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The Efficiency of Various Fire Protectants for Wooden Structures

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Abstract

The article deals with the scientific problem of the development and application of various fire protective compositions for wooden structures. Based on the results of theoretical and experimental studies, the authors for the first time attempted to state the influence of the chemical nature and mechanism of flame retardant action on the effectiveness of fire protection means. When assessing the effectiveness of fire protection, the authors paid special attention to the key parameters that determine the fire resistance of wooden structures. The possibility of developing effective fire protection systems, capable not only to provide a certain group of fire protection efficiency but also to influence the parameters of the charring process and the intensity of wood heating temperature is shown. Complex mechanisms of bloating (intumescence) and carbonization in combination with the mechanism of regulating the process of carbonization and wood carbonization, are able to provide the protected material with effective resistance to high temperatures (fire). The use of such types of fire protection allows forming an independent scientific direction associated with the development and use of fire protection systems contributing not only to the effective reduction of fire danger of wood and materials based on it but also to increasing the fire resistance of wooden structures.

1. Introduction

For several decades, the issue of creating effective fire protection technologies for various materials and structures of buildings and structures has been quite actively discussed in the field of fire safety all over the world. This issue was particularly acute in the development of the polymer chemical industry in the 60-80s of the last century, as well as technologies of innovative building materials and structures including those based on wood which is a natural chemically complex composite.

General trends in the world in the sphere of wooden housing construction (buildings and structures of medium story, high story and high-rise) predetermined the initiation of developments aimed at improving the efficiency of technical solutions including the use of various methods and types of fire protection. The most important problematic issue discussed by the scientific community in the sphere of development and application of fire protection technologies is to identify the effectiveness of various fire protection agents and the possibility of their use to reduce the fire hazard and increase the fire resistance of wooden structures. The general strategy with this problem is conditioned by the chemical and technological aspects of creating effective flame retardants with different mechanisms of fire action as well as the existing in some countries in the world problem of transition from the parameters of fire protection efficiency to the fire hazard of wood and materials based on it to increase the fire resistance of wooden structures.

Undoubtedly, this issue should first be transferred to studying the mechanisms of fire-action of fire protection means, their ability to contain and regulate the processes of temperature heating and

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charring of the wooden mass or wood-polymer composite, this allows to reasonably conduct the choice of the method and type of fire protection to achieve the required indicators of fire danger and fire resistance of wooden structures.

All the attempts to shed light on the possibility of effective fire protection for timber structures in the last century and at the beginning of the 21st century did not yield good results, despite great advances in the field of fire protection of cellulose and wood-based materials [1, 2]. This is the main reason for the limited technical solutions in modern times to provide the required fire hazard and fire resistance performance of wooden structures. The creation of effective methods and types of fire protection for wood based on progressive chemical technologies and their influence on peculiarities of fire behavior of wooden structures under fire conditions promotes the development of the theory of fire resistance of buildings and constructions under the conditions of modern tendencies in the field of wooden housing construction. This direction is relevant in the development of calculation-software complexes for predicting the assessment of the stability of wooden materials and structures in fire conditions.

To state the degree of influence of different types of fire protection on the key characteristics of temperature heating and charring of wood, experimental studies have been carried out in this work, making it possible to form an opinion on chemical approaches to create effective fire protection for wood and structures based on it, as well as methods of assessing their effectiveness. The authors have attempted to understand the possibility of using flame retardants differently in their mechanism of fire action for structures based on wood in conditions of high temperatures (fire) using small-scale available fire installations. Development of the methods of express-analysis of fire protection means efficiency characteristics opens big possibilities for the formation of experimental data array necessary for prognostic estimation of peculiarities of materials and constructions behavior in conditions of a fire.

The basic legal and regulatory concept for using fire protection products must be to protect people and property from the effects of fire hazards and/or limit the consequences of their effects and increase the stability of building structures under the conditions of fire exposure. This is achieved by using basic building timber structures with fire-resistance limits and fire hazard classes corresponding to the required fire resistance efficiency and structural fire hazard class of buildings and structures and by limiting the fire hazard of surface layers (finishing, cladding and fire protection mean) of building structures on escape routes. In addition, the fire resistance and fire hazard class of timber structures must be ensured by their structural design, the use of appropriate building materials and the use of fire protection products [3].

