite differences:

$$\frac{dT_i(t)}{dt}\approx\frac{1}{\tau_K}\left(T_i(t_{n+1})-T_i(t_n)\right) \tag{6}$$

An analogue of the second derivative, on the right side of the Fourier equation, can be obtained by replacing the differential of the continuous function and its argument with the corresponding increment.

Direct difference of the first order, as an analogue of the temperature differential along the Y coordinate, is a temperature difference between i and $(i+1)$ layers of the fabric:

$$\begin{gathered}\Delta T_i(t)=T_{i+1}(t)-T_i(t)\approx dT_i(t)\\ \Delta T_{i-1}(t)=T_i(t)-T_{i-1}\approx dT_{i-1}(t)\end{gathered} \tag{7}$$

Direct difference of the second order of the temperature in n moment of time along the Y coordinate can be considered as the difference between the finite differences of the first order:

$$\begin{gathered}\Delta^2T_i(t_n)=\Delta T_i(t_n)-\Delta T_{i-1}(t_n)=T_{i+1}(t_n)-\\ -T_i(t_n)-T_i(t_n)+T_{i+1}(t_n)=\\ =T_{i+1}(t_n)-2T_i(t_n)+T_{i+1}(t_n)\approx d^2T_i(t_n)\end{gathered} \tag{8}$$

Second-order differential

$$dY^2 = h^2 \tag{9}$$

Taking into account the necessity of formation of data array as a set of values of variables, when conducting experimental researches, the second derivative, which is on the right side of the Fourier equation, should be replaced by the finite difference of the second order.

Taking into account (6, 8) and (9), the equation (4) takes the form:

$$\begin{gathered}\frac{1}{\tau_K}\left(T_i(t_{n+1})-T_i(t_n)\right)=\\ =\frac{\alpha}{h^2}\left(T_{i-1}(t_n)-2T_i(t_n)+T_{i+1}(t_n)\right)\end{gathered} \tag{10}$$

where, $T_i(t_n)$ - the temperature in i layer of fabric in n moment of time; $T_i(t_{n+1})$ - the temperature in i layer of fabric in $(n+1)$ moment of time; $T_{i-1}(t_n)$ - the temperature in $(i-1)$ layer of fabric in n moment of time; $T_{i+1}(t_n)$ - the temperature in $(i+1)$ layer of fabric in n moment of time.

Whereof:

$$\mu = \frac{\left(T_i(t_{n+1}) - T_i(t_n)\right)}{\tau_K\left(T_{i-1}(t_n) - 2T_i(t_n) + T_{i+1}(t_n)\right)} \tag{11}$$

As a result of transformation (10, 11), we obtain the formula for calculating the temperature conductivity coefficient of α fabric:

$$\alpha = \frac{h^2\left(T_i(t_{n+1}) - T_i(t_n)\right)}{\tau_K\left(T_{i-1}(t_n) - 2T_i(t_n) + T_{i+1}(t_n)\right)} \tag{12}$$

Thus, the determination of the temperature conductivity coefficient comes down to its calculation, using the formula (12), inserting the instantaneous values of the temperatures in three adjacent layers of the packages of clothes with predicted thickness of the package h (T_{i-1}, T_i, T_{i+1}) at the previous moment (t_n) and at the moment after the interval τ_K (t_{n+1}).

The proposed method of studying thermal and physical properties of fabrics has a lot of significant advantages, which lie in the fact that the determination of thermal and physical values takes place in dynamic process of distribution of heat transfer in the layers of the package of materials; the received formula eliminates the possibility of significant additive and multiplicative measurement errors. It can be stated that the proposed method of research allows determining different thermal and physical properties of the fabrics with high accuracy when using modern means of microprocessor and computer technologies, thus creating the conditions for improving the quality of special clothes designing.

3 RESULTS AND DISCUSSION

The conducted analysis of modern thermal insulating materials used for production of means of hands protection against high temperature influences has proven that the following packages of materials should be used in the research: (TEX-1) – covering-stitched woolen wadding pads (Ukraine), thickness of the layer of material h = 6 mm; (TEX-2) – thread-stitched woolen-phenylene wadding pads (Ukraine), thickness of the layer of material h = 5 mm; (TEX-3) – needle-punched sheet, made from oxalone fibers (Russia), thickness of the layer of material h = 2.75 mm; (TEX-4) – needle-punched sheet, made from Nomex meta-aramid fibers (DuPont, Switzerland), thickness of the layer of material h = 3 mm; (TEX-5) – non-woven sheet, made from phenylene fibers (Russia), thickness of the layer of material h = 3 mm.

Temperature conductivity coefficient of the materials has been determined in the training laboratory of Kyiv National University of Technologies and Design on the results of unsteady distribution of the temperatures in separate layers of the package in the process of heating and cooling of the package [11].

