

To develop appropriate measures and means of fire protection at facilities, it is relevant to form an idea of the phenomenology of the processes of the occurrence, evolution, and termination of combustion. This paper proposes procedures for building mathematical models of the energy component of those physicochemical processes that occur in wood under the influence of fire, which make it possible to determine the time from the beginning of such an impact to the onset of the phase of flame combustion. The adequacy of mathematical modeling was tested experimentally at a standardized installation for studying flame propagation over the surface of wood. The samples used for the reported theoretical and experimental studies were the specimens of unprotected wood made from 20-mm-thick pine sapwood with a density of 400–550 kg/m<sup>3</sup>. The samples of fireproof wood (of the same variety, thickness, and density) were impregnated with a fire retardant based on diammonium phosphate and ammonium sulfate (at consumption of 168.2 g/m<sup>2</sup> of dry fire-retardant components). The modeling employed the results from the experimental determining of the ignition temperature of unprotected and fire-proof wood, specifically: 235 °C – for unprotected wood, 410 °C – for fire-proof wood, respectively.

The results of mathematical modeling and experimental studies confirm the possibility of significant lengthening of time from the onset of fire exposure to the ignition of fire load from wood when nitrogen-phosphorus impregnating agents are used for fire protection.

Procedures of mathematical modeling have been proposed to build models for determining the cooling effect from the use of impregnating fire retardants to protect the wood on the prolongation of the stage of a fire start.

Mathematical modeling data could be applied when making impregnating fire retardants

**Keywords:** fireproof wood, fire retardant, impregnating substance, ignition temperature, fire impact

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# PROCEDURE FOR CONSTRUCTING A MATHEMATICAL MODEL TO DETERMINE THE TIME OF THE INITIAL STAGE OF FIRE EVOLUTION

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## 1. Introduction

Analysis of global trends in the use of environmentally friendly materials in construction indicates that wood was

and remains a popular building material. However, at the same time, the use of combustible material – wood, combustion products of which are extremely toxic, is also increasing. Statistical analysis, carried out at the Research Institute for

Fire Protection (USSR, Russia), indicates that in the twentieth century more than 70 % of accidents involved wood and products made from it that formed the basis of fire damage to objects where fires occurred. And the number of deaths in these cases amounted to more than 90 % of the total number of casualties in fires. A similar trend is also observed in the most economically developed countries in the world. This is evidenced by significant material damage and human casualties in cascading fires in 2017 in the residential sector of Canada, where wood and wooden products are traditionally widely used. Similar fires with the same consequences occur almost annually in the United States [1]. These data are unacceptable, especially for critically-important objects and facilities where many people gather, all of which require special safety solutions [2, 3]. Thus, the task of improving the quality of fire protection of wooden building structures remains relevant [4, 5].

Ensuring fire protection of objects whose fire loading is generated by wood requires the implementation of special measures involving the use of fire protection means within the fire protection system of the object. Such a system is categorized as a complex system. In its structure, it is typically possible to define the subsystems of active and passive protection. In this case, active fire protection implies the application of fire extinguishing equipment and substances, as well as special means, which can be mobilized at any time to eliminate fires. Passive protection is characterized by certain fire protection measures carried out in advance, that is, there are no tasks for their emergency mobilization in the process of fire elimination.

As a rule, the measures and means involved in these subsystems are closely related, since they are mutually predetermined. Therefore, within the structure of the general system of protection of objects, they are often considered as an integrated subsystem of active-passive fire protection. However, when studying its functioning, it is advisable to highlight individual structural elements in which certain fire extinguishing and/or fire-protective factors (effects) are implemented [6].

The effectiveness of passive protection is characterized by the ability to counteract the occurrence of ignition of substances and materials that form the fire load on the object, or to prolong the stage of fire start (FSS) to ensure the timely arrival of rescue units. At the same time, it is known that the rated response standards (the arrival of these units to a fire site) at the state level are: for rural areas – 12 minutes, for cities – 5 minutes.

