Створення екологічно безпечних вогнезахисних матеріалів для дерев'яних будівельних конструкцій дозволить впливати на процеси термостійкості і фізико-хімічні властивості захисного покриття протягом його терміну експлуатації. Тому виникає необхідність дослідження умов утворення бар'єру для теплопровідності і встановлення механізму гальмування передачі тепла до матеріалу. У зв'язку з цим розроблена математична модель процесу теплопровідності при застосуванні вогнезахисної тканини в якості покриття, рішення якої дозволяє отримати зміну теплопровідності матеріалу. За експериментальними даними розраховано, що коефіцієнт теплопровідності при вогнезахисті, в межах температури від 0 до 110 °С, підвищується за рахунок випаровування води, а потім поступово знижується до згодом 0,25 Вт/(м·°С), що відповідає значенню пінококсу. Доведено, що процес гальмування температури полягає в утворенні сажоподібних продуктів які ізолюють дерев'яну конструкцію. Завдяки цьому стало можливим визначення умов вогнезахисту деревини, шляхом утворення бар'єру для теплопровідності з вогнезахищеної тканини. Експериментальними дослідженнями підтверджено, що зразок деревини вогнезахищеної тканиною витримав температурний вплив, а саме – при впливі теплового потоку відбувалося спучування покриття, теплоізолювання тривало протягом 900 с. Проведено оцінку максимально можливого проникнення температури через товщу покриття. Встановлено наступне: при створені температури поверхні зразка, що значно перевищила температуру займання деревини, під тканиною температура не досягла температури займання, а на необігрівній поверхні не перевищила 100 °С.

Таким чином, є підстави стверджувати про можливість спрямованого регулювання процесів вогнезахисту деревини шляхом застосування вогнезахисних покриттів, здатних утворювати на поверхні матеріалу захисний шар, який гальмує швидкість вигорання деревини

Ключові слова: захисні засоби, вогнестійкість, втрата маси, оброблення поверхні, вигорання деревини, вогнестійка тканина

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DETERMINATION OF THE LAWS OF THERMAL RESISTANCE OF WOOD IN APPLICATION OF FIRE-RETARDANT FABRIC COATINGS

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1. Introduction

Given that the main material for making structures is wood, which belongs to the group of medium flammability materials, there is a need for flameproofing with modern effective means. Its essence lies in providing wood with the ability to resist flame and flame propagation on the surface, preventing free access of oxygen, which accelerates the combustion process, can eliminate the risk of fire [1, 2].

Application of coatings allows slowing down material heating due to the formation of a protective layer and preserving its functions in case of fire for a given period of time [3, 4].

The peculiarity of fire protection of building structures consists in the creation of heat shields on the surface of structural elements, which withstand high temperatures and direct fire. In addition, they allow slowing down material heating and preserving its functions in case of fire for a specified period of time, thereby making wood hard-combustible. A promising way to reduce the fire risk of a wooden structure may be using fire-retardant fabric for wrapping wood or products.

2. Literature review and problem statement

The feature of flameproofing of wooden building structures consists in the creation of heat shields on the surface of elements that withstand direct fire and allow preserving their functions for a specified period of time. In [5], the description of the behavior of the fire-retardant coating is presented, which is a separate and complex task and covers both the swelling of the coating and the subsequent heat transfer. However, issues related to determining the temperature of coked foam formation remain unresolved. In [6], the effect of binder based on vegetable raw materials on the properties of flexible heat-insulating materials is also considered, but the issue of combustibility is not addressed. In [7], the effect of thermal modification as well as fire protection properties by such combustion characteristics as weight loss, burning rate is investigated, but no chemical changes caused by these factors are indicated. The materials given in [8] are characterized by high fire resistance, but the mechanism of coke formation and temperature transitions during thermal action are not shown.

The efficiency of organic coating components is shown in [9], where flame retardants based on polyphosphoric acids and foamers can affect coked foam formation. However, there is a need to investigate the conditions for forming a barrier to thermal conductivity and determine the effect of the coating to form a coke layer.

In [10], the most promising compositions of swelling coatings are presented, which are complex systems of organic and inorganic components, but the issues of the joint action of coating components during foaming remain unresolved.

A significant increase in the resistance, density and strength of the protective layer is achieved by directed formation of certain additives that form high-temperature compounds [11]. However, no relevant physicochemical calculations are provided to confirm this process.

In addition, many coatings have a number of disadvantages, such as the influence of individual components, loss of functional properties with increasing temperature [12]. This means that it is not known how the process proceeds at temperatures within the decomposition of the fire-retardant coating.