Therefore, the results of determination of temperature conductivity coefficient as an object parameter due to the algorithm, based on formula (12), do not depend on the initial and boundary conditions of the experiments. However, in order to confirm such a hypothesis, the evaluation of repetition of experiment results, as well as the determination of the most reliable value and confidence range of the values of temperature conductivity coefficient of the selected samples of materials were repeatedly carried out in two different modes in selectable initial and boundary conditions. The first mode consisted of heating of pre-cooled package, the second mode, vice versa, consisted of cooling of pre-heated package.

Figures with even numbering (Figures 2 - 20) present the curves of unsteady distribution of the temperature field in the layers of the investigated packages of materials in two modes (heating and cooling). Each curve shows each column of a five-dimensional array of a corresponding table, which is considered as a data series. Series 1, 2, 3, 4 correspond to the temperatures, measured by the channels of the module under the ordinal numbers 0, 1, 2, 3, which coincides with the number of the layer in the package.

Figures with uneven numbering (Figures 3 - 21) present the results of calculation of temperature conductivity coefficients of the packages of corresponding materials, using (12). The calculations are performed, taking i = 2, since the temperature, measured by the channel 2 of the module, is the temperature of the flatness, equally-spaced from two surfaces of heat-exchange capacities.

During the analysis of the curves of heating of the package layers, provided in Figure 2, stochastic oscillations, imposed on the growing curves, have been revealed, which cause more significant fluctuations in the values of temperature conductivity coefficient, calculated by the formula (12) and represented as a dotted line in the Figures 3 and 4 and require approximation of the obtained dependencies. The result of approximation of the function of dependence of the temperature conductivity coefficient on the relative time, the polynomial of the second order, demonstrates that there is a certain transition process, after the end of which the fixed value of the desired indicator $a_m = 5.1 \times 10^{-7}$ m^2/s is set.

The graph of cooling of the same package (Figure 4), as in the case of heating, shows the characteristic non-matching of the curves of heat changes in the inner layers, symmetrically relative to the middle layer, which is caused by the presence of convectional method of heat transfer over the thickness of the package during the experiment. The function of the change of temperature conductivity coefficient in the relative time, calculated and approximated by the corresponding polynomial (12), gives a fixed value $a_m = 5.05 \times 10^{7}$ m^2/s and indicates a high degree of repeatability of the experiment results, performed in different modes.

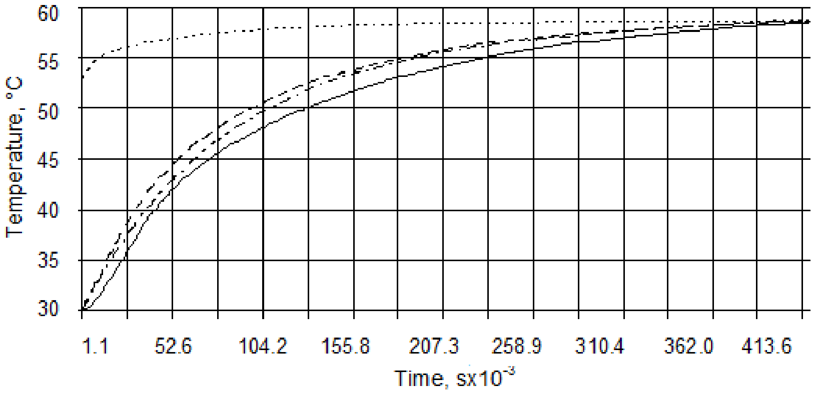


Figure 2 Curves of distribution of the temperature field in the TEX-1 package (heating mode)

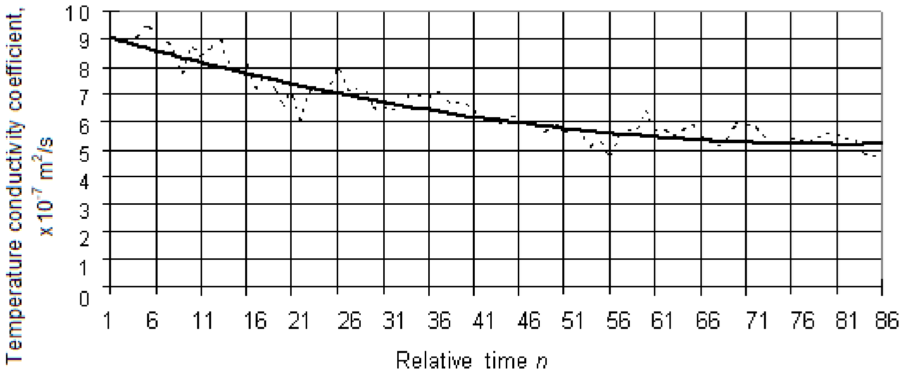


Figure 3 Approximated dependence at determining the temperature conductivity coefficient in the TEX-1 package