Typically, wood and wooden products (materials) form the base of fire load on objects [7]. The most common way to passively protect wood is its fireproof treatment; in the structure of fire retardants used, fireproof impregnation is the most common. Given such treatment, it is possible to significantly reduce the fire-danger rates of wood that is part of building structures. For example, the ignition temperature of untreated wood, which, for most varieties, is determined in the range of 230–250 °C, can be increased to values above 400 °C. On the other hand, FSS for objects whose fire load is related to unprotected wood is also determined by the time the average temperature in the object reaches about 250 °C and lasts on average up to 12 minutes [7]. Of course, at this stage, the fire is much easier to eliminate than at the stage of a developed fire. Increasing the ignition temperature of wood by the fireproof treatment could ensure the prolongation of FSS and, accordingly, would create opportunities for the confident elimination of fire with the least damage.

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## 2. Literature review and problem statement

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The development of fire protection measures and means requires devising the phenomenology of the physical and chemical processes in the development and termination of burning, which is quite a difficult scientific task. It is known that these fire-related processes can be mathematically represented by a system of the Navier-Stokes equations [8]. Such a system includes [9] an energy equation describing the transfer of energy due to radiation, thermal conductivity, convection processes, diffusion, physicochemical combustion reactions of substances and materials under fire load, the equations of state, heat transfer, inseparability, and diffusion. When trying to obtain an accurate solution to such a system of equations, scientists face difficulties in taking into consideration all the important factors to determine the boundary conditions. This is especially true of the difficulties associated with the notation of the physicochemical processes that form combustion products. Consequently, solving the specified system becomes an extremely difficult scientific task, especially in the context of addressing practical issues in transferring wood from a group of readily flammable materials to a group of flammable or heavy-combustible materials.

It is not possible to derive an analytical solution to a complete non-simplified system of the differential equations of a fire, supplemented with dependences for calculating gas exchange in a room with an atmosphere, heat exchange with fence structures, gasification, and heat generation rates. Therefore, researchers always use certain approaches to simplification. To model the process of fire development, three types of models are usually used [10], differing in the scope and degree of reproduction of the process: integrated, zonal, and field. All kinds of models take into consideration the type of fire load (its physicochemical parameters). This approach was used in work [11]. Its practical application is complicated by the fact that a large number of parameters (characteristics) for the material of a fire load should be known, which must be determined in advance for each specified object. Work [12] studied the processes of ignition of stacked wooden bars, which is why the practical applicability of the reported results is limited to the specific shape of fire-loaded material. At the same time, the application of results reported in [13] is limited to objects where only thick wooden structures are used. In addition, the cited work does not take into consideration a change in the thermal conductivity of wood during heating, which is an important component that should be taken into consideration, especially when studying FSS.

Paper [14] describes a model of wood self-ignition, taking into consideration the processes of thermal transformation of substances in the wood. The cited paper does not study the processes of the thermal transformation of fire retardants from the composition of fire-proof wood. It should also be noted that the cited paper is limited only to the process of wood self-ignition. Similar limitations are typical of study [15].

Approaches involving large full-scale models (for example [16]) are commonly used to investigate later stages of fire than the starting one. Which is more suitable for the study of cascading fires.

The most thorough approach was used in work [17], which provides a mathematical model of flame propagation over the surface of a thermally thin structure. In it, the thermal-thin structure denotes a structure whose thickness

is less than the thickness of its possible warming up. However, this assumption leads to significant errors in solving practical problems involving the calculation of FSS time, for example, for common construction objects with wooden coatings (roof craps that are 20–30 mm thick).

The impact of changes in the properties of the materials related to fire load (the improvement of their indicators of fire danger) on a change in the resource of time to eliminate a fire has also not been studied enough. Works [18, 19] made an attempt to determine, by mathematical modeling, the effect of the introduction of fire retardants into the surface layers of wood on the implementation of the cooling factor during the thermal irradiation of a sample of wood treated with a water-based fire protection agent. Paper [18] studied the physicochemical transformations taking place in untreated wood; work [19] – in fire-proof wood. However, their authors, first, solved the simplified problem with a one-dimensional spatial coordinate, which does not make it possible to assess the cooling of the wood sample with sufficient accuracy due to convection and radiation heat transfer to the environment. Second, the coefficient of thermal conductivity of wood was simplified to constant although the thermal conductivity of wood changes in the process of irradiation by a thermal flow (at least, in the process of irradiation, water evaporates from wood). Third, the simulation results were not tested on the physical models of fire.

