

Проведеними дослідженнями впливу індукційного періоду на займання очерету встановлено механізми процесу передавання тепла до матеріалу, що дає можливість впливати на цей процес. Доведено, що вони полягають у нагріванні матеріалу до критичної температури, коли починається інтенсивний розклад з виділенням необхідної кількості горючих газів та їх займання. Завдяки цьому стає можливим визначення впливу вогнезахисту та властивостей покрівельних композицій на процес гальмування процесу загорання очерету. Експериментальними дослідженнями підтверджено, що необроблений очерет, під термічною дією протягом 58 с зайнявся, що відповідно склав індукційний період розкладу матеріалу, полум'я поширилося по всій поверхні, що призвело до його повного згорання, тривалість індукційного періоду збільшується до 587,45 с за рахунок розкладання антипіренів під дією температури з виділенням негорючих газів, які гальмують процеси окиснення матеріалу та суттєво підвищує утворення на поверхні очерету теплозахисного шару коксу. Це приводить до підвищення товщини шару коксу та гальмування теплопередачі високотемпературного полум'я до матеріалу. Завдяки цьому стало можливим визначення умов вогнезахисту очерету, шляхом утворення бар'єру для теплопровідності. Окрім того, при застосуванні вогнезахисного покриття температурний вплив здійснюється у напрямку реакцій у передполуменевій області убік утворення сажеподібних продуктів на поверхні природного горючого матеріалу. Це дозволяє стверджувати про відповідність виявленого механізму формування властивостей вогнезахисту очерету спучуючими композиціями та практичну привабливість запропонованих технологічних рішень. Останні, зокрема, стосуються визначення кількості полімерної складової, оскільки очерет характеризується гідрофобністю і водний розчин антипірену стікає з поверхні. Таким чином, є підстави стверджувати про можливість спрямованого регулювання процесів формування вогнезахисту очерету шляхом використання комплексної покрівельної композиції з суміші антипіренів, яка містить природний полімер, здатний утворювати на поверхні матеріалу вогнезахисну плівку.

Ключові слова: вогнезахист очерету, вогнезахисні покриття, теплопровідність, оброблення поверхні, теплофізичні властивості

UDC 614.842

DOI: 10.15587/1729-4061.2019.156644

ESTABLISHMENT OF HEAT-EXCHANGE PROCESS REGULARITIES AT INFLAMMATION OF REED SAMPLES

Yu. Tsapko

Doctor of Technical Sciences*

Scientific-Research Institute for Binders and Materials named after V. D. Glukhovsky**

E-mail: juriyts@ukr.net

A. Tsapko

Posgraduate student*

E-mail: alekseytsapko@gmail.com

O. Bondarenko

PhD, Associate Professor

Department of Building Materials**

E-mail: bondolya3@gmail.com

*Department of Technology and

Design of Wood Products

National University of Life and

Environmental Sciences of Ukraine

Heroiv Oborony str., 15, Kyiv, Ukraine, 03041

**Kyiv National University of

Construction and Architecture

Povitroflotsky ave., 31, Kyiv, Ukraine, 03037

1. Introduction

At present, reed is growing in popularity as an environmentally safe roofing material. However, it is classified as a flammable material. To reduce this shortcoming, flame-retarding treatment is used, which makes this material resistant to inflammation.

Roofs are impregnated with flame-retarding means both from outside and inside. After drying, a secure protective coating is formed on the roof surface which is not washed away by rain or snow. The flame-retarding coating serves for several years and protects roofs against accidental exposure to inflammation sources.

Basic requirements to natural combustible materials with flame-retarding coating: they should withstand fire and not spread flame over their surface. After flame-retarding treatment, decomposition of such material changes towards release of non-combustible gases, formation of a fire-resistant coke residue and inhibition of oxidation in gas and condensed phases.

Special coatings are widely used for fire protection of building structures made of combustible materials. When

exposed to high temperatures, they emit water. However, they do not always provide fire resistance. Therefore, means were developed recently that are capable of forming a heat-insulating layer of foamed coke on the structure surface which greatly reduces heat transfer to the structure material [1, 2].