2. Investigation results and discussion

A set of proprietary flame retardants, different in their formulation and chemical nature, was taken for the study. The priority of the present research was to state the effect of flame retardants of different categories of effectiveness in reducing the intensity of the charring process and temperature heating of wood samples. Flame retardants were flame-retardant impregnating compositions comprising classical phosphorus-, nitrogen- and boron-containing flame retardants, bloating (intumescent) systems and heat-resistant flame retardants. The flame retardants under study are original balanced chemically stable formulations developed based on modern chemical technologies. The concentration of working components in the formulation varied over a wide range from 30 to75% not taking into account the binders. When selecting flame retardants (coatings and flame retardants), we proceeded from the fundamental differences in the mechanisms of fire activity and their different effects on the processes of thermal decomposition, carbonization and carbon formation of wood materials, which generally determine the fire danger and fire resistance of wooden structures. High flame retardant effects using the intumescent mechanism are also widely known for many polymeric materials of different chemical nature [4–6].

A standard installation (ceramic tube) according to GOST R 53292-2009 [7] was used to evaluate the effectiveness of fire protection. The assessment of the effectiveness of fire protection for wood is carried out by establishing the reaction of the flame retardant wood to a short-term flame exposure of 2 min.

The criterion for assessing effectiveness is the mass loss of the sample during testing, which is one of the most common indicators of combustibility of materials in various countries of the world, both in the last century and in modern fire test methodology. In addition to this, an experimental firing furnace consisting of a chamber with the possibility of one-way radiation heat treatment of the specimen surface with a given temperature increase in the furnace up to 1200 °C was designed for research purposes. The test chamber was upgraded to take into account the vertical fixation of the sample on the external panel of the furnace. A set of K-type thermoelectric transducers (chromel-copper) with a junction diameter of 0.8 mm was used to measure the temperature across the thickness of the sample. A layer of kaolin clay-based thermal lining was applied on the outside of the specimen to eliminate heat loss. The test duration of the samples, in this case, was 28 min with a dynamic temperature increase up to 800 °C (Fig. 1).

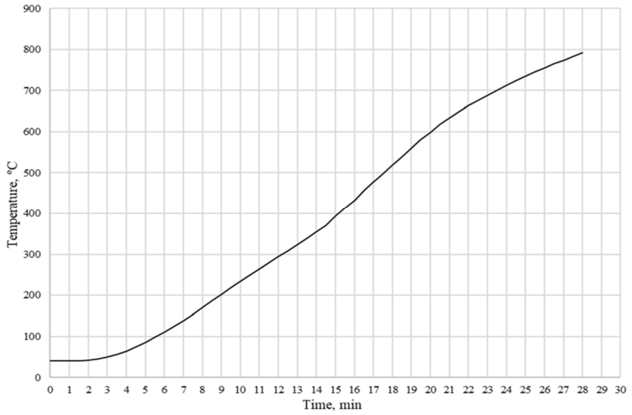

Fig. 1. Temperature increase in the chamber of the experimental installation during a fire test.

The characteristics of the flame retardants as well as the test results for the assessment of fire protection efficiency according to GOST R 53292-2009 are shown in Table.

To implement the goal, the authors have developed flame retardant systems based on innovative chemical technologies, including chemically active flame retardants with classical phosphorus-, boron- and nitrogen-containing compounds, as

Table
Test results of flame retardants to assess their fire protection efficiency according to GOST R 53292-2009

