This paper reports the analysis of compositions for fire protection of wood that established that there are not enough data to explain and describe the process of fire protection and, accordingly, the fire-hazardous properties of wood, in order to protect people. The development and research of a set of properties of fire-resistant materials leads to the design of new types of such materials. The object of this study was a fire-protective two-component intumescent varnish for wood. The essence of the research is to determine the indicators of fire danger of wood, fire-protected by coatings, and the impact exerted on them by the formed heat-insulating layer of coke, making it possible to justify the effectiveness of the fire-retardant coating under the influence of temperature. The volume of fire-retardant and hydrophobic coating has been optimized, which ensures the lowest value of loss of mass by fire-protected wood during thermal action. Its lowest value was determined when using flame retardant in the volume of 589 g/m^2 and a hydrophobic agent in the volume of 54 g/m^2. When determining the combustibility of fire-resistant wood, it was established that the temperature of flue gases during tests was no more than 103 °C, the length of damage to the sample did not exceed 143 mm. At the same time, the weight loss did not exceed 19 g, and the independent burning of wood did not exceed 23 s. In addition, the wood withstood the surface effect of a heat flow of 35 kW/m^2, while surface combustion did not occur, and the value of the coefficient of smoke formation was 432 m^2/kg during the smoldering of the fire-proof sample. Unlike wood protection with fire-retardant swelling paint, the fireproof wood with two-component varnish, does not change color and refers to low combustibility materials; it is hard to ignite, dose not spread the flame by surface, with moderate smoke-forming ability. The practical significance is the fact that a certificate of conformity was issued based on the reported results. Thus, there are grounds to assert the possibility of directed adjustment of wood fire protection processes by using coatings that can form a protective layer on the surface of the material

Keywords: protective equipment, fire-protected wood, indicators of fire danger of wood, weight loss, wood surface treatment

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ESTABLISHING REGULARITIES IN THE REDUCTION OF FLAMMABLE PROPERTIES OF WOOD PROTECTED WITH TWO-COMPONENT INTUMESCENT VARNISH

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1. Introduction

Wood and articles from it are widely used in engineering, construction, and everyday life and account for a significant percentage of the fire load. According to fire and building codes and rules, these materials are classified as materials of high combustibility, flammable, they significantly spread flames, with high smoke-forming ability. One of the methods of improving the level of fire safety of objects where construction structures made of wood are used is the application of their fire-retardant treatment.

Therefore, the effectiveness of fire protection of wood depends both on the quality of the fire retardant and on the class of operating conditions of the object where timber structures are used. The simplest high-temperature and fire protection means based on liquid glass during fluctuations in temperature and humidity fields do not provide sufficient adhesion strength since they have a large temperature coefficient of linear expansion. Therefore, their use for objects of mass stay of people, which are made of wooden structures and operated without heating, is not advisable. An example is a fire in the children's camp "Victoria", Odesa (Ukraine), when fire safety measures were ignored.

In addition, individual fire retardants on an organic basis, together with a decrease in combustibility at high temperatures, increase smoke-forming capacity and emit toxic combustion articles. In addition, the hydrophobic coating of the surface of the wood can increase flammability and spread flames.

Therefore, studies aimed at determining the fire-hazard properties of new flame retardant compositions, establishing the number of coating components for inhibiting the combustion process, are relevant.

2. Literature review and problem statement

One of the objectives of preventive protection of the structure against fire, described in [1], is to prevent the spread of fire and smoke for a certain period so that the necessary fire and rescue work can be carried out. This is achieved, among other things, due to the requirements for fire resistance of components exposed to fire. However, fire resistance coatings and tests must be adapted and refined for increasingly complex applications and tougher requirements. The cited work reveals material from prescriptive assessment to assessment based on the characteristics of complex components in individual fire scenarios. The research presents and discusses approaches to new challenges for reactive fire protection systems under extreme conditions, as well as options for their testing. The focus is on newly developed laboratory testing methods to examine new coating materials and to assess particular or material-specific aspects of fire resistance under extreme conditions. However, it is not shown for which classes of exploitation they belong.