Use of formulations of polymeric substances and fire retardants can improve fire protection of materials due to formation of a protective coke layer. This will ensure development of a new type of flame retarding materials for protection of roof structures using reed by transforming it into fire-resistant material. Moreover, fire protection of the building structures substantially impedes the process of inflammation [3, 4].

The process of inflammation (spontaneous inflammation) of various types of materials is characterized by an induction period, that is, duration of the time interval after which material is heated to a critical temperature at which critical amount of combustible gases is released. Knowledge of this period duration is necessary for substantiation of choice of the means for fire protection of building structures when flammable materials are used for them.

Therefore, modeling of the process of reed inflammation, study of thermal and physical parameters and the flame retardant itself and influence of its components on this process is an unsolved component of measures taken to ensure fire resistance of building structures. Accordingly, this necessitates conduction of such studies.

2. Literature review and problem statement

Studies conducted in the proposed direction in recent years are aimed at development of flame-retardant formulations using inorganic substances modified by organic compounds capable of forming a coke layer on the structure surface [5–7]. Results of study of fire protecting coating behavior under influence of high temperatures are given in work [5]. Both behavior of bloating coats and heat transfer resulting from coating was shown but the issues of establishing temperature of foamed coke formation remain unresolved which reduces importance of the results obtained. In most cases, such formulations are modified by means of polymeric complexes and flame retarders but they belong to materials characterized by low adhesion and release of toxic combustion products at high temperatures [6].

The most promising formulations of bloating flame retarding coatings are given in [7]. They are complex systems of organic and inorganic components. However, issues of manifestation of joint action of the coating components during foaming remain not elucidated. The materials discussed in [8] are characterized by high intumescent ability but the mechanism of coke formation and temperatures of coating transformation into foamed coke were not explained.

Expediency of using dolomite clay was confirmed by change of the foamed coke structure and a considerable fall of thermal characteristics which is explained by formation of intermediate compounds bringing about an essential number of nanostructures [9]. However, no relevant physical and chemical calculations were given to confirm this process. For example, according to [10], this is due to formation of a significant number of high-temperature compounds during decomposition of the coating fillers which thicken and form a solid skeleton at high temperatures.

In the line of these studies, an analytical model for calculating thermal conductivity of the protective coke layer was developed. It takes into account pore shapes [11]. However, this model does not take into account precisely how the change in the pore shape affects heat transfer to the structure proper. Besides, many coatings have a series of problems, such as applying individual components or loss of functional properties with increase in ambient temperature [12]. This means that it is not known how the process proceeds in the temperature range of the flame-retardant decomposition. From a practical point of view, this may cause difficulties with determining an optimal amount of inert additives. This is caused by the fact that their addition to formulations substantially changes mechanism and kinetics of the coking processes.

In order to overcome this problem, studies of influence of inorganic fillers on shear viscosity and fire protection properties of water-based bloating coatings have been carried out in [13]. It was shown that due to the established analytical dependences, it becomes possible to adjust content of modifiers to provide thermal protection of materials.

Therefore, simulation of inflammation parameters and the effect of fire protection coatings on this process is an unsolved component of measures providing fire resistance of building structures which has led to conduction of this study.

3. The aim and objectives of the study

This study objective was to reveal regularities of the heat exchange process and establish parameters of inflammation of reed samples. This would make it possible to justify use of fire protection.

To achieve this objective, the following tasks were solved:

- to simulate parameters of the heat exchange process during inflammation of reed samples and the effect of fire protection on inflammation suppression;
- to establish features of inflammation time change during heating of flame-retarded reed samples.

4. Materials and methods used in studying the front of phase transformations during bloating of flame retarding coatings

4.1. Materials used in the experiment

In order to establish heat conduction and inflammation, an uncoated reed sample and samples with a coat forming a colorless film on the reed sample surface and capable of forming a protective layer of foamed coke on the surface under influence of elevated temperatures were used. Skela-i roofing impregnation solution (a mixture of 28÷30 % carbamide, 23÷24 % phosphoric acids and 20 % starch) was used. The resulting mass was stirred, water added to 100 % and applied on reed samples.

For the study of effectiveness of the fire-retardant material, mats with dimensions of 310×140 mm and thickness of 28÷32 mm prepared from reed sticks having average diameter up to 10 mm and length of 310 mm were used. These mats were treated by applying the above roofing impregnation solution in an amount of 22÷23 g on the surface of all reed sticks in the mat with total area of 0.467 m² (surface area of one reed stick was ≈0.0078 m²). The coating weight after drying was ≈49.25 g/m².