#	Sample characteristic, chemical nature of composition	Defining mechanism of flame retardant effect	Consumption, g/m^2	Efficiency group according to GOST R 53292-2009 (mass loss, %)
1	Natural wood (pine, density 450–500 kg/m^3, humidity 6–8%)	-	-	- (more than 70%)
2	Intumescent flame retardant paint based on classic blowing system, polyhydrate compounds and thermoplastic polymers	Intumescence	650	Fire performance group I (8.4%)
3	Intumescent flame retardant paint based on classic blowing system, polyhydrate compounds and mineral additives	Intumescence	650	Fire performance group I (3.2%)
4	Composition based on P-containing substances, polyhydrate and aromatic compounds, N-containing gas formers	Coke formation	450	Fire performance group I (8.67%)
5	Formulation based on P-containing substances and a complex of polyhydrate compounds	Coke formation	550	Fire performance group II (18.8%)
6	Composition based on P-N containing substances, polyhydrate and aromatic compounds	Coke formation	500	Fire performance group II (19.0%)
7	Formulation based on P-, N-containing flame retardants and organic surfactants	Catalytic dehydration	350	Does not have flame retardant effect (36.0%)
8	Composition based on a complex of P-, N-containing flame retardants and thermoplastic polymers	Catalytic dehydration	400	Fire performance group II (25.0%)

well as coke-forming and blowing (intumescent) fire protective compositions, including in their composition functional chemical complexes consisting of classical flame retardants, gas formers, polyhydrate and aromatic compounds, thermoplastic polymers and mineral fillers. It was found that the flame-retardant efficiency of the developed fire-retardant compositions is revealed at the rate of their surface application in the range of 350–650 g/m^2 (2–3-layer application of compositions).

The mechanism of intumescence involves the use of flame retardant bloating with the thickness coatings up to 1 mm, which form a volumetric bloated thermal insulating layer (bloating multiplicity from 30 to 100) on the protected surface under fire exposure. The mechanism of coking is conditioned by the use of water-based impregnating compositions, capable of forming a foamed coking layer in the surface area of wood with a thickness up to 15 mm. These compositions form a thin functional film on the wood surface and penetrate the wood structure by 1–3 mm, this determining their coke-forming effect both directly on the surface and interaction with the carbohydrate complex of the wood composite. The compounds working by the mechanism of catalytic dehydration, penetrate the structure of the wood to a depth of 3–5 mm and their action is aimed at participation in the process of carbon formation directly in the wood. In this case, an additional flame retardant effect is the dilution of the gas phase by inert gases formed as a result of thermal transformations of flame retardants.

Under the conditions of standard fire tests with the use of a standard fire installation in the form of a ceramic pipe the loss of weight of the fire-protected wood samples is 3.2–36.0%, indicating significant differences in the ability of compositions to contain burning of wood as the main task to reduce combustibility of wood (mass loss of the native wood during the tests was 70%). Figure 2 shows photos of flame retardant wood samples after fire tests to demonstrate the mechanism of flame retardant action.

Taking into account the main criterion for evaluation of fire protection efficiency (mass loss), the developed chemical systems are classified as compositions of I and II groups of fire protection efficiency, as well as compositions not having fire protection efficiency (mass loss of the sample of more than 25 %).

The main process that determines the fire hazard and fire resistance of timber structures is the charring process. In normative practice, the charring rate for various types of timber structures (solid coniferous and hardwood structures, laminated veneer structures such as LVL, wooden glued structures), varies from 0.5 to 1.0 mm/min [8]. Many scientists studied the problems of determination of the charring rates of solid, glued and fire protected wood [9–15]. The results of the studies show that the charring rates of native and fire-retarded wood in the structures of the different cross-sections are almost identical, except for the work of E.K. Ivanova [9]. In this work, it was found that the charring rate of wood with surface fire-retardant treatment was higher than that of untreated

(a) (b) (c) (d)

Fig. 2. Photo of wood samples with fire protection after fire tests: (a) – 2; (b) – 3; (c) – 4; (d) – 5 (the sample numbers are shown in Table 1).

wood. It was found that the rate of charring of native wood averaged 0.6 mm/min, and the depth of charring was a linear function of the duration of heat exposure.

