

*This paper has analyzed materials for fire protection of textile products; it was found that there are not enough data to explain and describe the process of fire protection. Neglecting modern coatings leads to the ignition of fabric structures under the action of flame. Devising reliable methods for studying the conditions of fabric fire protection leads to the design of new types of fire-proof materials. Therefore, there is a need to determine the conditions that form a barrier to high fabric temperature and to establish a mechanism for inhibiting heat transfer to the material. In this regard, the thermal conductivity process was simulated on the fabric surface using an intumescent coating, which makes it possible to estimate the coefficient of thermal conductivity at high temperatures. Based on the experimental data and theoretical dependences, the thermal conductivity coefficient of the fire-retardant layer of coked foam was calculated, which is  $8.9 \cdot 10^{-6} \text{ m}^2/\text{s}$ , due to the formation of a heat-insulating layer. The study results proved that the process of thermal insulation of textile material involves not only the decomposition of flame retardants with the formation of inert gases that interact with the flame on the sample surface but also the inhibition of heat transfer to the material treated with an intumescent coating that forms a thermally-insulating layer of coked foam on the fabric surface. The maximum possible penetration of temperature was estimated, namely generating a temperature on the sample's surface that significantly exceeds the ignition temperature of the fabric, and does not exceed 215 °C on the unheated surface. Thus, there is reason to argue about the possibility of targeted adjustment of the processes of fabric fire protection by applying coatings capable of forming a protective layer on the surface of the material, which inhibits the rate of heat transfer*

*Keywords: protective means, textile material, combustion, weight loss, fabric surface treatment, swelling*

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# ESTABLISHING REGULARITIES OF TEMPERATURE CONDUCTIVITY REDUCTION WHEN PROTECTING FABRIC AGAINST FIRE BY INTUMESCENT COATING

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## 1. Introduction

Analyzing the use of easily built structures made of flammable textile products reveals a steady trend to increase their application during the temporary implementation of certain tasks by the Armed Forces of Ukraine and units from the State Emergency Service. When heating such facilities,

ignition and rapid spread of fire are possible, which leads to injuries and deaths. An example is a heavy fire that broke out in the tent camp of the 10th separate mountain assault brigade on the territory of the military unit (Fig. 1). One of the reasons for the rapid evolution of the fire was the lack of fire protection of such textile products. As a result of the fire, fifteen 50-seat large field tents were destroyed where the sol-

diers lived while the stationary barracks were being repaired. The cause of the fire was that the opening valve was adjacent to the chimney. Strong winds contributed to the rapid spread of the fire. Five servicemen lightly injured their hands while rescuing property as they collected personal belongings and some equipment.



Fig. 1. Consequences of the fire in the military town on the territory of the 10th separate mountain assault brigade

Mixtures of inorganic salts are widely used to protect natural materials from fire. However, fire protection with these substances is not suitable for fabrics because there is the formation of efflorescence on the surface, which crumbles when the structure oscillates and, as a result, the material loses its protective properties. Such mixtures reduce the processes of heat transfer to the material to some extent but require their application in significant amounts, increasing the atmosphere resistance and elasticity during vibrations of the structure. The use of special coatings on an inorganic base is characterized by a rigid structure and low adhesion over time, which causes shedding and, when exposed to high temperatures, leads to fire.

Taking into consideration that it is the flammability of the fabric that leads to such consequences, it is possible to increase the level of fire safety at facilities where textile materials are used by treating them with intumescent coatings.

Therefore, studies aimed at determining the patterns of reduction of thermal conductivity when protecting fabric against fire by an intumescent coating are relevant.

## 2. Literature review and problem statement

Paper [1] substantiated the areas of application of heat-resistant and fire-resistant fabrics, including military use. In addition, many fabrics are used in public transportation systems such as commercial airlines, luxury cruise liners, and modern high-speed trains. However, issues related to the fire protection mechanism of the material remain unresolved. The reason for this may be the principles of flame retardants, which makes such studies difficult.