4.2. The procedure used in determining properties of the samples

The study with modeling parameters of the heat exchange process taking place in inflammation of the reed samples was carried out according to the basic provisions of mathematical physics.

The study for experimental determination of parameters of reed inflammation was conducted according to a procedure consisting in the following. A sample was placed in the test chamber and exposed to heat from an IR radiation panel. Upon inflammation of the sample, inflammation time, maximum temperature of combustion products and time necessary for its achievement, time of passage of the flame front over the surface areas, length of the burnt sample section were measured [2].

Inflammation and jump-like rise in temperature of flue gases, time of passage of the flame front over the sections of the reed sample surface were taken as criterion for determining induction period of inflammation of the reed samples during their exposure to heat.

5. Modeling parameters of the heat exchange process depending on thermophysical properties of the material

The process of self-inflammation of various types of materials is characterized by duration of a time interval after which material becomes heated to a critical temperature (induction period). Knowledge of this period is necessary for substantiation of choice of means for fire protection of building structures made of highly inflammable materials. It was assumed that duration of this period coincides with the time interval t_m during which temperature of the heated material reaches critical value. Dependence of parameters of the heat exchange process on thermophysical properties of the material is determined on the basis of the heat transfer equation:

$$\rho c_p \frac{\partial T}{\partial t} + \varepsilon \cdot \tilde{c}_p \cdot \nabla(\tilde{\rho} \cdot \tilde{w} \cdot T) = \lambda \cdot \nabla^2(T) + \Psi, \tag{1}$$

where ε is relative medium voidness;

$$\varepsilon = \frac{\Pi}{\Pi - 1}, \tag{2}$$

where Π is medium voidness (void volume to medium volume ratio).

The “wave” sign above the symbol indicates its value for the gas phase; $\nabla(\tilde{w} \cdot F)$ is the operator of divergence (discrepancy) of the $F = \tilde{\rho} \cdot T$ function in terms of \tilde{w} vector [14]:

$$\nabla(\tilde{w} \cdot F) = \frac{\partial}{\partial z}(u \cdot F) + \frac{\partial}{\partial r}(v \cdot F), \tag{3}$$

where $\nabla^2(F)$ is the Laplace operator (divergence of the function gradient):

$$\nabla^2(F) = \text{div}(\text{grad}F) = \frac{\partial^2 F}{\partial z^2} + \frac{1}{r} \frac{\partial}{\partial r} \left(r \frac{\partial F}{\partial r} \right); \tag{4}$$

ψ – function of density of power of heat sources, W/m^3 ; ρ – material density, kg/m^3 ; c_p – heat capacity of material, $J/kg \cdot K$; T – material temperature, K ; t – time from the moment of material placement in the chamber, s ; λ – thermal conductivity of the material $W/m \cdot K$.

First, define the input function of power of the heat sources, $\Psi(t)$, in this equation. Because any elemental volume is in the same conditions, assume that the heat exchange process involves the entire volume. Assume that inflammation begins from the moment t_m of attaining the critical temperature, that is, taking into account the induction period of heating of the material volume, maximum heat emission is described by the following equation:

$$\Psi(t) = q \cdot \left\{ 1 - \text{th}^2 \left[\left(1 - \frac{t}{t_m} \right) \cdot \frac{\Delta}{2} \right] \right\}. \tag{5}$$

Taking into account the induction period of heating of the material volume, write equation (1) as follows:

$$\begin{aligned} \rho \cdot c_p \frac{\partial T}{\partial t} + \varepsilon \cdot \tilde{c}_p \cdot \left[\frac{\partial(\tilde{\rho} \cdot u \cdot T)}{\partial z} + \frac{\partial(\tilde{\rho} \cdot v \cdot T)}{\partial r} \right] = \\ = \lambda \left[\frac{\partial^2 T}{\partial z^2} + \frac{1}{r} \frac{\partial}{\partial r} \left(r \frac{\partial T}{\partial r} \right) \right] + q \cdot \left\{ 1 - \text{th}^2 \left[\left(1 - \frac{t}{t_m} \right) \cdot \frac{\Delta}{2} \right] \right\}. \end{aligned} \tag{6}$$