Paper [2] shows that polydimethylsiloxane, modified on the basis of silica geopolymer, makes it possible to create a new complex hybrid coating that does not cause combustion. Also considered is the effect of viscosity of polydimethylsiloxane on fire resistance and microstructure, which is estimated as 350 cps according to the results of cone viscosimeter. The inclusion of polydimethylsiloxane causes a decrease in the percentage of weight loss when burning to 52.51 % and an average combustion rate of up to 0.0674 m/s, as well as a good smoke suppression. However, excessive viscosity of polydimethylsiloxane shows unfavorable fire resistance to hypo-polymer coating based on silicon dioxide.

To improve fire resistance, work [3] used expanded graphite, carbon nanotubes, fuller. The effect of carbon materials on fire protection and smoke suppression of the water distribution coating is thoroughly investigated by a fire resistance test, thermogravimetry with a differential scanning heat meter, a smoke density test, and a water resistance test. The results of the fire protection test showed that the fire resistance of the coatings was increased by adding 1 % of the content of carbon materials. Analysis of thermogravimetry showed that carbon materials can increase residual mass and heat resistance of coatings. According to the results of the test for water resistance after immersion in water for 360 hours, carbon materials can form a barrier to increase the water resistance of coatings. In particular, graphene demonstrated the best performance among all carbon materials. It is not given what served as binders.

Work [4] uses an interphase treatment strategy to address the issues of delayed combustion, rather than adding flame retardants to composites. Composition in an aqueous solution of polyelectrolyte complexes consists of polyethylene exchange and ammonium polyphosphate at room temperature. The formed coating has a high fire resistance, demonstrating a high oxygen limit of 43 %, and a decrease in the maximum heat release rate by 47 % from tests for cone calorimetry. In addition, ammonium polyethylene and ammonium polyphosphate coating significantly improved the interaction between carbon fiber and matrix and improved the mechanical properties and bonding temperature of the composite. Therefore, the cited work presents an effective and attractive strategy for the development of fiber-reinforced composites with good fire retardant and mechanical properties for future mass production. However, there remain unresolved issues that are associated with the mechanism of formation of foam coke. The reason for this may be subtleties regarding the formation of a protective layer, which, accordingly, makes such studies difficult.

In [5] studies were aimed at creating compositions in which melamine-amino trimethyl phosphate was mixed with starch, chitosan, or sodium lignosulfonate. This composition was used to prepare a swelling flame retardant vinyl acetate-ethylene copolymer emulsion, which can be used to create adhesives, coatings, etc. The flammability of adhesives was assessed using the limiting oxygen index, vertical combustion, and cone calorimetry tests. The presence in the composition of 30 % by weight of amino trimethyl phosphate compounds in the polymer resulted in a 73 % decrease in the peak rate of heat release (from 139.2 to 37.1 kW/m^2). It is established that the formation of a bubble layer of carbon can be facilitated by polyphosphoric acid and benzol-sulphonic acid along with ammonia and sulfur dioxide, which are formed as a result of thermal decomposition of synthesized melamine-amino trimethyl phosphate and lignosulfonate during polymer combustion. In addition, that led to an increase in tensile strength and elongation by 56 % and 40 %, respectively, during tests, compared to a pure matrix. However, nothing is said about the impact of environmental change on the coating, its destruction in time.

Study [6] was conducted to obtain a new fire-retardant coating for wood using acrylate oligomers and functional monomers containing elements of phosphorus, nitrogen, and sulfur. To investigate the flammability and pyrolysis properties of coatings, a test for the limiting oxygen index and thermal gravimetric analysis and infrared spectroscopy were used. Experimental data have shown that the coating has better fire resistance on the surface of the wood at a molar ratio of phosphorus monomer and nitrogen of 2:4. Volatile substances formed in the coating degradation processes are confirmed by TGA-FTIR, namely the temperature of the maximum release speed of 99.80 °C, 170.96 °C, 346.75 °C, and 358.80 °C, respectively. In addition, the coating released NH_3 and CO_2 in the form of non-combustible gases during the degradation process, which diluted the concentration of oxygen during combustion and was favorable for the formation of a swelling layer of coal. The coating's TGA curves showed three degradations corresponding to water loss and rupture of the C–S binding networks, the degradation of phosphate and acrylates, the decay of unstable carbon layers, and polyphosphoric acid formation, respectively. The yield of coating charring reaches 27.16 % at 600 °C in the nitrogen atmosphere, demonstrating good fire-retardant properties. However, nothing is said about the impact of environmental change on the coating and its destruction over time.