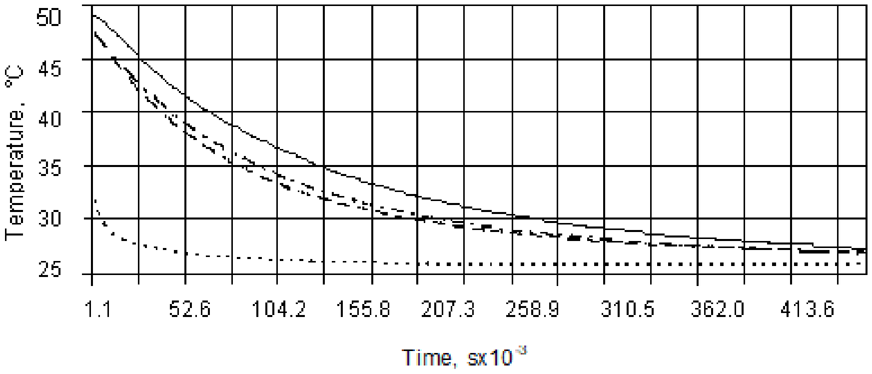


Figure 4 Curves of distribution of the temperature field in the TEX-1 package (cooling mode)

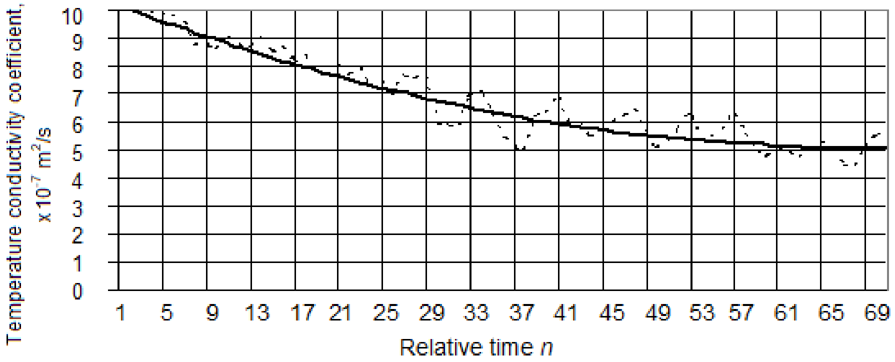


Figure 5 Approximated dependence at determining the temperature conductivity coefficient in the TEX-1 package

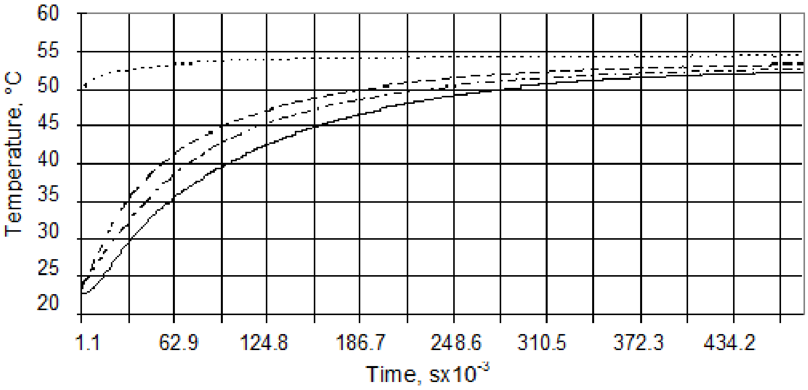


Figure 6 Curves of distribution of the temperature field in the TEX-2 package (heating mode)

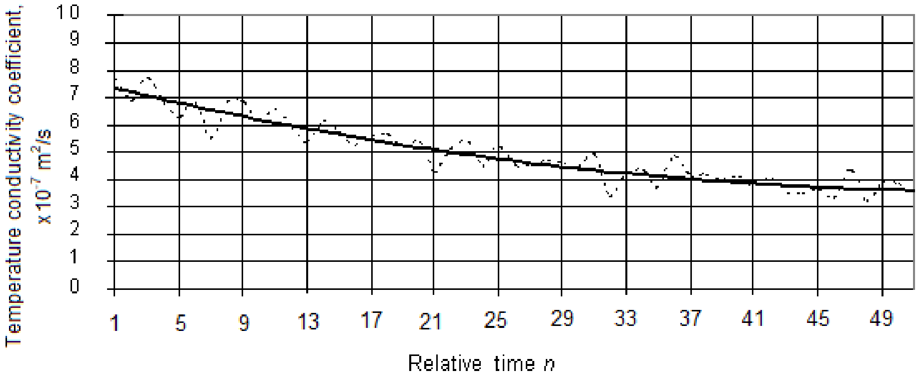


Figure 7 Approximated dependence at determining the temperature conductivity coefficient in the TEX-2 package