Assume that a temperature-critical situation arises when average temperature in some horizontal layer is close to inflammation temperature. Average temperature of the layer is called temperature $T_z = T(z, t)$, K , averaged over the volume cross section $S = \pi \cdot R^2$, according to this formula:

$$T_z = \frac{1}{S} \int_0^S T \cdot ds = \frac{1}{\pi \cdot r^2} \int_0^R T \cdot 2 \cdot \pi \cdot r \cdot dr = \frac{2}{R^2} \int_0^R T \cdot r \cdot dr, \tag{7}$$

where $ds = 2\pi \cdot r \cdot dr$ is the elementary cross-sectional area, m^2 ; dr is the elementary increase in the radial coordinate, m .

Convert (6) using the equation of state of the gas medium in the form:

$$p = p_0 \pm \Delta p = \tilde{\rho} \cdot T \cdot R, \tag{8}$$

where p_0 is atmospheric pressure, Pa ; Δp is deviation of the actual pressure in the bulk from atmospheric pressure caused by high pressure of filtration flows, Pa .

It is known [15] that speed of filtration flows in buildings where average diameter of reed varies within $d = 4.5 \dots 20.0$ mm does not exceed $w = 10^{-3}$ m/s. At the same time, according to [13], coefficient of permeability $k = 1.8 \cdot 10^{-6} \dots 1.0 \cdot 10^{-5}$ m^2 while macro-roughness of the material surface is of the order of $l = 7.0 \cdot 10^{-3}$ m. Considering that dynamic viscosity of air in the temperature range $T = 20 \dots 300$ °C practically does not differ from the $\mu \approx 1.8 \cdot 10^{-7}$ $Pa \cdot s$; $\tilde{\rho} = 1,2$ kg/m^3 at $T = 20$ °C; $\tilde{\rho} = 0,9$ kg/m^3 at $T = 230$ °C [16].

Estimate the characteristic of the presented filtration region at an average density of $\tilde{\rho} = (1,2 + 0,9) / 2 = 1,05$ kg/m^3 :

$$a = \frac{\mu}{k} + \frac{\tilde{\rho}}{l} w \leq \frac{1,8 \cdot 10^{-7}}{1,8 \cdot 10^{-6}} + \frac{1,05}{7,0 \cdot 10^{-3}} 10^{-3} \sim 10, \text{ kg/s} \cdot m^3. \tag{9}$$

Taking into account that filtration flows of air in the medium are modeled by the system of Euler differential equations [14], determine maximum flow of the possible limits of depression along the filtration path:

$$\begin{aligned} - \frac{\partial p}{\partial z} = |a \cdot u + (\tilde{\rho} - \rho_0) \cdot g| \leq \\ \leq |10 \cdot 10^{-3} + (1,05 - 1,2) \cdot 9,8| = 10^{-1} \text{ N/m}^3. \end{aligned} \tag{10}$$

Integrate (10) by the height of the reed volume $L = 30$ mm, then

$$\Delta p = - \int_0^L \frac{\partial p}{\partial z} = |a \cdot w + (\tilde{\rho} - \rho_0) \cdot g| \cdot L \leq 30 \text{ Pa}, \tag{11}$$

which is infinitely small in comparison with atmospheric pressure $p_0 \sim 10^5$ Pa .

Note that if forced ventilation increases speed of ventilation flows in the volume to a value being standard for industrial buildings and structures, $u_0 \sim 1$ m/s, and estimating

$$a \leq \frac{1,8 \cdot 10^{-7}}{1,8 \cdot 10^{-6}} + \frac{1,05}{7,0 \cdot 10^{-3}} 1,0 = 10 + 157 \approx 170 \text{ kg/s} \cdot m^3; \tag{12}$$

$$\Delta p \leq |170 \cdot 1,0 - 1| \cdot 30 \approx 5 \cdot 10^2 \text{ Pa}. \tag{13}$$

That is, deviation of pressure cannot exceed 0.5 % atmospheric pressure.