Thus, it can be argued that it is advisable to conduct additional research to determine the prospects of using mathematical models for calculating the time of FSS at facilities whose fire load is related to wood.

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

The aim of this work is to devise a methodology for constructing a mathematical model describing the physicochemical processes that occur in wood when it is heated to the ignition phase, in order to calculate the resource that could prolong FSS.

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

- to determine the structure and evaluate the parameters of the model that describes the processes that occur in wood when it is heated and is close to the physical model for determining the index of flame propagation over the surface of wood;

- to estimate the deviation in the values of FSS duration obtained from using the mathematical and physical fire models.

## 4. Mathematical and physical methods to study fire influence on unprotected and fire-proof wood

### 4.1. Procedure for constructing a mathematical model describing the physicochemical processes that occur in wood when it is heated

A step-by-step procedure is proposed to construct a mathematical model. The first stage implies the mathematical notation of the approximation of dependences of the amount of substances emitted from the sample of wood on the time of its exposure to the thermal effect. To this end, we employ available experimental data on the measurements of the yield of volatile substances [20, 21]. Taking into consideration the patterns in these dependences, a method of interpolation by cubic

splines has been chosen, which generates curves that are close to straight lines at boundary points. The use of this method brings us as close as possible to the actual dependences for the case being studied [22]. That makes it possible to establish dependences of the accumulated amount of substance (methane, carbon monoxide (II) and (IV), water vapor, hydrogen, etc.) that were released from a certain volume of wood on the time of its exposure to the thermal impact.

The second stage implies finding the dependences of the mass of volatile substances released during the heating of wood on the heating temperature, by fitting the derived approximation dependences to thermogravigrams.

The third stage is to establish the dependence of the specific energy of the formation of each substance released (1) and the total specific energy of the released substances (2) in the process of heating wood on temperature (using data on the enthalpy of the formation of the specified substances [23]):

$$\Delta A_i(T) = \frac{\Delta H_i}{mol_i} \cdot \rho_i(T), \quad (1)$$

where  $H_i$  is the enthalpy of the formation of the  $i$ -th substance,  $J \cdot mol^{-1}$ ;  $mol_i$  is the molar mass of the  $i$ -th substance,  $kg \cdot mol^{-1}$ ;  $\rho_i$  is the partial density of the  $i$ -th substance (that is, the share of the division of the mass of this substance, which is in the single volume of wood per single volume), formed in the process of heating over a given temperature range (from the initial to the current),  $kg \cdot m^{-3}$ ;  $T$  is the current process temperature, K.

Then:

$$\Delta A(T) = \sum_i^{i=k(T)} \Delta A_i(T), \quad (2)$$

where  $k(T)$  is the largest amount of substances (depends on the temperature  $T$ ).

In the process of heating a wood sample, all substances of its decomposition are heated, and the value of the corresponding accumulated energy is determined by expressions (3) and (4) [24]:

$$\Delta B_j(T) = c_j \cdot \rho_j(T) \cdot (T - T_0), \quad (3)$$

where  $c_j$  is the specific heat capacity of the  $j$ -th substance,  $J \cdot kg^{-1} \cdot K^{-1}$ ;  $\rho_j$  is the partial density of the  $j$ -th substance (that is, the share of the division of the mass of this substance, which is in the single volume of wood per single volume), formed in the process of heating over a given temperature range,  $kg \cdot m^{-3}$ ;  $T$  is the process temperature, K.

Then:

$$\Delta B(T) = \sum_j^{j=k(T)} \Delta B_j(T), \quad (4)$$

where  $k(T)$  is the largest amount of substances (depends on the temperature  $T$ ).