Analyzing the curves of total time of heating to the fixed value (TEX-2 and TEX-1 packages, Figures 6 and 2), its small difference can be noted. But considering the smaller thickness of the layers of TEX-2 package in comparison to TEX-1 package, there is a general assumption that the TEX-2 package temperature conductivity coefficient is smaller than the TEX-2 package temperature conductivity coefficient. The graph, provided in Figure 7, completely confirms this assumption, according to which the fixed value is $a_m = 3.7 \times 10^{7}$ m^2/s. Approximated superficial analysis of the curves of cooling of TEX-2 and TEX-1 packages, as provided in Figures 8 and 4, causes analogous assumptions, as in the case of heating of the packages, that the temperature conductivity coefficient in the TEX-2 package should be smaller than in the TEX-1 package. Figure 9, which illustrates the results of determination of specified thermal and physical parameter of the material, indicates that the fixed value of the temperature conductivity coefficient is 3.6×10^{-7} m^2/s and is slightly differ from the result, obtained during the heating of the package.

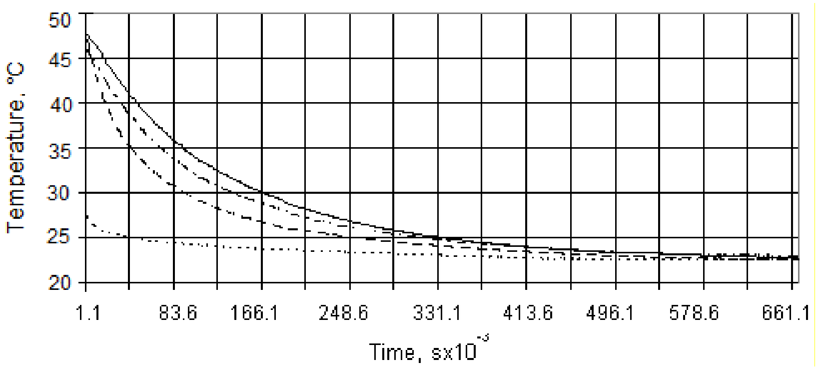


Figure 8 Curves of distribution of the temperature field in the TEX-2 package (cooling mode)

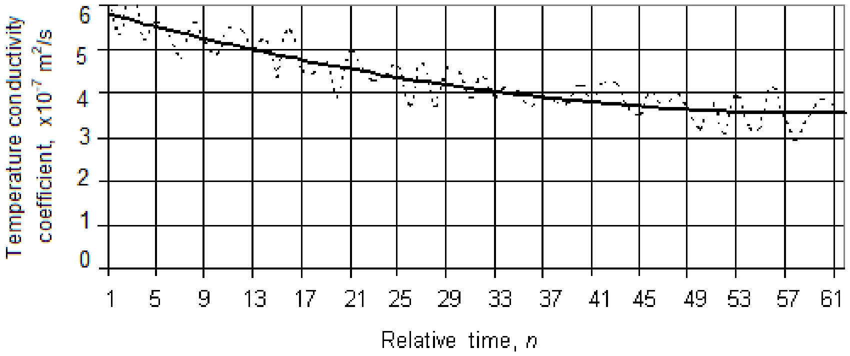


Figure 9 Approximated dependence at determining the temperature conductivity coefficient in the TEX-2 package

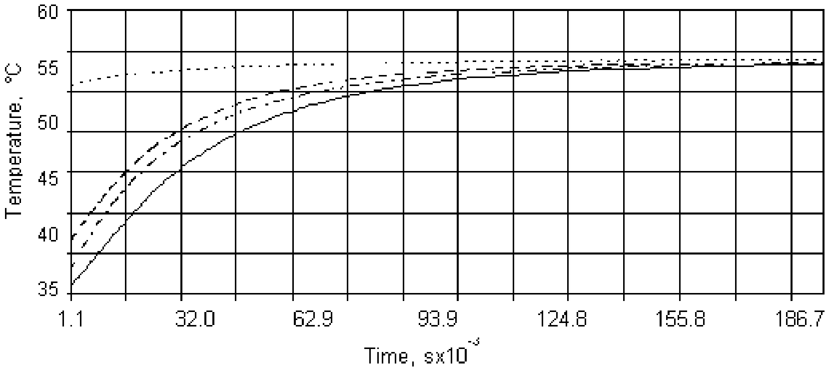


Figure 10 Curves of distribution of the temperature field in the TEX-3 package (heating mode)