Study [2] reported the production of fire-retardant textiles from polymer-blended cotton fabric by depositing the three-dimensional polymer coating tetrakis (hydroxymethyl) phosphonium chloride. For that purpose, mixed fabrics with different compositions, weaving structures, thickness, and density of threads were made, followed by chemical deposition of the polymer coating. The lowest length of the charred base under the action of heat flux of  $11 \text{ kW m}^{-2}$  and an oxygen index of 36.8 % were found in fabrics with

a content of 40 % cotton and 30 % polymer. Concerning water-repellent properties, all treated samples showed a positive result, expressed as the angle of contact with water up to  $141.70^\circ$  to  $151.50^\circ$ . These results provide a fundamental basis for the design of mixed textiles with the necessary functionality. But it is not specified to which classes of operation they belong.

The nylon fabric of the tent stops burning, at least in part, because it is treated with flame retardants from chemical compounds [3]. Fire-retardant coatings based on inorganic binders, the properties of which have already been studied, are considered to be the most effective. But these materials form a hard coating on the surface, which changes the color of the surface and, under the action of the atmosphere, loses adhesion and crumbles. The kinetics of the formation of a layer of coked foam, which is formed during swelling, has its features (characterized by a low swelling coefficient) and depends on the properties of substances in such mixtures. Therefore, it is necessary to study the conditions for the formation of a barrier to thermal conductivity and to establish the effective action of the coating with the formation of a layer of coked foam.

A synthesized series of boron-nitrogen polymers is presented in [4], which could provide an environmentally friendly alternative to the fire-resistant treatment of cotton fabrics. The organic combination of boron and phenyl with nitric acid was successfully linked to branched polyethyleneimine and confirmed by analysis. Thermogravimetric analysis showed that the obtained flame retardant demonstrates optimal thermal-oxidative stability, easily applied to cotton fabrics by a simple method of immersion with high absorption in acetone. The fabric with an admixture of 33.8 wt% has a self-extinguishing ability. Analysis of the charring morphology of the treated fabrics showed fire resistance of the coating due to swelling of the fire protection mechanism. However, it is not specified how these compositions can withstand changes in temperature and humidity fields.

Work [5] reports a test method for determining the rate of heat release, smoke formation, and flame propagation. In addition, large-scale tests were conducted to obtain information on the behavior of fire in real use and the possibility of using it as a reference in the evaluation of information obtained from classification tests. Large-scale tests have shown the importance of measuring smoke and flame droplets in the classification scheme. However, relevant physicochemical data on fabric changes during operation are not provided.

The need to measure the physical properties of fabrics, as well as the heat-protective characteristics of fabrics, was evaluated under the influence of fire, obtained as a result of laboratory modeling of a Molotov cocktail [6]. The efficiency was calculated from the amount of heat energy transmitted through the fabrics. Besides, the time required to obtain a second-degree burn on the bodies of the holders, which was predicted from the calculated heat transferred, was taken into consideration. For characteristics, the parameters that influenced the protective properties were identified and discussed in terms of the theory of heat and mass transfer. The relationship between the properties of fabric systems and their protective characteristics was statistically analyzed. The cited study showed that heat resistance and resistance to evaporation are two important properties that negatively affect the transferred heat energy through fabric systems. However, the authors did not specify the mechanism of protection of the material and the effect of flame retardants on fire resistance.

Melamine-based resins were considered in [7], which are widely used in fabrics to impart fire and heat resistance. Simulated washing experiments show that 76–90 % of melamine was removed from clothing in one round of water washing. Therefore, the task is to fix the flame retardant in the material.

Decomposition of refractory materials due to elevated temperature or contact with flame leads to the appearance of a number of chemicals, some of which can be quite toxic to humans [8]. Small or bench tests of decomposition products were performed in the past but questions had always been raised as to whether they were representative of full-scale flash test results. A full-scale test was conducted to determine whether it would suffice to measure decomposition products and whether different refractory materials would form a “branded” set of compounds. Textiles made from four common fire-resistant materials were evaluated. The methodology applied made it possible to determine the products of thermal decomposition under the influence of the flash. However, it is not said about the impact of environmental change on the coating, and its destruction over time.