At the fourth stage, we calculate the total specific energy of the physical and physicochemical transformations of substances undergoing both with the release and absorption of energy in the process of warming up a wood sample:

$$E_w(T) = -\Delta A(T) + \Delta B(T). \quad (5)$$

With sufficient accuracy for a given problem, the derivative from  $E_w(T)$  can be considered as the total (effective)

heat capacity of the process of the specified transformations, or as a specific heat capacity of the examined material:

$$c_{\rho_w}(T) = \frac{d}{dT} E_w(T), \tag{6}$$

where  $E_w(T)$  is the total specific energy of transformations (5),  $J \cdot kg^{-1}$ ;  $T$  is the process temperature, K.

The fifth stage requires solving a homogeneous thermal conductivity equation in a two-dimensional space at the boundary conditions of the third kind:

$$c_{\rho_w}(x, y, T) \cdot \rho_w(x, y, T) \cdot \frac{\partial T}{\partial t} - \text{div}(\chi_w(x, y, T) \cdot \text{grad}(T)) = 0, \tag{7}$$

where  $c_{\rho_w}(x, y, T)$  is the effective specific heat capacity of a wood sample, according to (6),  $J \cdot kg^{-1} \cdot K^{-1}$ ;  $\rho_w(x, y, T)$  is the wood sample density at this point,  $kg \cdot m^{-3}$ ;  $T$  is the current process temperature, K;  $\chi_w(x, y, T)$  is the coefficient of thermal conductivity of wood,  $W \cdot m^{-1} \cdot K^{-1}$ .

The initial (Dirichlet) conditions for any point of the spatial coordinate of the sample:

$$T(t=0) = T_0, \tag{8}$$

where  $t$  is the time, s;  $T_0$  is the initial temperature of the sample, which coincides with the temperature of the surrounding space.

The boundary (Robin) conditions of the mixed type [25], which corresponds to simultaneous heat exchange by convection (according to Newton's law) and thermal radiation (according to Stefan-Boltzmann law) of the environment:

$$-\chi_w(x, y, T) \cdot \frac{\partial T}{\partial n} = \alpha(T - T_0) + F_i \cdot \varepsilon \cdot \sigma \cdot (T^4 - T_0^4), \tag{9}$$

where  $\chi_w(x, y, T)$  is the coefficient of thermal conductivity of wood,  $W \cdot m^{-1} \cdot K^{-1}$ ;  $\alpha$  is the coefficient of convection heat transfer between the walls of the sample and the surrounding air,  $W \cdot m^{-2} \cdot K^{-1}$ ;  $\frac{\partial T}{\partial n}$  is the temperature gradient in the direction of normal to the  $i$ -th outer surface,  $K \cdot m^{-1}$ ;  $F_i$  is the angular irradiation coefficient for each outer surface of the sample (four, under the conditions set in the problem);  $\varepsilon$  is the effective coefficient of the grayness of the outer surfaces of the sample;  $\sigma$  is a constant in the Stefan-Boltzmann formula.

This equation is solved on the basis of a finite element method using a set of tools to numerically solve differential equations in partial derivatives, PDE Toolbox, in the MATLAB application package.

Fire protection of wood is achieved by impregnating it with protective agents (substances) that can destroy or counteract the formation of the Lavoisier triangle by implementing the effects of phlegmatization, inhibition, insulation, and cooling. The degree of implementation, that is, the quantitative assessment of each effect, is extremely difficult to determine, given that the above effects are interrelated.

The procedure for constructing a mathematical model describing the physicochemical processes that occur in wood protected by an impregnated fire-protection agent based on fire retardants, when it is heated by an ignition site, consists of the following stages. At the first stage, the density of the distribution of fire retardants through the surface layers of

wood to the depth from the surface of the wood sample is determined. According to [25], this value is described by an empirical dependence:

$$\rho_{FR}(x) = k_1 \cdot \exp(k_2 \cdot x), \tag{10}$$

where  $x$  is the coordinate of the distance from the surface deep into the wood sample, m;  $k_1$  is the coefficient, described by a linear approximating function,  $kg/m^3$ ;  $k_2$  is the coefficient, described by a quadratic approximating function,  $m^{-1}$ .