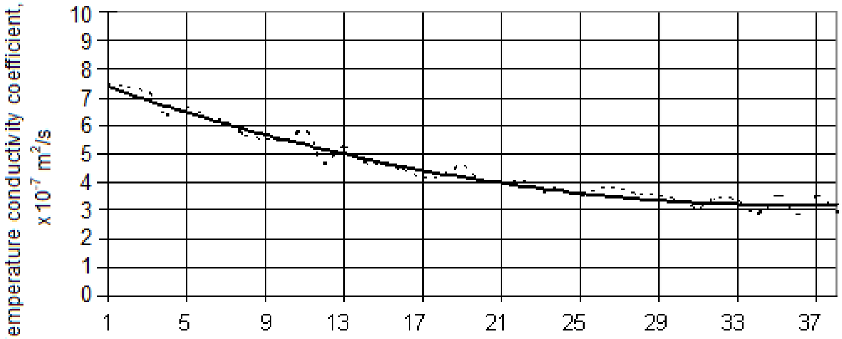


Figure 11 Approximated dependence at determining the temperature conductivity coefficient in the TEX-3 package

Since the thickness of the TEX-3 package is almost twice less than the thickness of the TEX-1 and TEX-2 packages, the comparative analysis of the curves of heating, provided in Figures 10, 6 and 2, do not provide an opportunity to make previous assumptions regarding the values of temperature conductivity coefficients. Analyzing the diagram of changes of this parameter (Figure 11), we can conclude that the material in the TEX-3 package has a fixed value of the temperature conductivity coefficient, equal to 3.2×10^{-7} m^2/s, that is 1.6 times smaller than in the TEX-1 package and 1.2 times smaller than in the TEX-2 package.

In the cooling mode (Figure 12), as well as in the heating mode, it is impossible to make previous assumptions regarding the value of temperature conductivity coefficient for the TEX-3 package due to the above motives. It can be noted that the value of temperature conductivity coefficient in the cooling mode (Figure 13) $a_m = 3.1\times10^{-7}$ m^2/s, slightly deviates from the coefficient value, obtained in the heating mode.

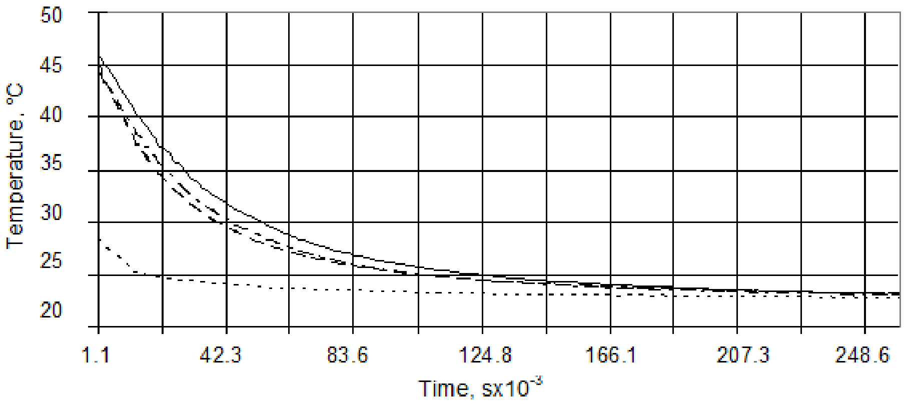


Figure 12 Curves of distribution of the temperature field in the TEX-3 package (cooling mode)

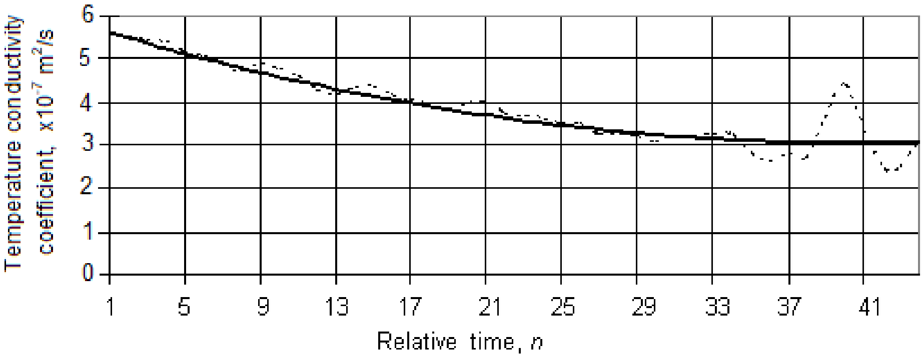


Figure 13 Approximated dependence at determining the temperature conductivity coefficient in the TEX-3 package