It is difficult to imagine the protection of human lives against fire without fire-retardant coatings on textiles [9]. Precisely defined standards allow determining the requirements for textile materials that have fire protection. It is hardly possible to prevent textile inflammation due to their physical parameters (melting point, flash point, etc.). However, it is possible to extend the time for people to escape to start rescue operations by using appropriate fire protection systems or a combination of individual active ingredients. However, the effect of aging on fire protection and the mechanical properties of fire-retardant textiles are not studied.

In [10], the newly-devised fire-retardant textile composites with the use of fire-retardant linen nonwoven fabric are reported. The non-woven material applied in the composites acts as a fire barrier, reducing the vulnerability of the filler material to the development and spread of fire. However, the areas of application of those products are not specified.

The influence of the homogeneity degree of SiO<sub>2</sub> sol on the duration of the induction period and the quality of fire-resistant coatings on textile materials was studied [11]. Prospects for the use of IR spectroscopy as an express method for studying the phase composition of the gel coating, the degree of completion of the hydrolysis of the organosilicon component, are promising for obtaining high-quality fire-resistant coating based on SiO<sub>2</sub>. However, the areas of application of those products are not specified.

Thus, our review of the scientific literature has established that fire-retardant coatings can protect the surface of the textile material from the effects of a fire during operation but no parameters are defined that ensure the resistance of fire-retardant coatings to heat inhibition. The lack of mathematical models to explain and describe the process of fire protection of fabrics, as well as neglecting the use of intumescent coatings, lead to the ignition of textile-based structures under the action of flame. Therefore, determining the parameters for the protection of textile materials and the impact of coatings on this process has necessitated research in this area.

**3. The aim and objectives of the study**

This work aims to identify patterns of reducing the thermal conductivity when protecting fabric against fire using an

intumescent coating. This would make it possible to justify the use of fire-retardant coatings at sites where textile materials are applied.

To accomplish the aim, the following tasks have been set:

- to model the process of thermal conductivity in the formation of a layer of coked foam during the decomposition of an intumescent coating under the influence of high temperature;
- to establish the effectiveness of fire protection of fabric by an intumescent coating.

**4. The study materials and methods**

**4.1. The studied materials used in the experiment**

To determine the flammability of the fabric, we used samples of tarpaulin fabric measuring 310×140×6 mm, article number 11293 (41 % cotton/59 % flax), and applied an intumescent agent (“FIREWALL-WOOD”) in the amount of about 330 g/m<sup>2</sup> (Fig. 2) [12].



Fig. 2. Fabric with an intumescent coating

After conditioning to constant weight, the treated fabric samples were tested for resistance against fire.

**4.2. Procedure for determining the fire-protection properties of the fabric with an intumescent coating**

To conduct the study, an installation for determining the flammability of materials was used, which was equipped with a device for measuring and recording temperature on the sample surface (Fig. 3).

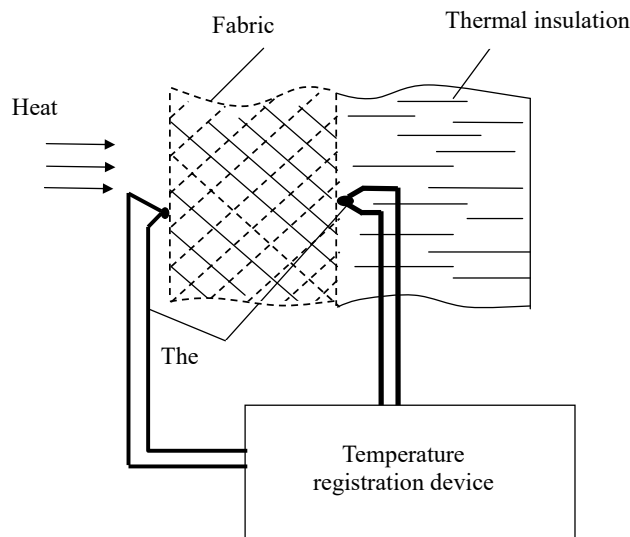


Fig. 3. Schematic showing the temperature conductivity test of the fire-protected fabric

A fabric sample treated with an intumescent coating was fixed in a holder and placed in a test chamber. The sample

was fixed so that the end of the thermocouple was pressed against the inner surface of the sample.