Work [26] shows that there is an optimal concentration of fire retardants in the working solution of an impregnating agent in order to achieve the maximum saturation of surface layers of wood during surface impregnation.

The second stage implies calculating the energy components of the elements from the fire-protective impregnation during the heating process. A technique similar to that used for wood without impregnation is used. Thus, the specific energy of the transformations of fire-protective impregnation takes the following form:

$$E_{FR}(T) = - \sum_{i=1}^{i=k(T)} \frac{\Delta H_i}{mol_i} \cdot \rho_i(T) + \sum_{j=1}^{j=n(T)} c_j \cdot \rho_j(T) \cdot (T - T_0), \tag{11}$$

where  $\rho_i(T)$  is the partial density of the  $i$ -th substance (that is, the share of the mass division of this substance, which is in a single volume of wood per single volume), formed as a result of heating over a given temperature interval from  $T_0$  to  $T$ ,  $kg \cdot m^{-3}$ ;  $\rho_j(T)$  is the partial density of the  $j$ -th substance (that is, the share of the division of the mass of this substance, which is in a single volume of wood per single volume), which formed, or existed before reaching the temperature  $T$ , K;  $\Delta H_i$  is the enthalpy in the formation of the  $i$ -th component,  $J \cdot mol^{-1}$ ;  $mol_i$  is the molecular weight of the  $i$ -th component,  $kg \cdot mol^{-1}$ ;  $c_j$  is the heat capacity (specific) of the substance that formed, or existed before reaching the temperature  $T$ ,  $J \cdot kg^{-1} \cdot K^{-1}$ ;  $k(T)$  is the amount of substances formed in the entire temperature range of the heating process;  $n(T)$  is the amount of substances that formed, or existed before the  $T$  temperature was achieved.

At the third stage, we determine the total (effective) heat capacity of the process of transformation of a fire protection agent's components:

$$c_{\rho_{FR}}(T) = \frac{d}{dT} E_{FR}(T), \tag{12}$$

where  $E_{fr}(T)$  is the amount of energy (specific) diverted by fire-protective impregnation per unit volume,  $J \cdot m^{-3}$ .

The fourth stage requires solving a homogeneous thermal conductivity equation in a two-dimensional space with the boundary conditions of the third kind, which takes the following form:

$$\left( c_{\rho_w}(x, y, T) \cdot \rho_w(x, y, T) + c_{\rho_{FR}}(x, y, T) \cdot \rho_{FR}(x, y, T) \right) \cdot \frac{\partial T}{\partial t} - \text{div}(\chi_w(x, y, T) \cdot \text{grad}(T)) = 0, \tag{13}$$

where  $c_{\rho_w}(x, y, T)$ ,  $c_{\rho_{FR}}(x, y, T)$  is the effective specific heat capacity of a wood sample and, accordingly, the fireproof impregnation,  $J \cdot K^{-1} \cdot m^{-3}$ ;  $\rho_w(x, y, T)$ ,  $\rho_{FR}(x, y, T)$  is the wood sample density and, accordingly, the fireproof impregnation at this point,  $kg \cdot m^{-3}$ ;  $T$  is the current temperature of the pro-

cess, K;  $\chi_w(x, y, T)$  is the thermal conductivity coefficient of wood,  $\text{W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$ .

The initial (Dirichlet) conditions for any point of the spatial coordinate of the sample with a fire-protective impregnation:

$$T(t=0) = T_0, \tag{14}$$

where  $t$  is the time, s;  $T_0$  is the initial temperature of the sample, which coincides with the ambient temperature, K.