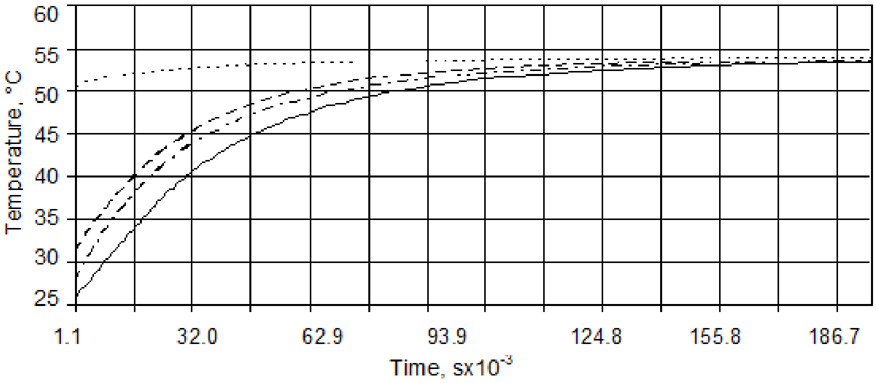


Figure 14 Curves of distribution of the temperature field in the TEX-4 package (heating mode)

Comparing the curves of the temperature change during the heating of the TEX-4 package (Figure 14) with the corresponding graph for the TEX-3 package, it is possible to note almost the same time of completion of the transition process. Considering that the thickness of each layer of the TEX-4 package is bigger than of the TEX-3 package, it can be presumably assumed that the TEX-4 package temperature conductivity coefficient should be greater. This assumption is confirmed by a graph (Figure 15), according to which the fixed value of the temperature conductivity coefficient is 3.7×10^{-7} m^2/s.

Comparative analysis of the curves of cooling of the TEX-4 (Figure 16) and the TEX-3 packages (Figure 12), taking into account the thickness of the packages, makes it possible to draw a preliminary conclusion that the value of temperature conductivity coefficient of the TEX-4 package is bigger. The result of the determination according to the curve (Figure 17) confirms the preliminary conclusion, since the temperature conductivity coefficient equals to 3.6×10^{-7} m^2/s.

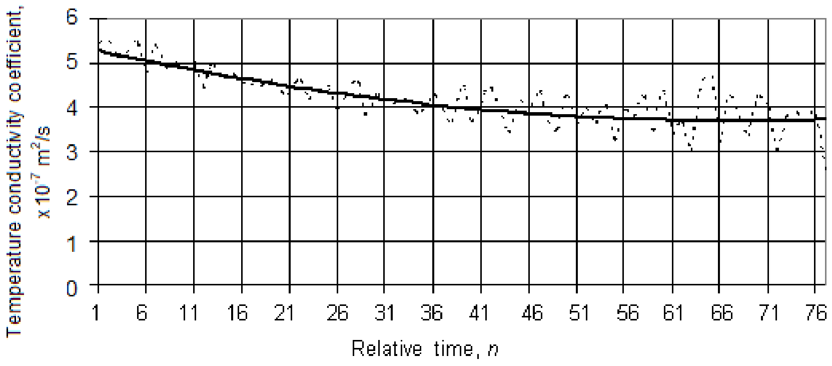


Figure 15 Approximated dependence at determining the temperature conductivity coefficient in the TEX-4 package

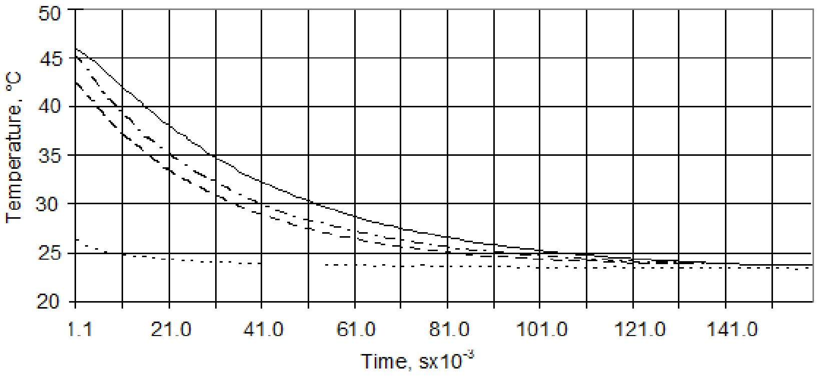


Figure 16 Curves of distribution of the temperature field in the TEX-4 package (cooling mode)

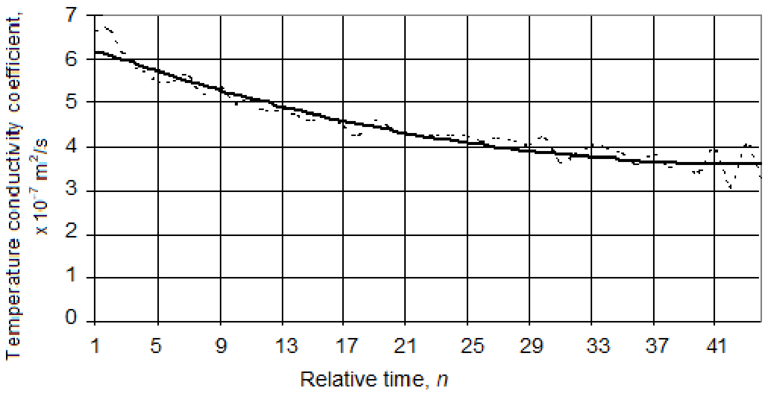


Figure 17 Approximated dependence at determining the temperature conductivity coefficient in the TEX-4 package

Superficial comparative analysis of thermal and physical properties of the materials in the TEX-4 and the TEX-5 packages is simplified by the fact that the layers of the packages have the same thickness. In such a case temperature conductivity coefficient is greater for the material, the package of which warms up to the established mode faster. In accordance with Figures 14 and 18, the material of the TEX-5 package is such material. The value of coefficient, as provided in Figure 19, is 4.6×10^{-7} m^2/s.