Studies of protective materials made of organic substances with colemanite ore solution are also carried out [13]. It is shown that due to the determined ratios it is possible to adjust the contents of components to ensure the heat resistance process.

The synergistic effect of ammonium polyphosphate and alumina trihydrate as flame retardant components for an epoxy composition reinforced with natural fibers, as a flame retardant material is given in [14]. It shows that the compositions were not always able to provide effective flame resistance when the temperature changed. Therefore, there was a burning process with heavy weight loss, and new approaches are needed to solve this problem.

So, determining the parameters of the burnout rate of fire-resistant materials and the influence of their components on this process is an unresolved issue of ensuring the fire resistance of wooden building structures. This necessitated research in this area.

3. The aim and objectives of the study

The aim of the study is to identify patterns of heat resistance of wood when using fire-retardant fabric.

To achieve this aim, the following objectives were accomplished:

– to carry out a simulation of heat advancement in the wood when protected with fire-retardant fabric;

– to determine the features of a decrease in the heat permeability of wood during thermal action on a sample when applying a fire-retardant fabric coating.

4. Materials and methods of studying the burning rate of wood

4. 1. Materials used in the experiment

To determine the combustibility of wood, 310×140×6 mm samples of straightgrained pine wood with a density of 450×470 kg/m^3, covered with tarpaulin of article number 11293 (41 % cotton/59 % linen) were used, and a fire retardant was applied to wooden structures ("FIRE-WALL-WOOD") with a flow rate of 330 g/m^2 (Fig. 1).

Fig. 1. Wood covered with fire-retardant fabric

After drying to constant weight, the treated wood samples with the fire-retardant fabric coating were tested.

4. 2. Methods for determining the heat resistance of wood

For the study, a device was used to determine the flammability index of materials [2], which was additionally equipped with a device for measuring the surface temperature of the sample during thermocouple tests (Fig. 2).

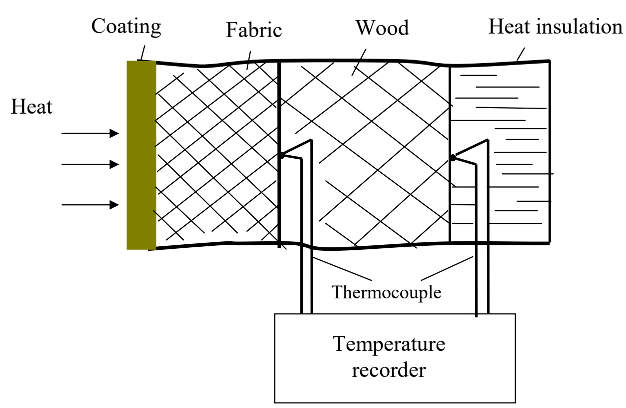

Fig. 2. Scheme of testing the heat resistance of the sample

Studies to determine the heat resistance of wood were carried out according to the method, which consisted in exposing the fire-resistant wood sample to a radiant panel and ignition, measuring the temperature in the sample layers and the time it was reached.

5. Modeling of heat resistance of wood when using fire-retardant fabric coating

To determine the effect of fire-retardant fabric on the thermal conductivity of wood and heat flux propagation through the wall of a wooden structure from external thermal impact, a numerical method was used [15].

The thermophysical model for the two-layer plate is presented in Fig. 3.

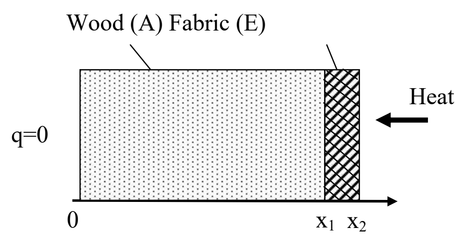

Fig. 3. Thermal scheme of the wooden structure wall

On the side of the fire-retardant fabric at the boundary x_2, convective-radiation heating is performed. In the model, sandwich heating is considered, so at the boundary $x=0$, the symmetry condition of the temperature curve corresponding to the absence of heat flow is accepted.