The boundary (Robin) conditions of the mixed type [25], which corresponds to the simultaneous heat exchange by convection (according to Newton's law) and thermal radiation (according to the Stefan-Boltzmann law) of the environment:

$$\frac{(c_{pW}(x, y, T) \cdot \rho_W(x, y, T) + c_{pFR}(x, y, T) \cdot \rho_{FR}(x, y, T))}{\rho_W(x, y, T) + \rho_{FR}(x, y, T)} \times \frac{\partial T}{\partial n} = \alpha(T - T_0) + F_i \cdot \varepsilon \cdot \sigma \cdot (T^4 - T_0^4), \tag{15}$$

where  $c_{pW}(x, y, T)$ ,  $c_{pFR}(x, y, T)$  is the effective specific heat capacity of the wood sample and, accordingly, the fireproof impregnation,  $\text{J}\cdot\text{K}^{-1}\cdot\text{m}^{-3}$ ;  $\alpha$  is the coefficient of convection heat transfer between the walls of the sample and the surrounding air,  $\text{W}\cdot\text{m}^{-2}\cdot\text{K}^{-1}$ ;  $\frac{\partial T}{\partial n}$  is the temperature gradient in the direction of normal to the  $i$ -th outer surface,  $\text{K}\cdot\text{m}^{-1}$ ;  $F_i$  is the angular irradiation coefficient for each (four, under the conditions of the set problem) outer surfaces of the sample;  $\varepsilon$  is the effective coefficient of the grayness of the outer surfaces of the sample;  $\sigma$  is a constant in the Stefan-Boltzmann formula.

The initial data derived from mathematical modeling are the dependences of the temperature of the surface of the sample wood at the side of the site of fire irradiation on the time of fire impact. Thus, the model being built according to the presented procedure makes it possible to determine the time before reaching the set (pre-experimentally determined) ignition temperature of the fire-loaded material. Thus, our mathematical model makes it possible to determine the duration of FSS. It is known that FSS is equivalent to the resource of time, which is available for responsible units for the elimination of fire at minimal losses at a facility with and without fireproof wood treatment [7].

**4.2. Procedure to study experimentally the propagation of flame over the surface of wood exposed to fire**

To test the adequacy of mathematical models, we propose using a method for determining the index of flame propagation over the surface according to the standardized procedure for fire tests [27] at the appropriate installation (Fig. 1).

A sample is fixed at a bench with a frame tilted at an angle of 30° from the vertical towards the electric heating panel; the edge of the sample is set aside by 70 mm from the panel. The side surface of the frame is marked to control the propagation of the flame.

In the exhaust area, there is a thermocouple to control the temperature of the released combustion products. During the tests, forced ventilation (no more than 0.35 m/s) is used.

We tested wooden samples of the following dimensions: length,  $320 \pm 1$  mm; thickness,  $20 \pm 1$  mm; width,  $140 \pm 1$  mm (Fig. 2). Samples are aged at least 48 hours in advance in a dry room at a temperature of  $20 \pm 2$  °C.

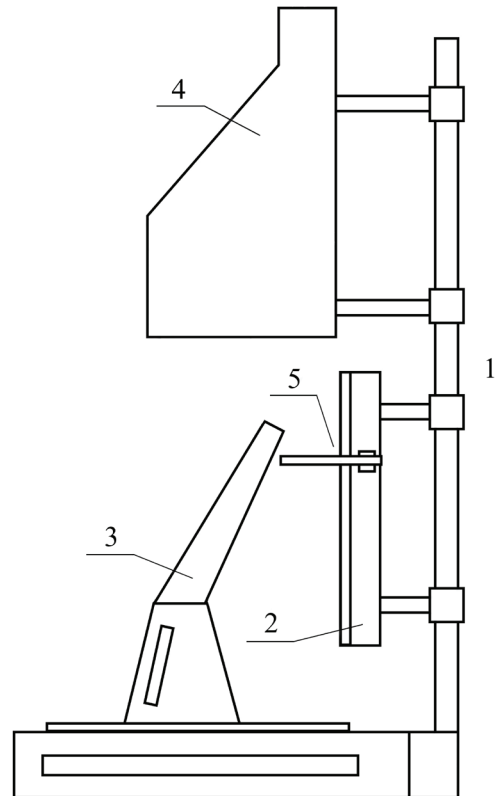


Fig. 1. General view of the installation for determining the index of flame propagation over the surface of wood: 1 – rack, 2 – electric heating panel, 3 – sample holder frame, 4 – exhaust area, 5 – burner



Fig. 2. Photographs of wood samples before testing: a – untreated, b – fire-proof

Next, the installation is brought to a working mode. To this end, we set the flame height of the gas burner to about 10 mm; the regulator of a heat flow provides for the rated values of the heat flow at control points (from 32 to 12  $\text{kW}/\text{m}^2$ ).