Consequently, given the insignificant variation of the gas constant of air from the value of $R=0.237$ J/kg·K, equation (8) can be represented with sufficient accuracy as:

$$\tilde{\rho} = \rho_0 \frac{T}{T_0}. \quad (14)$$

This means that air is thermally deformed in volume, but because $\Delta p \ll p_0$ is an incompressible gas medium in hydrodynamic sense, that is, $\partial \rho / \partial t = 0$, the equation of air continuity is represented as follows:

$$\nabla(\tilde{\rho} \cdot \vec{v}) = 0, \quad (15)$$

or in projections on the coordinate axes:

$$\frac{\partial(\tilde{\rho} \cdot u)}{\partial z} = 0, \Rightarrow \tilde{\rho} \cdot u = \rho_0 \cdot u_0; \quad (16)$$

$$\frac{\partial(\tilde{\rho} \cdot v)}{\partial r} = 0, \Rightarrow \tilde{\rho} \cdot v = \rho_0 \cdot v_0, \quad (17)$$

where variables with the index "0" refer to the characteristic layer of the reed, for example, to the top layer which is the boundary between the material volume and the free storage space.

Substitute expressions (16) and (17) into equation (6), then

$$\begin{aligned} & \rho c_p \frac{\partial T}{\partial t} + \varepsilon \rho_0 \tilde{c}_p u_0 \frac{\partial T}{\partial z} + \varepsilon \rho_0 \tilde{c}_p v_0 \frac{\partial T}{\partial r} = \\ & = \lambda \left[\frac{\partial^2 T}{\partial z^2} + \frac{1}{r} \frac{\partial}{\partial r} \left(r \frac{\partial T}{\partial r} \right) \right] + q \cdot \left\{ 1 - \text{th}^2 \left[\left(1 - \frac{t}{t_m} \right) \cdot \frac{\Delta}{2} \right] \right\}. \end{aligned} \quad (18)$$

Multiply both parts of equation (18) by elementary area ds , integrate for r within $r=0 \dots R$ and divide by area of the cross section, S . As a result, in view of expression (8), the following is obtained:

$$\begin{aligned} & \rho c_p \frac{\partial T_z}{\partial t} + \varepsilon \rho_0 \tilde{c}_p u_0 \frac{\partial T_z}{\partial z} = \\ & = \lambda \frac{\partial^2 T_z}{\partial z^2} + q \left\{ 1 - \text{th}^2 \left[\left(1 - \frac{t}{t_m} \right) \frac{\Delta}{2} \right] \right\}. \end{aligned} \quad (19)$$

Estimate the order of quantities in equation (19). For this purpose, introduce dimensionless variables: coordinate ξ , time τ and temperature θ as follows:

$$\xi = \frac{z}{H}; \quad \tau = t \frac{u_0}{H}; \quad \theta = \frac{T_z - T_0}{T_{\text{cr}} - T_0}. \quad (20)$$

Write equation (19) for these variables:

$$\begin{aligned} & \frac{\partial \theta}{\partial \tau} + \varepsilon \frac{\rho_0 \tilde{c}_p}{\rho c_p} \frac{\partial \theta}{\partial \xi} = \frac{H}{u_0 \rho c_p (T_{\text{cr}} - T_0)} \times \\ & \times \left(\frac{\lambda}{H^2} \frac{\partial^2 \theta}{\partial \xi^2} + q \left\{ 1 - \text{th}^2 \left[0,5 \Delta (1 - \tau / \tau_m) \right] \right\} \right), \end{aligned} \quad (21)$$

where $\tau_m = t_m \cdot u_0 / H$ is the relative value of the induction period.

Let us pass to estimation. The first term in the left-hand side of equation (21) is magnitude of order 1. It was established

in [16] that $\rho_0 \tilde{c}_p \sim 10^3$ J/kg·K for air and $\rho c_p \sim 10^4$ J/(kg·K) for a plant raw material and $\varepsilon < 0.5$. Then the second addend in the left part does not exceed 0.01 and it can be neglected in comparison with the first addend $\lambda / H^2 = 9 \cdot 10^3$. Because the heat flux acting on the material thickness (0.03 m) is within $q = 333 \div 1500$ kW/m³, the first addend in the round brackets is considerably smaller than the second one and is not taken into account.