The mathematical model of the thermal conductivity process in such a two-layer plate describing the physical model is given as a one-dimensional equation of thermal conductivity with boundary conditions of the third kind at the boundary $x=x_2$. At the boundary $x=0$, this system is heat-insulated. The model is described by the equation of thermal conductivity and unambiguity conditions and has the following form:

– for $t>0,\ \ \delta_E<x<\delta,$

$$\theta_E=\theta_E(x,t),\ \ \theta(x,0)=\theta_0, \tag{1}$$

$$\frac{\partial}{\partial x}\left(\lambda_E\frac{\partial\theta}{\partial x}\right)=c_E\cdot\rho_E\frac{\partial\theta}{\partial t}, \tag{2}$$

$$\lambda_E\frac{\partial\theta(\delta_E,\ \mathrm{t})}{\partial x}=\alpha^*\left(\theta(t)-\theta(\delta_E,\ \mathrm{t})\right), \tag{3}$$

$$\alpha^*=\alpha_k+\frac{C_0\varepsilon}{\theta_E(t)-\theta(\delta_E,t)}\times$$
$$\times\left\{\left(\frac{\theta(t)+273.15}{100}\right)^4-\left(\frac{\theta(\delta_E,t)+273.15}{100}\right)^4\right\}; \tag{4}$$

– for $t>0,\ \ x=\delta_A,$

$$\lambda_E\frac{\partial\theta_E(0,t)}{\partial x}=\lambda_A\frac{\partial\theta_A(\delta_A,t)}{\partial x}; \tag{5}$$

– for $t>0\ \ 0<x<\delta_A,\ \ \theta_E=\theta_E(x,t),$

$$\frac{\partial}{\partial x}\left(\lambda_A\frac{\partial\theta}{\partial x}\right)=c_A\cdot\rho_A\frac{\partial\theta}{\partial t}; \tag{6}$$

– for $t>0,\ \ x=0,$

$$\lambda_A\frac{\partial\theta}{\partial x}\Big|_{x=0}=0, \tag{7}$$

where θ is the wall temperature, °C; x is the coordinate, m; t is time, s; λ_A, λ_E is the coefficient of thermal conductivity of wood and fabric, W×m^{-1}·°C^{-1}; c_A, c_E is the specific heat capacity of wood and fabric, J×kg^{-1}×°C^{-1}; ρ_A, ρ_E is the density of wall material and fabric, kg×m^{-3}; α^* is the total coefficient of heat transfer on the heated surface, W×m^{-2}×°C^{-1}; α_k is the coefficient of convection heat transfer on the heated surface, (25 W×m^{-2}×°C^{-1}); C_o is the radiating power of the black body, (5.67 W×m^{-2}×°C^{-4}); ε is the combined coefficient of thermal radiation of the "heating medium – heated surface" system, (0.5).

To solve the problem (1)–(7), numerical methods of analysis [15] using an explicit scheme were applied.

The calculation grid for determining the temperature in the fire-retardant fabric is represented by nodes in the space $k=1...K$, obtained by conditional division of the sample into sections with a step $x_k=\Delta x\cdot(k-1)$, $\Delta x=\delta_E/(K-1)$ and time layers n with a step ΔFo. This grid provides the stability of the explicit scheme in the calculation by the four-point pattern, provided that

$$\Delta Fo=\frac{\lambda_E\cdot\Delta\tau}{c_E\cdot\rho_E\cdot\Delta x^2}\langle 0{,}5$$

and replacing differential equations with finite difference equations.

Accordingly, the system of finite difference equations (1)–(7) takes the following form:

– the temperature $\theta_E^{t+1}(\delta_E)$ at time $\tau+\Delta\tau$ with the coordinate $x_k=\delta_E$, located on the surface of the fire-retardant fabric, is determined by the expression:

$$\theta_E^{t+1}(\delta_E)=\theta_E^t(\delta_E)-$$
$$-2\cdot\Delta Fo\left[\theta_E^t(\delta_E)-\theta_E^t(\delta_E-\Delta x)\right]+$$
$$+\frac{2\cdot\alpha^*\cdot\Delta Fo\cdot\Delta x}{\lambda_E}\cdot\left[\theta_t-\theta_E^t(\delta_E)\right]; \tag{8}$$

– the temperature $\theta_E^{t+1}(x_k)$ at the inner points of the fire-retardant fabric with coordinates $x_k=\Delta x\cdot(k-1)$ is determined by the expression:

$$\theta_E^{t+1}(x_k)=\theta_{E,k}+\Delta Fo\cdot\begin{bmatrix}\theta_{E,k}(x_{k+1})-\\-2\cdot\theta_{E,k}(x_k)+\\+\theta_{E,k}(x_{k-1})\end{bmatrix}; \tag{9}$$

– for the point $k=1$ and the corresponding coordinate $x_1=0$, located on the "fire-retardant fabric – wood" boundary, the temperature at time is determined by the expression:

$$\theta_{E,t+1}(0)=\theta_{E,k}(0)+2\cdot\Delta Fo\times$$
$$\times\left[\theta_{E,k}(x_k)-\theta_{E,k}(0)\right]/\left(1-\frac{2\cdot c_A\cdot\rho_A\cdot\delta_A}{c_E\cdot\rho_E\cdot\Delta x}\right). \qquad (10)$$

The calculation grid for determining the wood temperature is presented in the same way, with the same step, and the temperature $\theta_A^{t+1}(x_k)$ at the inner points of wood is determined by the expression:

$$\theta_A^{t+1}(x_k)=\theta_{A,k}+\Delta Fo\times$$
$$\times\left[\theta_{A,k}(x_{k+1})-2\cdot\theta_{A,k}(x_k)+\theta_{A,k}(x_{k-1})\right]. \qquad (11)$$

Thus, temperature dependencies are derived for calculating the thermal conductivity when using the fire-retardant fabric coating on wood.