In work [7], phosphate-acrylate monomer (PGMA) was used for fire protection, which was synthesized with phosphoric acid and glycidyl methacrylate using a ring opening reaction and melamine-acrylic ether (MAAR). As a result, a set of refractory coatings with different proportions and fire resistance of wood was created. The properties were investigated using a limit oxygen index (LOI) test, a temperature test, and a cone calorimeter test. When wood was covered with a composite containing 33.3 % PGMA and 66.7 % MAAR, the total heat release decreased from 39.0 to 38.2 MJ/m^2, showing significant improvement in fire resistance. Thus, this fire-retardant coating is easy to prepare, cheap and efficient, and can contribute to the wider use of timber. However, the effect of aging on fire protection and mechanical properties of fire-retardant coating has not been studied.

Paper [8] investigated the durability of the fire-retardant properties of a transparent fire-resistant coating for the structure of wood using accelerated hygrothermal aging. The effects of aging were analyzed using morphological analysis and a fire test. The results show that after 21 days of aging, fire retardant components gradually fall to the surface. The coating mainly loses the ability to expand, and the charred layer demonstrates a low-strength plate structure. Fire resistance of the coating decreased by 43.48 % from 23 minutes to 13 minutes.

Studies have been conducted in paper [9] to investigate the bio functionality of wood that was fireproofed. To do this, the wood was treated with sodium silicate, and subsequent means, such as boric acid, ammonium borate, diammonium phosphate, were used to fix fire protection. At the same time, the leaching resistance was improved by 10 %. The flame retardant combination, which contains sodium silicate, boric acid and diammonium phosphate, showed high hygroscopic properties and corrosion efficiency against metals. However, nothing is said about the impact of environmental change on the coating and its destruction over time.

Paper [10] prepared a new TW fire retardant (FRTW) with excellent optical properties and fire resistance through the use of ether phosphate-polyethylene glycol (PEAG). During thermogravimetric analysis, TW/PEAG has a 60 % decrease in peak mass loss and a 2.5-fold increase in foam coke residues compared to natural wood, indicating increased thermal stability. Its peak heat release rate, total heat release, and heat of combustion were reduced by 82.4 %, 84.3 %, and 80.8 % to the indicators obtained when using a fire retardant based on epoxy resin. The limiting oxygen index and experimental flammability results also indicate increased fire-retardant characteristics of TW/PEAG. The increased fire resistance of TW/PEAG was associated with ether phosphate-polyethylene glycol, which contributed to the formation of a thermal insulation layer of carbon and reduced heat release. In addition, TW/PEAG showed good mechanical performance as it demonstrated a tensile strength of 153.6 MPa and a 2.2 GPa elasticity module. However, nothing is said about the impact of environmental change on the coating and its destruction over time.

Thus, our review of literary sources [1, 3, 4, 6, 8, 10] has revealed that fire retardant coatings are able to protect the surface of wood from the effects of fire during operation but parameters that ensure the resistance of fire retardant coatings to high temperatures have not been defined. The lack of experimental studies to explain and describe the process of fire protection of wooden structures of objects of mass stay of people leads to a decrease in effective protection. Moreover, neglecting fire danger indicators such as combustibility, flammability, the spread of flames by the surface, smoke-forming ability leads to the death of people under the influence of flames. Therefore, the establishment of parameters for the protection of wood and the impact of coatings on this process predetermined research in this area.

3. The aim and objectives of the study

The purpose of this work is to identify patterns of reducing the fire danger indicators of wood in fire protection with two-component intumescent varnish, namely combustibility, flame spread by the surface, smoke-forming ability. This makes it possible to justify the use of fire-retardant coating at the objects of mass stay of people.

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

– to optimize the volume of fire retardant and hydrophobic coating, which provides the lowest value of weight loss by fire-protected wood during the decomposition of fire-retardant coating under the influence of high temperature;

– to establish indicators of fire danger of wood protected by fire retardant varnish and hydrophobic coating.

4. Materials and methods to study the rate of burnout of wood

4. 1. Examined materials used in the experiment

The object of our study is a fire-protective two-component intumescent varnish for wood. The scientific hypothesis is to reduce the indicators of fire danger of wood in fire protection with two-component intumescent varnish.