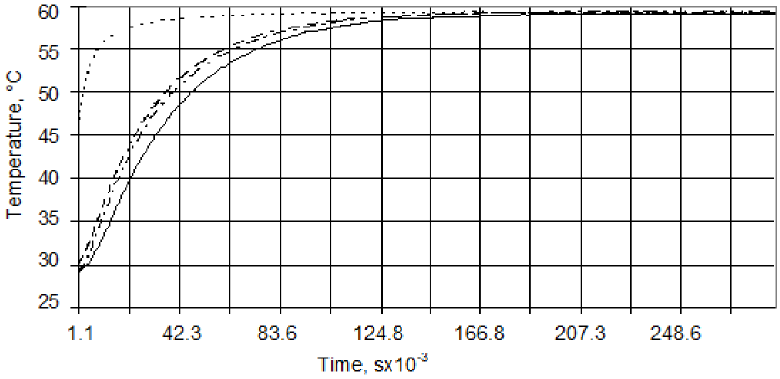


Figure 18 Curves of distribution of the temperature field in the TEX-5 package (heating mode)

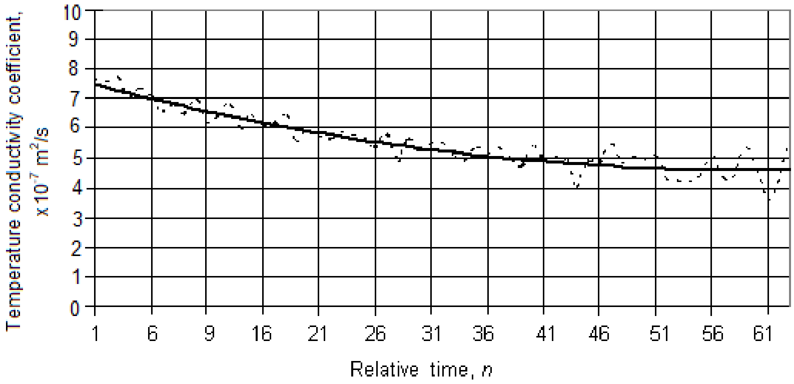
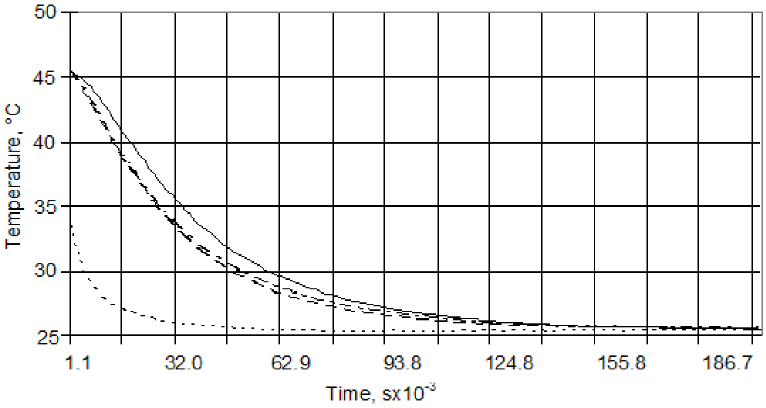


Figure 19 Approximated dependence at determining the temperature conductivity coefficient in the TEX-5 package



Figurer 20 Curves of distribution of the temperature field in the TEX-5 package (cooling mode)

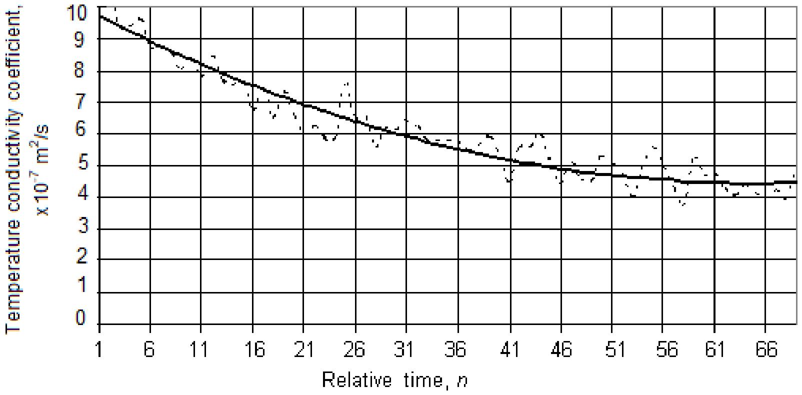


Figure 21 Approximated dependence at determining the temperature conductivity coefficient in the TEX-5 package