As a result of estimation, equation (21) is reduced to the following:

$$\frac{\partial \theta}{\partial \tau} = \frac{qH}{\rho u_0 c_p (T_{\text{cr}} - T_0)} \left\{ 1 - \text{th}^2 \left[0,5 \Delta (1 - \tau / \tau_m) \right] \right\}. \quad (22)$$

Assume that the material temperature does not differ from the ambient temperature in the initial moment but is equal to the critical temperature by the end of the induction period:

$$T_z|_{t=0} = T_i = T_0 = 20 \text{ }^\circ\text{C}; \quad T_z|_{t=t_m} = T_{\text{cr}} = 230 \text{ }^\circ\text{C} \quad (23)$$

or, in dimensionless variables:

$$\theta|_{\tau=0} = 0; \quad \theta|_{\tau=\tau_m} = 1. \quad (24)$$

Integrate expression (22) in terms of time to obtain:

$$\theta = \frac{qH\tau_m}{\rho u_0 c_p (T_{\text{cr}} - T_0)} \frac{1}{x} \left\{ \text{th}x - \text{th} \left[\left(1 - \frac{\tau}{\tau_m} \right) x \right] \right\}, \quad (25)$$

where x is the integration constant obtained with an account of the initial condition (24):

$$\theta|_{\tau=0} = 0 \Rightarrow x = \Delta / 2.$$

Using expressions (20), write formula (25) in dimensional variables

$$T_z = T_0 + \frac{qt_m}{\rho c_p} \frac{1}{x} \left\{ \text{th}x - \text{th} \left[\left(1 - \frac{t}{t_m} \right) x \right] \right\}. \quad (26)$$

Since, according to the second boundary condition (23), it is necessary that $t = t_m; T_z = T_{\text{cr}}$, then based on expression (26), an equation is obtained with respect to the parameters of the exchange process, t_m and $x = \Delta / 2$:

$$\text{th}x = \frac{\rho c_p}{qt_m} (T_{\text{cr}} - T_0) \cdot x. \quad (27)$$

Parameter χ is thermophysical characteristic of the material:

$$\chi = \frac{\rho c_p}{qt_m} (T_{\text{cr}} - T_0), \quad (28)$$

which is equal to duration of the time interval during which temperature of the unit volume of material increases by one degree.

Fig. 1 presents the results of processing data on duration of the induction period during reed inflammation. The data were processed using the Microsoft Excel's static function:

$$t_m = a \cdot q^{-b}, \quad (29)$$

where a and b are empirical constants s and m³/W.

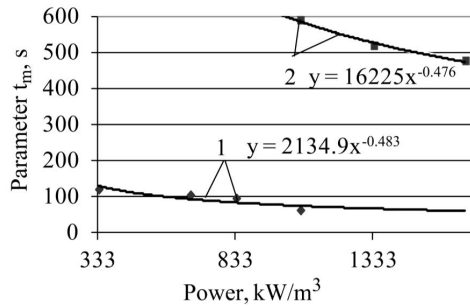


Fig. 1. Dependence of the parameter of induction period of reed inflammation on the power of temperature influence on the material volume: untreated (1), flame-retarded (2)

Based on equation (28), turn to definition of the second parameter of the exchange process, χ . The task was solved in the following order. First, thermophysical characteristic of the material, χ , was calculated, for example, for reed, at inflammation temperature [16] $T_{cr}=503$ K; at initial temperature $T_0=293$ K; $\rho \cdot c_p=0.5 \cdot 10^4$ J/m³·K at $q=1.01 \cdot 10^5$ W/m³:

$$\chi = \frac{0,5 \cdot 10^4}{1,01 \cdot 10^5} (503 - 293) = 10,4 \text{ s.} \tag{30}$$

The following is obtained in approximation of curve 1 from Fig. 2:

$$a=436.77 \text{ s}; b=0.265 \text{ m}^3/\text{kW}.$$

Then, according to (29), duration of the induction period is:

$$t_m = 2134,9 \cdot 1066^{-0,483} = 76,61 \text{ s.} \tag{31}$$

Calculate the parameter:

$$A = \chi / t_m = 10,4 / 76,61 = 0,141 \tag{32}$$

and solve graphically equation (27) to get $x=\Delta/2=7.0$ (Fig. 3).