The ignition source was brought to the fabric sample; the temperature on the fabric surfaces was measured. Based on the measured values, heat-insulating properties were determined and changes in the coating were recorded [13].

Research on modeling the thermal conductivity of the coating under thermal action was carried out using the basic principles of mathematical physics [14].

**5. Results of studying the fire-protection process of the fabric with an intumescent coating under the high-temperature impact**

**5.1. Modeling the thermal transfer process on the fabric surface protected against fire with an intumescent coating under the high-temperature impact**

When a fire-retardant coating is exposed to high temperature, it decomposes to form non-combustible gases and hard-to-ignite coke residue, which significantly insulates heat and reduces heat transfer to the fabric.

Determining the thermal physical characteristics of the fire-retardant layer of the fabric coating is associated with the need to measure the temperature in a thin layer of the fire retardant (up to 0.5 mm), which has some difficulties.

Therefore, in this case, a method for solving the thermal conductivity problem for a two-layer plate with different thermophysical properties is proposed. Thus, at the initial moment, a heat flux, constant in time, is supplied to the sample surface of a fire-retardant fabric, which is maintained constant throughout the heating process. Given this, the temperature propagates through the coating until the critical temperature of the fabric is reached. The opposite part of the sample is adiabatic.

To establish the dependences for calculating the rate of advance of the phase transformations of the swelling coating under thermal action, the following model is proposed, in which two regions are considered (Fig. 4):

- 1 - a zone of the swollen layer of coked foam,  $0 < x \leq \xi(\tau)$  ( $\xi$  is the coordinate of the front of the phase transformation of the coating film into the swollen layer of coked foam, m);
- 2 - a sample of the material with a solid substance,  $\xi \leq x \leq R$  ( $R$  is the thickness of the sample, m).

At the initial time ( $\tau=0$ ), the temperature in the environment is characterized by the maximum temperature  $T_f$ , and in the sample material - the minimum  $T_0$ .

The differential equation describing this process [15]:

$$\frac{\partial^2 T}{\partial x^2} - \frac{1}{a} \frac{\partial T}{\partial \tau} = 0. \tag{1}$$

The initial and boundary conditions can be written as follows:

$$T|_{x=0} = T_f, \quad T|_{x=\xi(\tau)} = T_\xi, \quad \xi(0) = 0, \tag{2}$$

$$\lambda_1 \frac{\partial T}{\partial x} \Big|_{x=0} = \lambda_2 \frac{\partial T}{\partial x} \Big|_{x=\xi(\tau)}, \tag{3}$$

where  $T_i$  is the temperature in the  $i$ -th region, °C;

$x$  is a coordinate, m;

$\tau$  is the time the sample spends in a high-temperature environment, s;

$a_1, a_2$  are the coefficients of temperature conductivity of the swollen layer of coked foam and fabric,  $m^2 \times s^{-1}$ ;

$\lambda_1, \lambda_2$  are the coefficients of thermal conductivity of the swollen layer of coked foam and fabric,  $W \times m^{-1} \times \text{°C}^{-1}$ .

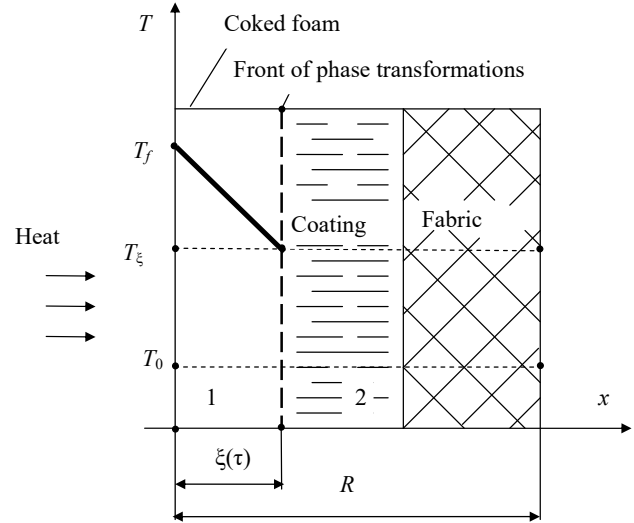


Fig. 4. Schematic showing the heat transfer process when the intumescent coating swells: 1 - a coked foam layer; 2 - an intumescent coating

Consider the process of formation of a layer of coked foam, on the surface of which the temperature  $T_f$  is maintained, and on the moving front of the phase transformation with the coordinate of the front of the phase transformations throughout the process. A constant value of temperature  $T_\xi$  is set, which can be determined experimentally.