The surface of the wood sample, oriented towards the heat flow, has control tags pre-applied every  $30 \pm 1$  mm. The control sample of heat flow values is replaced with the examined type of wood; the time is counted before ignition; the propagation of flame over the surface is controlled.

Control values are:

- the interval of time when the flame reaches a zero bar  $t_0$ , s;
- the interval of time before the flame front reaches the  $i$ -th mark  $T_i$  (where  $i=1, 2, \dots, 9$ ), s;
- the length of the propagation of the front flame, mm;
- the highest temperature of combustion products released through the exhaust area  $T_{max}$ , °C;
- the time interval for reaching the highest temperature of gaseous products, s.

## 5. Results of studying the fire impact on unprotected and fire-proof wood

### 5.1. Results of the mathematical modeling of processes that occur in wood when it is heated at an ignition site

Using the reported procedures, we modeled the processes that occur in a wood sample when it is heated at an ignition site.

We modeled processes in the sample of unprotected wood on the basis of a numerical solution to the differential equation of thermal conductivity in a two-dimensional space (7) at the boundary conditions of the third kind (8), (9) and, for fire-proof wood, on the basis of a numerical solution to the differential equation of thermal conductivity in a two-dimensional space (13) at the boundary conditions of the third kind (14), (15).

The modeling results are shown in Fig. 3.

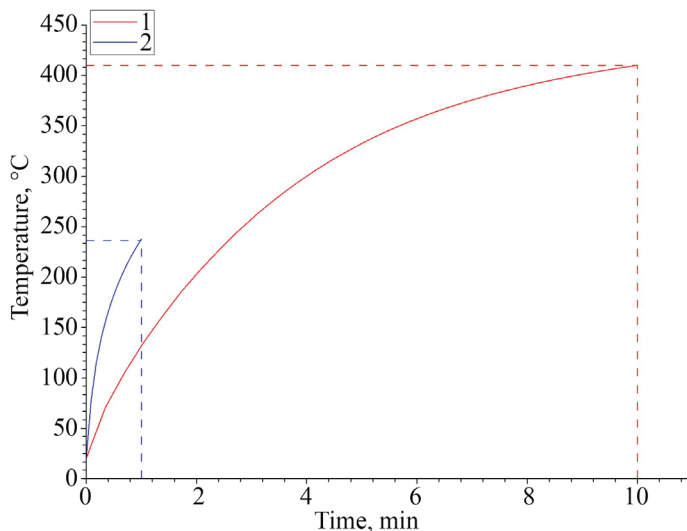


Fig. 3. Results of the mathematical modeling of the physicochemical processes in non-fire-proof and fire-proof wood (across the fibers) during heating: the dependence of the temperature of the outer surface of the irradiated sample on time (blue – for unprotected wood, red – for protected wood)

The unprotected wood was studied: pine swamp, 20 mm thick, 400–550 kg/m<sup>3</sup> in density. Wood of the same variety, thickness, and density, impregnated with a fire protection agent based on diammonium phosphate and ammonium sulfate (consumption, 168.2 g/m<sup>2</sup> of dry components of fire retardants) was investigated as fireproof wood. Our modeling employed the results from determining experimentally the ignition temperature of unprotected and fire-proof wood, specifically, 235 °C – for unprotected wood, 410 °C – for fireproof wood, respectively.

### 5.2. Results from studying experimentally the propagation of flame over the surface of wood exposed to fire

Our research was carried out at the installation (Fig. 4), certified in accordance with the requirements set in [27].



Fig. 4. Photograph of the installation to determine the index of flame propagation over the surface

Fig. 5 shows the photograph of samples of the untreated and fire-proof wood after 10 minutes of testing (according to the requirements of the standard). The calculated flame propagation index was: 30 – for untreated wood, 0 – for fire-proof wood. No flame burning of fire-proof wood occurred over 10 minutes of fire exposure (only carbonation of the surface is recorded).