It is obvious that the question of the effect of different types and methods of fire protection on the charring parameters of wood should be transferred to the plane of consideration of the problem of fire hazards and fire resistance of wooden structures. A priori, analyzing the values of charring rates of wood with fire protection, it can be unequivocally concluded that fire protection systems with different chemical nature and mechanisms of fire action will also affect the values of the fire resistance limits of structures. This is supported by our fire tests of timber structures (beams) with two types of flame retardants under load under standard fire temperature conditions [16]. In the tests with wooden beams with surface application of flame retardant, which had a complex mechanism of fire action, the main mechanism being the ability to coke, an increase in the fire resistance by 10% was found. At the same time, for a timber beam with a typical P-, N-containing flame retardant, the fire resistance limit was actually unchanged compared to an unprotected timber structure.

In this case, not only the fact of increasing the fire-resistance limit of wooden structures with the use of coke-forming flame retardants is of interest but also finding out the reason for their effective impact on the processes of wood charring. Reduction of the charring process of intensity and, consequently, the increase in the fire-resistance limit of wooden structures allows singling out impregnating compositions with a complex mechanism of fire-retardant action with the coke-forming effect because according to GOST 12.1.033 [17] the mechanism of action is aimed exclusively at reducing the flammability of the material. In this regard, it is also important to study the effect of retardants on other fire properties of the material including the smoke-forming ability and toxicity of combustion products.

The most important result of this work is to clarify the ability of different fire retardants to modify the charring and heating intensity of timber structures. Differences in the effectiveness of chemical fire-protective systems allow predicting the possibility of their influence on the fire-resistance limits of wooden structures, in particular the charring process characteristics and the intensity of wood heating. To study these characteristics, the authors developed an original unit of external radiation exposure with the possibility of isothermal and dynamic high-temperature one-way exposure to the surface of test specimens. During the study, such charring characteristics as charring rate, the thickness of the charred layer, effects of manifestation of fire-retarding mechanisms (coke formation, bulging, etc.), as well as the size of characteristic wood layers across the thickness of the specimen were analysed. The results of the study demonstrate the possibility of certain classes of flame retardants, coke-forming and intumescent materials not only influence the intensity of wood charring but also influence the properties and structure of the charred layer, the intensity of heating of the inner layers of wooden structures, as well as the size of characteristic layers of wood. The analysis of the obtained results shows that the experimental data on the evaluation of fire-protection systems efficiency is a peculiar response to the ability of their influence on the processes of charring and temperature heating of wooden structures.

For example, the most effective flame retardant systems that affect the charring rate are bloating coatings (35–70 mm thick bloated layer). When using these coatings, the rate of wood charring decreases twice, and the intensity of wood sample heating by thickness is reduced by 30% or more. For coke-forming flame retardants (thickness of bloating layer is 3–15 mm) an interesting feature is revealed, caused by a slight decrease in the rate of wood charring in 1.1–1.2 times, but with an effective ability to influence the intensity of temperature heating of the sample, comparable to fire-retardant bloating coatings. The use of chemically active components in flame retardant systems solves another important fire protection problem, namely the regulation of the formation of the charcoal layer of wood with a particular structure and properties, which also leads to an effective increase in its thermal insulating capacity. We are talking about peculiar regulators of the charring process, influencing the physico-chemical processes of carbon formation of the wood complex. In addition, the studies have revealed another significant interesting feature, namely a characteristic change in the size of the inner carbonized layer, which has lost its original mechanical characteristics (variations from 3 to 5 mm). Positive effects in the reduction of wood charring rate, as well as the intensity of temperature heating of the samples, appear to a greater extent for fire retardants having fire protection group I (weight loss up to 9%). The use of such types of fire protection, in the opinion of the authors' team, allows forming an independent scientific direction associated with the development and use of fire protection systems, contributing not only to the effective reduction of fire danger of wood and materials based on it but also to increasing the fire resistance limits of wooden structures by 10–15% or more.

Ambiguity in the reduction of wood charring rate appears in the analysis of the results of assessing fire-retardant effectiveness of coke-forming compositions of efficiency groups I and II. So, application of compositions of II group of efficiency, having actually the identical loss of weight of samples at tests on a ceramic pipe, leads in one case to a decrease in the charring rate of wood in 1.2 times, and in other cases to its increase in 1.1 times. In addition, the opposite effect was also found for coke-forming compositions of groups I and II of fire-retardant efficiency, which have a comparable ability to reduce the charring rate. For wood with chemically active flame retardants, the fire-retardant action of which is based on a pronounced mechanism of catalytic dehydration, a decrease in the rate of charring is observed in some cases, while in other cases the process of charring increases by 1.1–1.2 times. Obviously, in this case, the issue of flame retardant efficiency is related to the possibility of regulating the charring process with the formation of a carbon layer with appropriate properties and characteristics.