The linear temperature distribution in the movable part of the coating under boundary conditions takes the following explicit form [16]:

$$T(x, \xi) = (T_f - T_\xi) \frac{x}{\xi} + T_\xi, \tag{4}$$

where  $\xi$  is the time function, unknown yet.

If we disregard the volume of coating used to form a coked foam (zone 1) compared to the remaining amount (zone 2), except for moments close to the full formation of coked foam. Therefore, the relative proportion of the initial amount of the coating remaining in the material up to time  $\tau$  can be determined geometrically depending on the position of the front of phase transformations:

$$\delta(\tau) = \frac{(R - \xi)T_0}{RT_0} = 1 - \frac{\xi}{R}, \tag{5}$$

where  $R$  is the size of the formed coked foam layer, m.

The gradient of the formed temperature depends on the difference and thickness of a layer of coked foam:

$$dT / dx = (T_f - T_\xi) / \xi, \tag{6}$$

and, therefore, the amount of heat retained in the coked foam layer for a period  $d(\tau)$  from the outer surface to the front of phase transformations is equal to:

$$a(T_f - T_\xi) d\tau / \xi. \tag{7}$$

This amount corresponds to the movement of the front by the amount of increase in a coating temperature.

Thus, we obtain a differential equation to determine a coordinate of the front of phase transformation inside the coating:

$$a \frac{T_f - T_\xi}{\xi} = T_0 \frac{d\xi}{d\tau}, \tag{8}$$

the integration of which under the initial condition  $\xi|_{\tau=0} = 0$ :

$$\xi|_{\tau=0} = 0, \tag{9}$$

produces a parabolic dependence for the current coordinate of the front:

$$\xi = \sqrt{2a \frac{T_f - T_\xi}{T_0} \tau}. \tag{10}$$

Therefore, the rate of advance of the phase transformation front in the process of creating coked foam is slowed down because the thermal resistance of the foam layer increases with increasing its thickness.

The current value of the relative proportion of undamaged coating in a sample is determined from the following ratio:

$$\delta(\tau) = 1 - \left( 2 \frac{a}{R^2} \frac{T_f - T_\xi}{T_0} \tau \right)^{1/2}. \tag{11}$$

The resulting time of the complete decomposition of the coating and the formation of a coked foam layer, the value of which is derived from equation (11) at  $\delta=0$ :

$$\tau_m = \frac{R^2}{2a} \cdot \frac{T_0}{T_f - T_\xi}. \tag{12}$$

Kinetic ratio (11) can be used to experimentally determine the value of the thermal conductivity coefficient  $a$  if, during the experiment, a change in the relative temperature over time is measured.

### 5.2. Results of determining the temperature conductivity at the surface of a sample of the fire-proof fabric under the thermal impact

To establish the temperature conductivity through an intumescent coating on the surface of the fabric, studies were conducted using a radiation panel that simulates an ignition source [17]. The results of studying the ignition of a fabric sample under laboratory conditions are shown in Fig. 5, 6.