6. Results of determining the heat permeability of wood during thermal action on the sample

Fig. 4 shows the process of ignition and flame propagation on the sample of wood covered with the fire-retardant fabric.

a *b* *c*

Fig. 4. Sample burning process: *a* – effect of flame, *b* – swelling of the fire-retardant fabric, *c* – wood after testing

As can be seen from Fig. 4, under the influence of temperature, the fire-retardant fabric swelled and formed a protective layer of coke on the sample surface. This significantly affected the wood burning process, but at the point of the greatest thermal impact, the wood changed color.

Fig. 5 shows the dependence of temperature on the sample surface and at points according to Fig. 2. As can be seen from Fig. 5, a temperature exceeding the ignition temperature of the wood was created on the sample surface, the temperature under the fabric did not reach the ignition temperature and did not exceed 100 °C on the unheated surface.

The regression dependencies of wood surface temperature on the time of fire action are obtained, described by the following dependencies:

$$\nu(t)=a_0+a_1\cdot t+a_2\cdot t^2, \qquad (12)$$

where t is the time of thermal action on the sample, s; a_0, a_1, a_2 are regression coefficients.

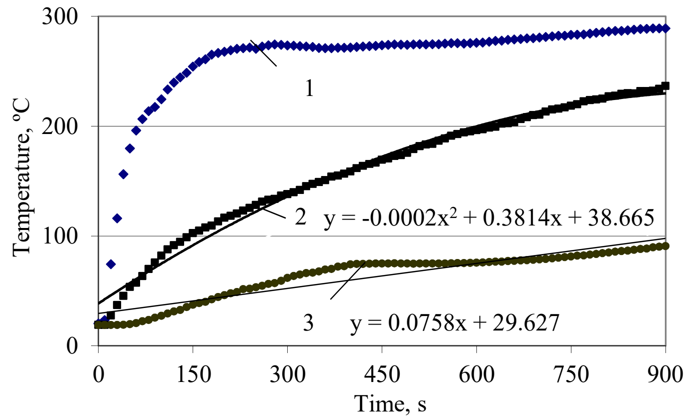

Fig. 5. Temperature dependence during the fire resistance test of the wooden structure with the fire-retardant fabric on the duration of fire exposure: 1 – on the surface of the fire-retardant fabric; 2 – beyond the fire-retardant fabric and on the wood surface; 3 – on the unheated wood surface

Table 1 shows a sample of experimental data on thermal penetration of the sample during thermal action.

Table 1

Sample of experimental data on penetration

Time, s	Sample surface temperature, °C during thermal action		
	External	Beyond the fabric	wood
0	20.1	19.1	18.8
30	116	37	18.9
60	196.1	57.4	20.5
90	217.4	75.7	25.5
120	239.7	91.5	31.1
150	254.3	102.6	37.2
180	265	109.4	42.1
210	269.1	118.3	47.7
240	271.5	125.5	51.9
270	273.5	132.8	56.2
300	273.4	137.9	61.7
330	272.5	145.1	66
360	271	150.6	69.4
390	271.3	156.6	72.3
420	272.4	163.8	74.5
450	273.6	169.4	74.9
480	274.2	173.6	74.9
510	274.5	181.7	74.8
540	274.6	186.8	74.9
570	275.4	192.8	75.1
600	275.9	196.3	75.5
630	277.5	199.5	76.5
660	278.9	203.4	77.2
690	280.1	210	78.2
720	281.7	215.1	79.5
750	283	218.6	81.3
780	284.3	223.8	83
810	286.2	227.2	84.9
840	287.3	230	86.6
870	288.5	231.9	88.4
900	289	236.7	90.7

The experimental data were processed by the least squares method. Variance was minimized

$$D = \left[\nu(t_i) - T_i \right]^2, \quad (13)$$

where $\nu(t_i)$ are the theoretical values of the temperature defined by the formula (2); T_i are experimental values of temperature.