Fig. 5. Photographs of wood samples after tests according to the requirements set in p. 7.20 [27]: a – untreated, b – fire-proof

The average values of the time of ignition achievement were: for unprotected wood – 55 s, for fireproof wood – 12.5 minutes.

## 6. Discussion of results of studying the prospects for using the mathematical modeling of a fire start stage

The mathematical models that are built according to our procedures make it possible to determine the period from the

beginning of the action of fire exposure to the achievement of the experimentally established ignition temperature for unprotected and fire-proof wood. Thus, mathematical modeling can determine the duration of FSS, which is equivalent to the time resource for the confident elimination of fire at objects whose fire load is formed by wood. The data on the duration of reaching the temperature of ignition of wood (Fig. 3) allow us to assert the following:

- non-fireproof pine swamp (density, 400–550 kg/m<sup>3</sup>) with a thickness of 20 mm is ignited in 57 s when irradiated by a thermal flow with a density of 32 kW/m<sup>2</sup> (max); the fire-proof – after 10 minutes;

- due to the implementation of the cooling factor caused by the flame retardant-based treatment, the calculated interval of time from the onset of fire exposure to the moment of the start of fireproof wood burning (impregnated with a flame retardant based on phosphates and ammonium sulfates) is an order of magnitude greater compared to such interval for non-fire-proof wood;

- to extend the time of the initial stage of fire evolution, it is advisable to carry out the fire-protective impregnation of wood with fire retardants, which makes it possible to increase the ignition temperature of its surface layers.

The experimental studies of flame propagation over the surface of wood indicate the following:

- the ignition of non-fireproof pine swamp (density, 400–550 kg/m<sup>3</sup>, 20 mm thick) when irradiated by a thermal flow with a density of 32 kW/m<sup>2</sup> (max.) occurs on second 55 of testing, which practically corresponds to the estimation data;

- the ignition of the same wood samples, fire-protected by an impregnated agent based on phosphates and ammonium sulfates (consumption, 168.2 g/m<sup>2</sup> of dry fire retardant components), occurs later than calculated (by about 25 %), which can be explained by taking into consideration only the cooling factor in the mathematical model, due to the use of impregnation with fire retardants (that is, the insulating, phlegmatizing, and inhibiting factors were disregarded).

Our results indicate that in order to further approximate the results of theoretical and experimental studies of fire-proof wood, all these fire protection factors should be taken

into consideration. Thus, the search for a phenomenological description of the full fire-protective effect should be considered promising.

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## 7. Conclusions

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1. It was established that our procedures of mathematical modeling make it possible to construct mathematical models for determining the time of the stage of starting a fire at facilities whose fire load is formed by wood. Mathematical and physical modeling data have been obtained for wooden boards made of pine, 20 mm thick (density, 400–550 kg/m<sup>3</sup>), which are widely used in construction. Thus, the results of the reported research could be used when creating the formulations for impregnating fire retardants for wooden roof structures. Our data from mathematical modeling and experimental studies confirm the possibility of significant lengthening of time before wood ignition when using impregnating agents based on phosphates and ammonium sulfates for fire protection.

2. It is proven that the proposed mathematical model makes it possible to determine the time of a fire start stage and can be used to assess the fire danger of objects whose fire load is formed by wood. The value of the relative error between the experimental and calculated data does not exceed 3 % and does not exceed the relative error of experimental determination of time before wood ignition, which indicates the adequacy of calculations. Mathematical modeling data make it possible to quantitatively determine the effect of the cooling factor exerted by the use of fire retardants on the extension of the stage of a fire start. For fire retardants based on phosphates and ammonium sulfates (consumption, 168.2 g/m<sup>2</sup> of dry components), the contribution of the cooling factor is determined at the level of 75 % in the total fire protection effect. Consequently, the data from calculations could be used for setting the standards for the arrival of fire brigades to the fire site. The standards to be calculated in this way should be further refined when it is possible to quantify other fire-protective factors (insulating, phlegmatic, inhibiting).

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