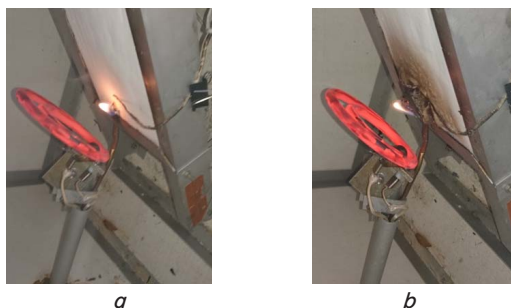


Fig. 5. Determining the fabric fire-protection effectiveness under the action of a burner: *a* – thermal impact on fabric; *b* – coating swelling



Fig. 6. Results of testing the fire-protected fabric: forming a thermally insulating layer of coked foam on the surface of the fabric

When the samples of the fire-retardant fabric were exposed to the flame of the burner, intense swelling occurred, and a slight increase in the temperature on the inverted surface of the sample began. As a result of our tests, it was found that under the influence of the flame of the radiation panel, the swelling for the model sample of the fabric treated with a flame retardant composition was about 20 mm.

The study results after experimentally determining in the laboratory the dynamics of the temperature of fabric samples are shown in Fig. 7 in the form of experimental curves, which were built by using the above procedure.

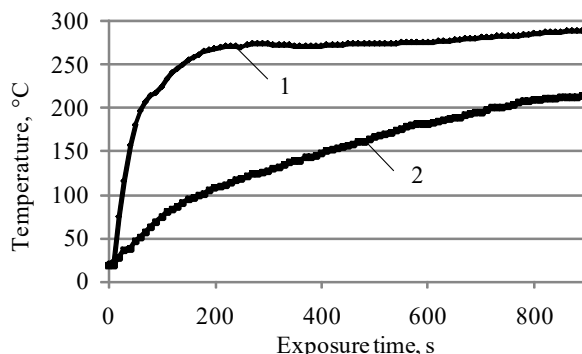


Fig. 7. The dynamics of a temperature increase at the fabric surface under the influence of a burner: 1 – flame temperature; 2 – temperature on the inverted surface

Our studies have shown that when a burner flame acts on a fabric sample during an exposure time of 900 s, the temperature is above 270 °C (curve 1), which is sufficient to ignite it [18]. The coating swelled for 300 s, and the temperature (curve 2) on the inverted surface did not exceed 215 °C.

Fig. 8 shows experimental data on the process of decomposition of the coating into a layer of coked foam in the coordinates  $\delta - \tau^{1/2}$  s, where  $\delta$  is the current value of the relative proportion of intact coating.

After measuring the tangent of the tilt angle of the experimental line, we obtain the following expression:

$$\text{tg}\alpha = \left( 2 \frac{a}{R^2} \frac{T_f - T_\xi}{T_0} \right)^{1/2}, \tag{13}$$

whence the value  $a$  can be calculated for the known values of  $T_f$ ,  $T_\xi$  and  $R$  as we assume the following:

$$\operatorname{tg}^2\alpha = \frac{2a}{R^2} \cdot \frac{T_f - T_\xi}{T_0}, \quad (14)$$

$$a = \frac{R^2}{2} \operatorname{tg}^2\alpha \frac{T_0}{T_f - T_\xi}, \quad (15)$$

where  $R$  is the thickness of the coked foam layer that is formed on a fabric surface, 16 mm;

$T_0$  is the initial temperature of the sample, °C;

$T_f$  is the temperature of a heated surface under the thermal impact, °C;

$T_\xi$  is the temperature on the inverted surface of the sample, °C.

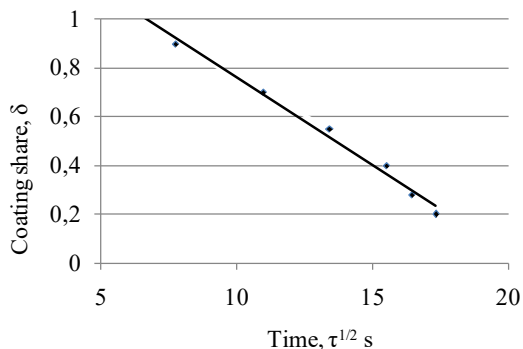


Fig. 8. Experimental data on the process of coating decomposition into a layer of coked foam

Based on the plot, we determine  $\operatorname{tg}\alpha$ , and then calculate the value of the thermal conductivity of coked foam, which is  $8.9 \times 10^{-6} \text{ m}^2/\text{s}$ . The calculated time of complete decomposition of the coating and the formation of a layer of coked foam is 57 s.