The results of the evaluation of the effectiveness of flame retardants by the index of intensity of temperature increase indicate a weak correlation of the fire protection efficiency group with the ability of flame retardants to restrain the advancement of the temperature front along with the depth of wood samples.

The maximum effect is in reducing this indicator about intumescent and coke-forming flame retardants, which have a stable efficiency rating (Fig. 3).

Figures 4 and 5 show the temperature increase at 10 mm from the external surface of a sample of wood with different types of fire protection during the fire test.

The decrease in the heating temperature of fire-retardant samples compared to natural wood occurs by 2 or more times. The same indicator is the performance indicator of the composition of the fire protection group II (the mass loss of the samples is at the limit of 25%), working according to the mechanism of catalytic dehydration. At the same time, a prerequisite for achieving this effect should be to reduce the value of the charring rate of wood.

In contrast, a coke-forming composition with a Group I flame retardant efficiency (test weight loss 8.67%), which can reduce the charring intensity of wood, may be inferior in its effectiveness in reducing the heating temperature to a composition that promotes a higher charring rate of wood (test weight loss 19.0%).

The effect of reducing the considered characteristics is due not only to physical and chemical processes occurring in the surface zone of wood (intumescence, coke formation, enhancing the charring process) but also to the ability of fire protection to regulate the formation of the carbon layer. In addition, consideration of the results obtained should be in the plane of the peculiarities of fire tests, taking into account the conditions and duration of fire exposure, contributing to the implementation of the mechanism of fire-action of the studied flame retardants.

(a)

(b)

Fig. 3. The appearance of the foamed thermal insulation layer on the surface of wood after fire tests: (a) – 2; (b) – 4 (sample numbers listed in Table).

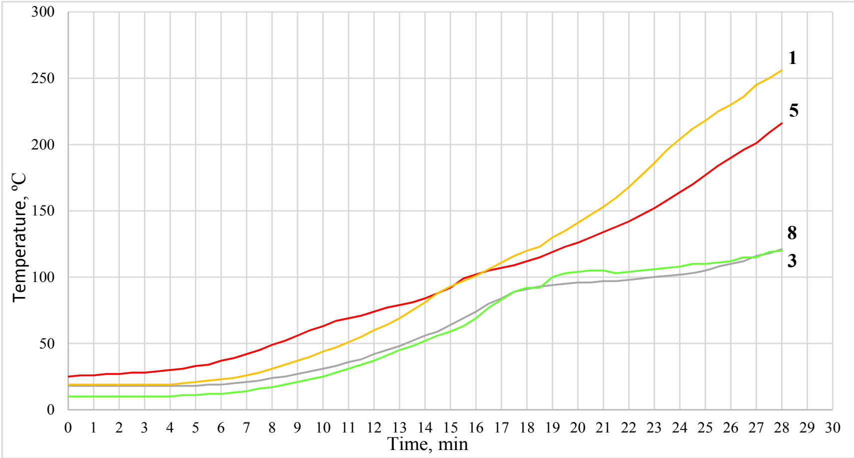

Fig. 4. Dependences of the temperature increase at 10 mm from the external surface of a sample of wood with different types of fire protection (intumescent and coke-forming compositions) during fire tests (sample numbers correspond to those presented in Table 1).