To establish the effectiveness of fire protection of wood, we used samples of straight-layer wood pine; density, 420...470 kg/m^3. The fire retardant for wooden structures ("FIREWALL-LAC") (Ukraine) and the protective finishing varnish "Alkydno-Polyurethane varnish" (TM "Composite") (Ukraine) (Fig. 1) were applied onto the surface of the wood. To establish the indicators of fire danger of wood, wood samples were used in accordance with test methods and in accordance with their quantity.

After drying to a constant mass of fire-retardant wood, tests of treated wood samples were carried out.

Fig. 1. Model samples of wood for testing

4. 2. Methodology for determining the indicators of the properties of fire-retardant coating samples of wood

We determined the effectiveness of fire protection of wood in accordance with [11]. The essence of the test method for the effectiveness of fire protection of wood is to influence the sample located in the installation by the flame of the burner with specified parameters. At the same time, an increase in the temperature of flue gases and weight loss of the sample are recorded, according to which the parameters of wood combustion are assessed [12].

Requirements for combustibility, flammability, flame index, and wood smoke formation and their classification complied with [13]. The evaluation of wood treated with coating was carried out based on the results of thermal action of high temperature on a wood sample [14].

The method for determining combustibility is to evaluate samples after thermal action according to the following parameters: flue gas temperature, the degree of damage by length, the degree of damage by weight, the duration of self-combustion [15]. Building materials, depending on the values of combustibility parameters, are divided into four groups of combustibility G1, G2, G3, G4 in accordance with Table 1. When during the tests we obtained different values of combustibility, they are attributed to a lower value [16].

Table 1

Classification of combustible building materials

Combustibility group of materials	Flammability parameters			
	Flue gas temperature	Degree of damage in length	Degree of damage in weight	Duration of self-combustion
G1	<135	<65	<20	0
G2	<235	<85	<50	<30
G3	<250	>85	<80	<60
G4	>250	>85	>80	>60

Materials must be attributed to a certain group of combustibility, provided that all the parameter values set by Table 1 are matched.

The essence of the method for determining the parameters of the flammability of the material is at specified levels of impact on the surface of the sample of radiant heat flow from 30 kW/m^2 and a flame from the ignition source for 900 s [17]. In this case, the flash of the sample is recorded. According to the results of the tests, combustible building materials, depending on the value of the critical surface density of the heat flow, are divided into three groups (Table 2).

Table 2

Classification of combustible building materials by flammability

Flammability group of the material	Critical surface heat flux density, kW/m^2
B1	exceeding or equal to 35
B2	from 20.0 but less than 35.0
B3	less than 20.0

Tests to determine the group of flame spread across surface layers were determined by the method of experimental studies [18]. The essence is to determine the critical surface density of the heat flow at specified standard levels on the surface of the sample of radiant heat flow from the ignition source for 600 s. The length of the flame propagation is recorded. According to the results of the tests, combustible building materials, depending on the value of the critical surface density of the heat flow, are divided into three groups (Table 3).

Table 3

Classification of combustible building materials by flame distribution group

Flame spreading group	Critical surface heat flux density, kW/m^2	Flame propagation length according to the heat flux surface density distribution plot, mm
RP1	11. 0 and larger	less than 105
RP2	from 8.0 but less than 11.0	from 105 to 255
RP3	from 5.0 but less than 8.0	from 256 to 410
RP4	less than 5.0	larger than 410

When determining the coefficient of smoke formation, the optical conductivity of the formed flue gases is defined [19]. The essence of the method to experimentally determine the coefficient of smoke formation of solids and materials is to define the optical density of smoke, which is formed by flame combustion or smoldering of a sample of solid material of a certain volume [15]. Samples are tested in two modes. In the smoldering mode, only the heat flow with a density of (35±3.5) kW/m^2 operates, and under the mode of flame combustion, there is a heat flow and the flame of a gas burner.

The coefficient of smoke formation (D_m) in m^2/kg is determined from the formula:

$$D_m = \frac{V}{L \cdot m} \ln \frac{T_0}{T_{\min}}, \quad (1)$$

where V is the volume of the measurement chamber, V=(0.664±0.004) m^3;

L is the path of the beam of light in smoke, L=(0.800±0.002) m;

m is the sample weight, kg;

T_0, $T_{\min}$ are, respectively, the value of the initial and final light-passing, %.