Thus, our studies to determine the thermal conductivity of the foam layer on the fabric surface match the properties of the formation of a heat-resistant foam layer under the action of high-temperature flame and thus demonstrate the resistance of the intumescent coating to high flame temperatures.

## 6. Discussion of results of studying the thermal conductivity process when protecting fabric against fire using an intumescent coating

When studying the process of protecting fabric against fire using an intumescent coating, it follows from the results (Fig. 7, 8) that it is natural to extend the time of temperature transfer through the fireproof fabric. This is due to the formation of a swollen layer of coked foam on the surface of the fabric during the decomposition of the intumescent coating under the action of flame, which slows down the processes of heat transfer to the fabric and its ignition.

It should be noted that the presence of an intumescent coating leads to the formation of an elastic film on the surface of the fabric resistant to vibrations under normal conditions. Obviously, this operational mechanism of the intumescent coating is the factor regulating the process, due to which the fire resistance of the fabric is maintained. In this sense, there is an interpretation of our results from determining the non-combustibility of the fabric after exposure to flame, namely the formation of a heat-insulating layer of coked foam when exposed to heat. The temperature on the inverted sur-

face of the sample was not more than 215 °C. This indicates the formation of a barrier for temperature, which can be identified by the method of thermal effect on the examined samples.

This means that considering this fact opens the possibility for effective adjustment of the properties of fire-retardant fabric directly under the conditions of industrial production.

The comparison of the experimental studies into the formation of a coked foam layer in the fabric fire protection with an intumescent coating and the theoretical studies of thermal insulation of the fabric indicates the inhibition of thermal conductivity processes. The temperature on the inverted surface did not exceed 215 °C, and the formed layer of coked foam is more than 16 mm. This does not differ from the practical data known from [4, 5], the authors of which also link the effectiveness of fire protection with the formation of a coked foam layer during the decomposition of the intumescent coating under the influence of the burner flame. But, in contrast to the results of studies reported in [6, 11], our data regarding the effect of coked foam on the process of inhibition of temperature transfer, allow us to suggest the following:

- the main regulator of the process is not so much the formation of a significant amount of gases that inhibit the flame since some fire-retardant coatings are destroyed under the influence of high temperatures;

- a significant influence on the process of fabric protection when applying a fire-retardant coating is exerted towards the formation of a layer of coked foam from the intumescent coating on the surface of the fabric resistant to destruction under the action of vibrations of the article.

Such conclusions can be considered appropriate from a practical point of view as they provide a reasonable approach to determining the required amount of a flame retardant. From the theoretical point of view, they allow us to argue about determining the mechanism of temperature inhibition processes, which are certain benefits of this study. However, it is impossible not to note that the results (Fig. 6) indicate an ambiguous effect of the coked foam layer on a change in fire-retardant efficiency. This is manifested primarily by the temperature on the inverted surface of the sample when testing fire-retardant fabric. Such uncertainty imposes certain restrictions on the use of our results, which can be interpreted as shortcomings of this study. The inability to remove these limitations in the current study points to potentially interesting areas for further research. In particular, it can be focused on detecting the time at which the fall of fire-retardant properties and the ignition of the fabric under the influence of high temperature begin. Detecting that would make it possible to investigate the structural transformations of the intumescent coating, which begin to occur at that time, and to determine the input variables of the process that significantly affect the onset of such a transformation.

## 7. Conclusions

1. The process of temperature transfer by fabric during its protection by intumescent coating has been modeled; the coefficient of thermal conductivity was determined, and the dependences have been built, which make it possible to find a change in the heat transfer dynamics when a coating swells. Based on the experimental data and the established dependences, the coefficient of thermal conductivity of the

coked foam layer on the fabric surface was calculated, which is  $8.9 \times 10^{-6} \text{ m}^2/\text{s}$ , due to the formation of the heat-insulating coked foam layer.

2. Features of inhibition of the process of temperature transfer to the material treated with an intumescent coating are the formation of a heat-protective layer of coke on the fabric surface. Thus, a temperature was achieved at the surface of the sample that significantly exceeded the ignition temperature of the fabric, and, at the unheated surface, did not exceed 215 °C.

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