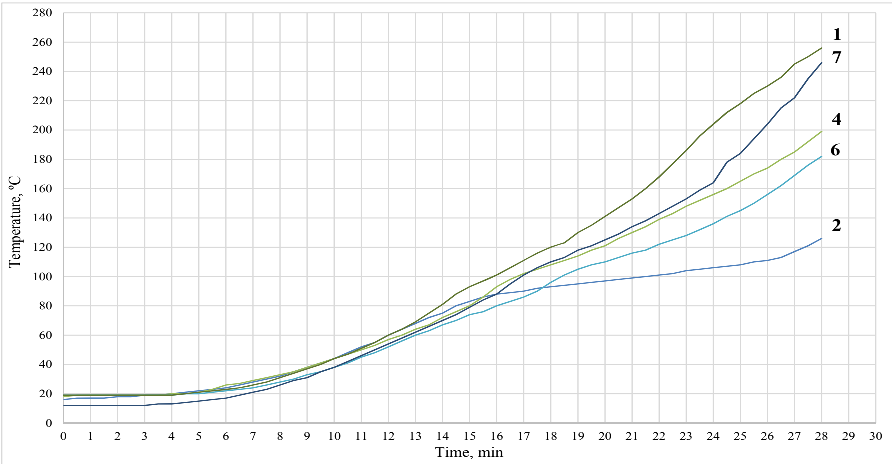

Fig. 5. Dependences of the temperature rise at 10 mm from the external surface of a sample of wood with different types of fire protection (coke-forming compositions and chemically active flame retardants) during fire tests (sample numbers correspond to those shown in Table 1).

The results of the studies conducted indicate the need to implement new methodological approaches to assess the effectiveness of fire retardants taking into account the ability to predict the ability of fire protection to contain the heating of the material of the structure, to influence the processes of carbon formation (formation of a carbon layer with the required parameters and properties), the intensity of the loss of mechanical (strength) characteristics of wood as well as the fire resistance of wooden structures.

3. Conclusion

The article presents the results of studies on the influence of the chemical nature and mechanism of flame retardant action on the effectiveness of flame retardants. Flame retardant impregnation compositions, including classical phosphorus- and boron-containing flame retardants, bloating (intumescent) systems and heat-resistant flame retardants were taken for the study. When selecting fire retardants (flame retardants), we proceeded from the considerations of multifaceted mechanisms of fire activity and their different effects on the processes of thermal decomposition, carbonization and carbon formation of wood.

The results obtained confirm the possibility of reducing the intensity of the process of charring and temperature heating of wooden structures when using different fire-retardant systems, which will ultimately lead to an increase in the fire resistance of wooden structures. At the same time, the compositions having the appropriate fire protection effect (fire protection efficiency groups I and II by GOST R 53292-2009 [7]) must result in an effective reduction of the fire hazard of wood, materials and structures based on it. To a greater extent, this is facilitated by the formation of a dense blown thermal insulating layer on the protected surface, which has a relatively small value.

The most effective flame retardant systems, that influence the intensity of the charring process are bloating coatings (thickness of the bloated layer is 35–70 mm). When using these coatings, the rate of wood charring decreases twice, and the intensity of wood sample heating by thickness decreases by 30% or more. For coke-forming flame retardants (thickness of the bloated layer is 3–15 mm) an interesting feature is revealed, conditioned by a slight decrease in the rate of wood charring in 1.1–1.2 times, but with an effective ability to influence the intensity of temperature warming of the sample comparable to flame retardant bloating coatings.

The prospects for developing special flame retardant compositions capable of regulating the process of forming the charred layer of wood with the appropriate structure and properties are shown. Complex mechanisms of bloating (intumescence) and coke formation in combination with the mechanism of regulation of the process of carbonization and coal formation of wood, can provide the protected material with effective resistance to high temperatures (fire). The use of such types of fire protection allows for forming an independent scientific direction, associated with the development and use of fire protection systems, contributing not only to the effective reduction of fire danger of wood and materials based on it but also to increasing the fire resistance of wooden structures. The effects of reducing the intensity of charring and temperature warming for wood samples with flame-retardant compositions are a kind of response to the results of fire tests according to GOST R 53292-2009.

The results of the studies conducted indicate the need to implement new approaches to assess the effectiveness of fire-retardant materials, taking into account the possibility of predicting the ability of fire protection to contain the processes of heating of the structure material structure, to influence the processes of charring (the formation of a charred layer with the required parameters and properties) and the intensity of the loss of load-bearing capacity of wooden structures.

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