Depending on the resulting coefficient of smoke formation, the materials are distinguished as follows:

– with a low smoke-forming ability – exceeding 50 m^2/kg;

– with a moderate smoke-forming ability – exceeding 50 m^2/kg up to 500 m^2/kg inclusive;

– with a high smoke-forming ability – smoke making coefficient is larger than 500 m^2/kg.

We determined the optimal ratio of the flame retardant and hydrophobic agent by finding the loss of mass by pine wood using a three-factor simplex-central method of planning an experiment in the mathematical environment Statistica 12 (Ukraine).

5. Studying the effectiveness of fire protection of wood coating based on organic and inorganic substances

5. 1. Optimization of the volume of the fire retardant and hydrophobic coating when studying the effectiveness of fire protection of wood

We established the volume of flame retardants and a hydrophobic agent in wood, provided that the minimum weight loss by the sample is achieved, during tests to determine fire retardant efficiency according to the standard procedure. As an object of our research, wood was used, coated with the fire retardant "Firewall Varnish" and the hydrophobic agent, single-component alkyd-polyurethane varnish, of the trademark "Composite" (Ukraine), which provides for wood coating in the volume of about 55...60 g/m^2. The results of our data are illustrated in Fig. 2, 3.

a *b*

Fig. 2. Wood sample:
a — before testing; *b* — after thermal action

As one can see from Fig. 5, the greatest efficiency of fire protection of pine wood is achieved at the slightest loss of mass when burning samples, that is, when the ratio of the volume of a hydrophobic agent to a flame retardant is minimal.

Taking into consideration the results of determining the weight loss by pine wood (Fig. 3), with the help of a three-factor simplex-central method of planning an experiment in the mathematical environment Statistica 12, statistical treatment of the results was carried out.

The following factors of variance were chosen: the volume of a hydrophobic agent, g/m^2 (factor X_1); the volume of coating, g/m^2 (factor X_2); the changes in them is given in Table 4.

Table 4

Variance factors

Factors	Code	Variance levels			Variance interval
		−1	0	+1	
hydrophobic agent volume, g/m^2	X_1	50	55	60	5
coating volume, g/m^2	X_2	500	580	660	80

As the initial parameter (response function), the loss of mass by the material was chosen, the value of which was recorded on samples exposed to fire. The matrix of planning the experiment and its mathematical implementation are given in Table 5.

As a result of our simulation, regression equations were built and the ternary surfaces of changes in the original parameter were constructed depending on changes in variance factors (Fig. 4).

Table 5

The matrix of the experiment and its implementation

No. of entry	Factor, designation		Planning matrix		Response function	
	X_1	X_2	hydrophobic agent volume, g/m^2	coating volume, g/m^2	Y actual	Y estimated
1	1	1	60	660	9	8.93
2	1	−1	60	500	14	13.67
3	−1	1	50	660	7	7.07
4	−1	−1	50	500	10	9.80
5	1	0	60	580	11	11.40
6	−1	0	50	580	8.4	8.53
7	0	1	55	660	6.2	6.20
8	0	−1	55	500	9.4	9.93
9	0	0	55	580	8.2	8.17
10	0	0	55	580	8.8	8.17
11	0	0	55	580	9.1	8.17

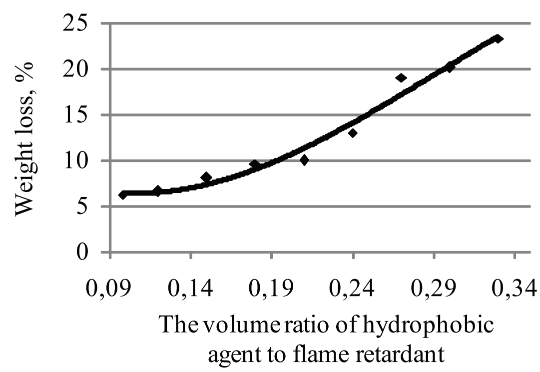

Fig. 3. Determining the mass loss (%) depending on the ratio of a hydrophobic agent to a flame retardant for pine wood samples