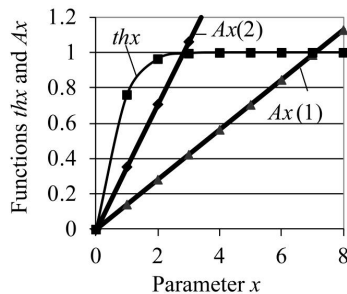


Fig. 2. Determination of the exchange process parameter x for reed: untreated (1), flame-retarded (2)

Similarly, perform calculations for the case of using fire protection. For example, for a flame-retarded plant material, $\rho \cdot c_p=0.5 \cdot 10^5$ J/m³·K [16], induction period increases: parameter $\chi=207.9$ s; $t_m=587.45$ s; $A=0.35$; $x=\Delta/2=2.8$ (Fig. 3).

Thus flame-retarding treatment of reed results in decomposition of the coating components and formation of foamed coke that isolates material from high temperature

and increases duration of the induction period by more than 8 times.

6. Experimental studies of the process of reed inflammation and inhibition of this process by fire protection. Study results

In order to establish fire resistance of reed, studies were conducted on reed inflammation under the action of a burner simulating a low-power heat source.

Results of the studies conducted to determine increase in maximum temperature of gaseous combustion products (Δt , K) and duration of the induction period of reed inflammation were simulated according to the procedure and equipment given in [2] in laboratory conditions. The results are shown in Fig. 3.

Studies have shown that reed not subjected to treatment by flame retardant under the action of heat was inflamed in 74 seconds, maximum temperature of flue gases has risen to 733 K, flame has spread throughout the reed surface which led to its combustion.

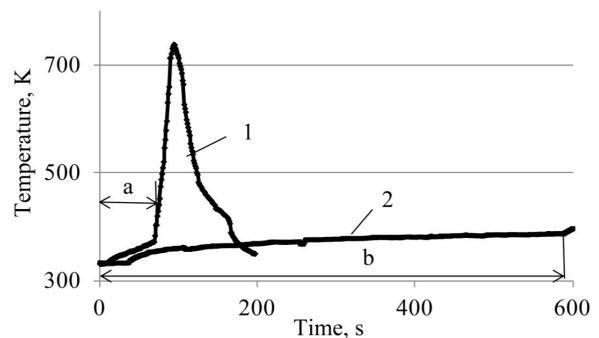


Fig. 3. Dynamics of increase in temperature of flue gases in tests with reed: nontreated (1); flame-retarded (2); induction period for nontreated reed (a); induction period for flame-retarded reed (b)

Next, tests of a flame-retarded sample were conducted. It was established that the sample treated with a roofing impregnation solution was inflamed at 588 s, spread of flame on the surface occurred only in the first section (flare), maximum temperature of flue gases was 387 K.

Thus, based on the derived dependences of thermophysical characteristics of materials (27)–(29) and experimental studies (Fig. 1, 2), parameters of the heat-exchange process during inflammation of reed, including flame-retarded reed were established.

7. Discussion of results obtained in the study of the process of advancement of the phase change front

Under the influence of high-temperature flame on the reed sample, as evidenced by the results of studies (Fig. 2, 4), the process of inflammation can occur when material is heated up to a critical temperature. Intensive reed fission occurs at this temperature with formation of a critical amount of combustible gases and their inflam-

mation and spread of flame over the surface. Therefore, one of the ways to inhibit the process of reed fission is material isolation from heat influence. The process of inflammation is suppressed by means of flame retardants. Obviously, such a mechanism of influence is the factor regulating release of combustible gases and effectiveness of heat insulation with flame retardants. This agrees with the data known from studies [5, 6] which also associated the process of material inflammation with the induction period and addition of flame retarders. In contrast to the results of studies [7, 8], the obtained data on influence of the inflammation process on heat transfer to the material and change of the insulation properties have allowed us to assert the following:

- the main regulator of the inflammation process is not merely achievement of the critical temperature but also release of a critical amount of combustible gases and decomposition of flame retardants under the influence of temperature with absorption of heat and release of non-combustible gases, inhibition of the oxidation process in the gas and condensed phases;

- substantial influence on the process of inflammation of combustible materials in the case of application of a flame-retardant coating is exerted in the way of reactions in the pre-flaming region with formation of soot-like products on the surface of natural combustible materials.