After minimizing D, the mean square deviation σ was calculated by the formula

$$\sigma = \sqrt{D / (n - n_0)}, \quad (14)$$

where n is the number of measurements; n_0 is the number of unknown parameters.

The results of processing experimental data are given in Table 2.

Table 2

Results of processing experimental data on the thermal penetration of the sample during thermal action

Temperature measurement point	Parameter value			
	a_0	a_1	a_2	σ
beyond the fire-retardant fabric	38.665	0.3814	–0.0002	3.12
on the unheated wood surface	29.6270	0.0758	0	2.44

Based on the results of temperature measurements obtained during the tests (Fig. 5), as well as temperature sampling, the coefficient of thermal conductivity of the fire-retardant fabric at different temperature values was calculated using a computer program based on equations (8)–(11).

As can be seen from Fig. 6, as the temperature increases, the coefficient of thermal conductivity of fire-retardant fabric increases due to water loss and degassing of the coating, and then gradually decreases to 0.25 W/(m·°C), which corresponds to the value of the coke residue.

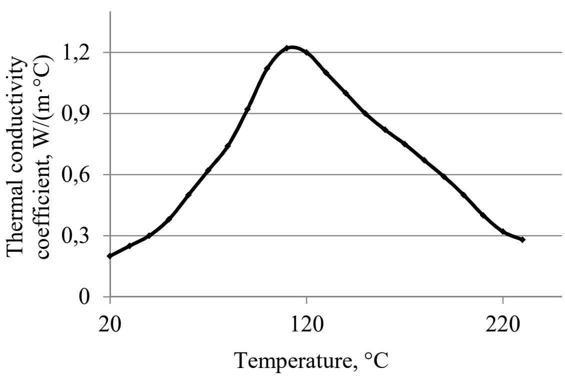

Fig. 6. Dependence of the coefficient of thermal conductivity of the fire-retardant fabric on temperature

The presence of extremes of thermophysical characteristics in the region of 110 °C is explained by the fact that at this temperature there is the process of water dehydration in the wood, accompanied by endothermic reaction and intense thermal conductivity due to water vapor.

7. Discussion of the results of the study of the heat transfer process

Under the action of high-temperature flame on the wood sample with fire-retardant fabric, as indicated by the results of studies (Fig. 4), the ignition process can occur when the material is heated to a critical temperature. At this temperature, there is an intense decomposition of organic material with the formation of the required amount of combustible gases and their ignition and flame propagation on the surface. Therefore, one way to slow down the decomposition of wood is to insulate high temperature. When creating a shield of fire-retardant fabric, the ignition process is suppressed, the temperature on the unheated surface did not exceed 100 °C (Fig. 5). Obviously, such a mechanism of influence is a factor in controlling the formation of combustible gases and efficiency of thermal insulation. This is in agreement with the data known from [5, 6], whose authors also associate the process of material ignition depending on the effectiveness of fire protection of the fabric. In contrast to the results of [7, 8], the data obtained on the influence of the ignition process on heat transfer to the material and changes in insulating properties suggest the following:

– the main regulator of the ignition process is not only the achievement of the critical temperature, but also the formation of the required amount of combustible gases, decomposition of flame retardants under the action of temperature with the absorption of heat and release of non-combustible gases, inhibition of the oxidation process in the gas and condensed phase;

– the process of protection of combustible material when applying fire-retardant fabric is significantly affected by creating a heat shield of a non-combustible layer of coke on the fabric surface.

The results of detecting the inhibition of ignition and flame propagation on the material based on wood and fire-retardant fabric are associated with the formation of a heat-insulating layer (Fig. 4) and indicate the ambiguous effect of flame retardant. Such uncertainty cannot be resolved within the framework of this study, since sufficient data are required for the inhibition of heat transfer. Such detection will allow investigating the transformation of the surface of the material based on wood and fire-retardant fabric and identifying those variables that significantly affect the beginning of the transformation of this process.

8. Conclusions

1. Simulation of the heat transfer process in wood with fire-retardant fabric coating is carried out, the coefficient of thermal conductivity is determined, and dependencies are obtained, which allow obtaining changes in the heat transfer dynamics when the fire-retardant fabric is swollen. According to the obtained dependences, it is found that the coefficient of thermal conductivity during fire protection within the temperature range from 0 to 110 °C increases due to water evaporation and then gradually decreases to 0.45 W/(m·°C), which corresponds to the value of coked foam.

2. Features of inhibition of heat transfer to the material with fire-retardant fabric cosist in forming the heat-insulating layer of coke. Thus, a temperature was created on the sample surface that significantly exceeded the ignition temperature of the wood, the temperature under the fabric reached the ignition temperature, and on the unheated surface did not exceed 100 °C.

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