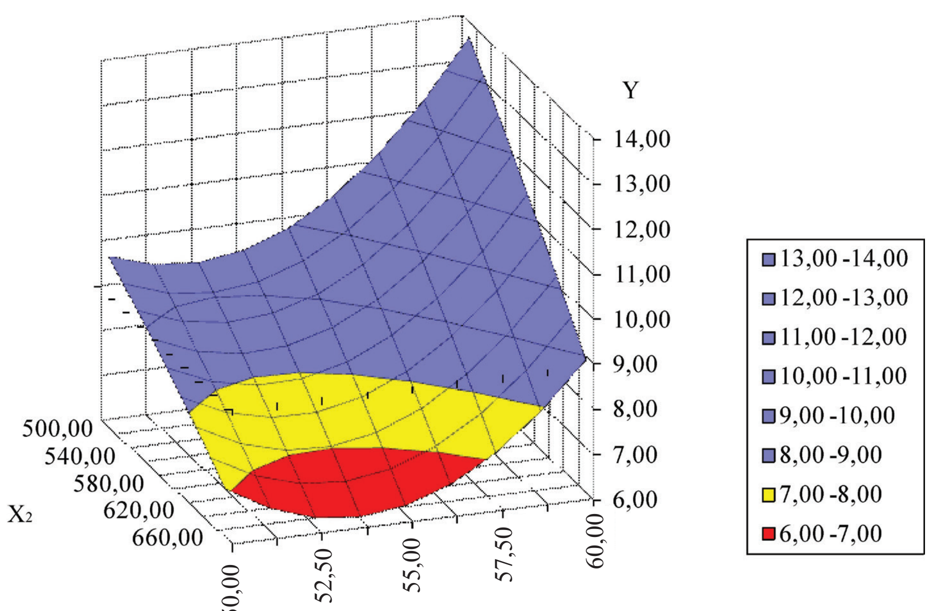

Fig. 4. Ternary surfaces of changes in the original parameter, depending on changes in the variance factors for the volume of protective coating

Regression equation:

$$Y=8.176+1.443X_1-1.867X_2+$$
$$+1.8X_1{\cdot}X_1-0.1X_2{\cdot}X_2-0.5X_1{\cdot}X_2, \quad (2)$$

where X_1 is the code value corresponding to the volume of a hydrophobic agent, X_2 is the code value corresponding to the volume of a coating.

On the basis of computer simulation, the best value of the volume of protective coating that ensures the implementation of the task has been determined, namely, the lowest value of the weight loss by fire-protected wood, which is obtained with the volume of flame retardant of 589 g/m^2 and the volume of a hydrophobic agent of 54 g/m^2.

5. 2. Experimental studies of indicators of fire danger of wood protected by fire retardant varnish and a hydrophobic coating

Based on the results of mathematical planning of the experiment and taking into consideration the technological features of flame retardant, since it is difficult to apply such a volume of substance, a study was conducted on the following technology:

– application of the first layer of a flame retardant with an average flow rate of 173.7 g/m^2;

– application of the second layer of a flame retardant with an average flow rate of 136.8 g/m^2;

– application of the third layer of a flame retardant with an average flow rate of 126.3 g/m^2;

– application of the fourth layer of a flame retardant with an average flow rate of 142.1 g/m^2;

– application of a layer of the protective varnish “Composite” with an average consumption of 56.8 g/m^2.

After applying each layer of the coating to the wood, the samples were kept in the laboratory for 24 hours. The average total thickness of the dry layer of the fire-retardant coating on wood samples was 0.3 mm.

The results of research to experimentally determine the combustibility group of fire-resistant wood are shown in Fig. 5, 6 and in Table 6.

a

b

Fig. 5. Samples of wood during combustibility tests: *a* — before testing; *b* — after thermal action

Fig. 6. Swelling of the fire-retardant varnish during thermal action

It is established (Table 6) that the wood protected by the fireproof coating refers to building materials of low combustibility (G1).

Table 7 gives the results of determining the flammability of wood.

As one can see from Table 7, fire-resistant wood refers to hardly flammable building materials (B1).

Table 8 gives the results of determining the group of spread of flames by fire-resistant wood.

According to the results of our experiments, the samples of wood protected with the fire-resistant coating are attributed to materials that do not spread the flame with the surface (RP1).