Comparing the curves of cooling of the TEX-5 and the TEX-4 packages (Figures 20 and 16), it is undeniable that the TEX-5 package cools to the constant temperature faster than the TEX-4 package. With equal thickness of the package layers, it means that temperature conductivity coefficient for the TEX-5 package should be greater. The constant value of temperature conductivity coefficient in the cooling mode, as determined in Figure 21, is 4.5×10^{-7} m^2/s.

Analysis of transient characteristics, provided in the figures with even numbering (Figures 2-20), shows that the curves of warming and cooling of the first and third layers do not coincide in some way, although both are at the same distance from the surface of heat-exchange capacities with the same temperature.

Figures with uneven numbering (Figures 3-21) show changes in temperature conductivity coefficient over time. The curves clearly show the decrease of the coefficient to the full set value both during the heating and the cooling of the package. This fact can be explained due to the nonlinear properties of the materials, the essence of which is that the temperature conductivity coefficient depends on the temperature gradient between the adjoining layers of the materials. At the beginning of heating or cooling these gradients are bigger than when approaching the steady-state mode. That is why at the beginning of transition process the temperature conductivity coefficient is maximal, then, when approaching the static condition, it decreases and acquires the steady-state value.

Determination of temperature conductivity coefficient should be attributed to the indirect measurements, during which the search value is calculated using the appropriate formula (12), which considers the value of temperature, measured by direct measurements. The processing of the experiment results is as follows: determination of the most reliable value and confidence range at the value of the confidence coefficient of 0.95 is carried out in accordance with the method [12, 13].

The results of experimental determination of temperature conductivity coefficients of the packages are provided in Table 1.

Table 1 Determination of temperature conductivity coefficient in the process of heating and cooling the package of the materials

Package code (raw material composition)	Package thickness h [m]	Material density ρ [kg/m^3]	Temperature conductivity coefficient a_m [x10^{-7} m^2/s]	
			Heating	Cooling
TEX-1 (covering-stitched woolen wadding pads)	0.024±0.001	69	5.10±0.18	5.05±0.15
TEX-2 (thread-stitched woolen-phenylene wadding pads)	0.020±0.001	65	3.70±0.14	3.60±0.12
TEX-3 (needle-punched sheet, made from oxalone fibers)	0.011±0.0005	49	3.20±0.11	3.10±0.1
TEX-4 (needle-punched sheet, made from Nomex meta-aramid fibers)	0.012±0.0006	42	3.70±0.16	3.60±0.14
TEX-5 (non-woven sheet, made from phenylene fibers)	0.012±0.0006	52	4.60±0.17	4.50±0.15

Analyzing the data obtained in the experimental study, it should be noted that the value of temperature conductivity coefficient has a good repeatability, which indicates the stability of processes that take place in opposite directions (heating – cooling). Some difference in the values of the given thermal and physical parameter of the material for different modes can be explained by the impact of the abovementioned nonlinear properties of the materials. Therefore, during the forced heating of the package, the temperature conductivity coefficient is slightly greater than during the free cooling (the difference does not exceed 2%).

4 CONCLUSIONS

To conclude, analyzing thermal and physical parameters of the researched materials, presented in Table 1, it may be deduced that despite the fact that the TEX-1 package and the TEX-2 package have almost the same density of the material, the temperature conductivity coefficient of the material with phenylene fibers additions is almost 1.5 times smaller than of the material, made from natural raw materials. The material, made from meta-aramid fibers (TEX-4 package), having low density and thickness in comparison with other researched materials, has a small value of temperature conductivity coefficient, which indicates its advantage. From an ergonomic point of view, it is more appropriate to use it in special clothes as it has average thermal and physical parameters at a small thickness. Comparing the results of the obtained data on determination of temperature conductivity coefficient using different methods, it should be noted that such results differ in the range of not more than 3%, which is the permissible error in measurements of thermal and physical characteristics of the materials.

The proposed method of studying thermal and physical properties of fabrics has a lot of significant advantages, which primarily lie in the fact that the determination of thermal and physical values takes place in dynamic process of distribution of heat transfer in the layers of the package of materials; the received formula eliminates the possibility of significant additive and multiplicative measurement errors. It can be stated that the proposed method of research allows determining different thermal and physical properties of the fabrics with high accuracy when using modern means of microprocessor and computer technologies, thus creating the conditions for improving the quality of special clothes designing.

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