Table 9 gives the results of determining the coefficient of smoke formation of fire-resistant wood.

As one can see from Table 9, the coefficient of smoke-forming ability of fire-resistant wood refers to materials with moderate smoke-forming ability (D2).

Table 6

Results of research on determining a combustibility group of fire-resistant wood

Parameter	Sample No.											
	1	2	3	4	5	6	7	8	9	10	11	12
T_i, °C	25	30	28	27	22	24	23	25	27	25	24	28
T, °C	95	103	98	96	102	106	101	103	96	102	102	98
Mean value T, °C	98.00				103.00				99.50			
L, mm	130	140	135	130	135	140	135	145	135	145	145	140
ΔL_a, mm	133.75				138.75				141.25			
S_L, %	13.38				13.88				14.13			
m_1, g	1935	1950	1950	1940	1945	1940	1940	1930	1930	1950	1940	1945
m_2, g	1920	1940	1930	1930	1925	1920	1925	1910	1910	1940	1930	1925
Δm_a, g	13.75				18.75				15.00			
S_m, %	0.71				0.97				0.77			
τ, s	12				23				15			

Note: T_i – initial temperature, T – flue gas temperature, L – length of damage to samples, ΔL_a – average damage to samples by length, S_L – degree of damage to samples by length, m_1 – mass of samples before testing, m_2 – mass of samples after testing, Δm_a – average weight damage, S_m – degree of damage to samples by weight, τ – duration of self-combustion of samples

Table 7

Results of tests to determine the flammability of fire-resistant wood

Sample No.	The value of the surface heat flux density acting on the sample, kW/m^2	The period before ignition of the sample, s	Critical surface, kW/m^2
1	30	absent	35
2	40	206	
3	35	287	
4	35	302	
5	35	314	
6	30	absent	
7	30	absent	
8	30	absent	

Table 8

Results of tests to determine the group of spread of flames by fire-resistant wood

Sample No.	Ignition time of the sample from the beginning of the tests, s	The duration of the flame combustion of the sample, s	The length of the damaged part of the sample, mm	The average value of the damaged part of the sample, mm	Critical surface heat flux density, kW/m^2
1	absent	did not occur	35	39.6	exceeding 11.0
2	absent	did not occur	42		
3	absent	did not occur	45		
4	absent	did not occur	37		
5	absent	did not occur	39		

Table 9

Results of tests to determine the coefficient of smoke-forming ability of fire-resistant wood

Test mode and heat flux density	Sample number for testing	Sample weight (m), kg×10^{-3}	Light transmission, %		Smoke generation factor for each sample (D_m), m^2/kg
			(T_0) initial	(T_{min}) resulting	
Flame burning (35 kW/m^2)	1	1.25	100	68	197.5
	2	1.26	100	66	211.1
	3	1.26	100	67	203.4
	4	1.26	100	67	203.4
	5	1.24	100	69	191.5
The average value of the smoke coefficient, m^2/kg 211.0					
Smoldering (35 kW/m^2)	1	1.25	100	44	420.3
	2	1.26	100	42	440.6
	3	1.24	100	44	423.7
	4	1.25	100	43	432.1
	5	1.26	100	42	440.6
The average value of the smoke coefficient, m^2/kg 432.0					

Thus, pine wood, on which a fire-retardant coating is applied based on organic and inorganic substances (“Firewall Varnish”) with the external coating with the single-component alkyd polyurethane varnish “Composite” can withstand the temperature effect. When determining the combustibility of fire-resistant wood, it was established that the temperature of flue gases during tests was no more than 103 °C, the length of damage to the sample did not exceed 143 mm, the weight loss did not exceed 19 g, and the independent combustion of wood did not exceed 23 s. In addition, the wood withstood the surface effect of a heat flow of 35 kW/m^2 while surface combustion did not occur, and the value of the smoke coefficient was 432 m^2/kg during the smoldering of the fire-proof sample. According to the fire classification, fire-proof wood belongs to materials of low combustibility, it is a flammable material that does not spread flames on the surface, with a moderate smoke-forming ability.

6. Discussion of results of studying the process of combustibility of wood protected by two-component varnish

When studying the process of fire protection of wood with two-component varnish, the process of inhibition of high temperature transfer to wood flows from the results obtained (Fig. 5, 6, Tables 6–9). This is due to the formation of a swollen coke layer on the surface of the wood during the decomposition of varnish under the action of flame, which slows down the processes of heat transfer.

It should be noted that the presence of two-component varnish leads to the formation of an elastic film on the surface of the fabric, resistant to vibrations under normal conditions. Obviously, such a mechanism of operation of this coating is the factor in regulating the process by which the fire resistance of wood is maintained. In this sense, there is an interpretation of the results of determining the hard flammability of wood after exposure to flame, namely the formation of a heat-insulating layer of foam coke under thermal exposure. The temperature of the flue gases during the tests was no more than 103 °C, the length of damage to the sample did not exceed 143 mm, the weight loss did not exceed 19 g, and the independent combustion of wood did not exceed 23 s.

This means that there is an opportunity for effective adjustment of the properties of wooden structures directly under the conditions of industrial processing of wood at objects for various purposes.

The comparison of experimental studies into the formation of a layer of foam coke in the fire protection of wood and studies of fire-hazard properties indicates the inhibition of the processes of transmission of high temperature to wood. At the same time, the temperature of flue gases during tests was no more than 103 °C, and the resulting layer of foam coke is more than 16 mm (Fig. 6). This does not diverge from the practical data well known from [4, 5] where the authors also associate the effectiveness of fire protection with the formation of a layer of foam coke when decomposing the coating under the influence of the burner flame. However, unlike the results of studies reported in [6, 7], our data on the effect of foam coke on the process of inhibition of temperature transfer, suggest the following:

– the main regulator of the process is not so much the formation of a significant amount of gases released during the coating decomposition and inhibiting flames, since individual fire retardant coatings under the influence of high temperature emit water vapors;

– a significant impact on the process of wood protection when using fire retardant coating is exerted in the direction of the formation of a layer of foam coke on the surface of the wood.

Such conclusions shall be considered appropriate from a practical point of view because they allow for a reasonable approach to fire protection of wood and coating with a hydrophobic agent. From a theoretical point of view, they make it possible to assert determining the mechanism of processes of both temperature inhibition and water absorption, which are certain advantages of this study. However, it is impossible not to note that those results (Tables 6–9) indicate an ambiguous impact of fire-retardant efficiency on the change in fire-hazard properties. This is manifested, first of all, in the temperature that is formed on the surface of the sample during tests.

Such uncertainty imposes certain restrictions on the use of the results obtained, which can be interpreted as shortcomings of this study. The inability to remove these restrictions in the framework of our study gives rise to potentially interesting areas of further research. It can be focused on identifying the moment of time from which the fall in fire retardant properties begins and the ignition of wood under the influence of high temperature. This will allow us to investigate the structural transformations of the coating that are beginning to occur at this time, and to determine the input variable parameters of the process that significantly affect the onset of such a transformation.

7. Conclusions

1. We have optimized the volume of a fire retardant and a hydrophobic coating, which ensures the lowest value of weight loss of fire-proof wood during the decomposition of the fire-retardant coating under the influence of high temperature. This establishes the lowest value of weight loss by fire-resistant wood during thermal action in the volume of flame retardant of 589 g/m^2 and the volume of a hydrophobic agent of 54 g/m^2.

2. The wood, on which we applied 4 layers of the fire retardant coating in the volume of 578.9 g/m^2 and one layer of the protective varnish “Composite” with an average consumption of 56.8 g/m^2, showed the following results in the study of fire danger indicators:

– when determining the combustibility of fire-resistant wood, it was established that the temperature of flue gases during tests was not more than 103 °C, the length of damage to the sample did not exceed 143 mm, the weight loss did not exceed 19 g, and the independent combustion of wood did not exceed 23 s;

– the fire-protected wood withstood the surface effect of the heat flow of 35 kW/m^2 and did not ignite;

– the surface combustion of fire-resistant wood at a critical surface density of heat flow of 11, kW/m^2 did not occur;

– the average value of the coefficient of smoke formation was 432 m^2/kg during the smoldering of a fire-resistant sample of wood.

According to these data, the wood that is fireproofed with two-component varnishes refers to materials of low combustibility, it is a flammable material that does not spread flames to the surface, with a moderate smoke-forming ability.

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