Such conclusions can be considered expedient from a practical point of view as they allow one to reasonably approach to determination of the induction period and search for a proper formulation of a flame retardant. The results of determining thermal conductivity of fire protected reed (Fig. 7) demonstrate an ambiguous effect of the nature of protection means on temperature changes. In particular, this is implied by availability of data sufficient for qualitative execution of the process of temperature growth inhibition and establishment on their basis of the time moment from which drop in heat resistance comes. This knowledge will make it possible to study transformation of the coating surface towards the high temperature side with coke formation and identify the variables significantly affecting the process. These study results are applicable to building structures from plant raw materials. Therefore, it is expedient today to take building materials from renewable sources, protect

them against destruction and ensure the environmental friendliness of the products obtained.

This study is a continuation of the studies discussed in [1–4] where mechanism of fire protection of natural organic materials, foamed coke formation, transfer and implementation of high temperature thermal insulation were considered in detail.

8. Conclusions

1. Heat-exchange process regularities in inflammation of reed samples were modeled and effect of flame-retardant coating on this parameter was revealed. Characteristics of induction period of inflammation were determined and calculated dependences were obtained which makes it possible to change dynamics of the heat exchange process during decomposition of flame-retardant coatings. Based on the obtained dependences, the heat exchange parameter characterizing duration of the time interval during which temperature of the material unit volume increases by one degree was calculated. It is about 10 seconds and extends to 210 seconds in presence of a flame-retardant coating. Accordingly, it manifests itself in more than eightfold extension of the induction period of inflammation.

2. The features of formation of a foamed coke layer as a result of thermal action on a flame-retardant coating containing a fire-retarding agent and a polymeric component consists in release of non-combustible gases from the phase and formation of a heat-protective layer of coke on the wood surface. Thanks to such a mechanism established by experimental studies, fire protection of reed shifts this material from an easily flammable to a hard-flammable group of materials. Compared to untreated reed having induction period of inflammation of 58 s, this makes grounds to assert that effectiveness of fire protection improves as it extends duration of the induction period of inflammation due to decomposition of flame-retardant components and inhibits temperature rise during 587.45 s. This confirms possibility of controlled regulation of formation of a foamed coke layer by means of reed treatment with a mixture of a flame retardant and a polymeric component.

References

1. Tsapko Y., Tsapko A. Modeling a thermal conductivity process under the action of flame on the wall of firerretardant reed // Eastern-European Journal of Enterprise Technologies. 2018. Vol. 2, Issue 10 (92). P. 50–56. doi: <https://doi.org/10.15587/1729-4061.2018.128316>
2. Tsapko Y., Tsapko A. Establishment of fire protective effectiveness of reed treated with an impregnating solution and coatings // Eastern-European Journal of Enterprise Technologies. 2018. Vol. 4, Issue 10 (94). P. 62–68. doi: <https://doi.org/10.15587/1729-4061.2018.141030>
3. Tsapko J., Tsapko A. Simulation of the phase transformation front advancement during the swelling of fire retardant coatings // Eastern-European Journal of Enterprise Technologies. 2017. Vol. 2, Issue 11 (86). P. 50–55. doi: <https://doi.org/10.15587/1729-4061.2017.73542>
4. Tsapko Y., Tsapko A. Influence of dry mixtures in a coating on the effectiveness of wood protection from the action of a magnesium flame // Eastern-European Journal of Enterprise Technologies. 2017. Vol. 5, Issue 10 (89). P. 55–60. doi: <https://doi.org/10.15587/1729-4061.2017.111106>
5. Neue Wege: Reaktive Brandschutzbeschichtungen für Extrembedingungen / Krüger S., Gluth G. J. G., Watolla M.-B., Morys M., Häbler D., Schartel B. // Bautechnik. 2016. Vol. 93, Issue 8. P. 531–542. doi: <https://doi.org/10.1002/bate.201600032>

6. Effects of Complex Flame Retardant on the Thermal Decomposition of Natural Fiber / Xiao N., Zheng X., Song S., Pu J. // *BioResources*. 2014. Vol. 9, Issue 3. doi: <https://doi.org/10.15376/biores.9.3.4924-4933>
7. Graphene-Borate as an Efficient Fire Retardant for Cellulosic Materials with Multiple and Synergetic Modes of Action / Nine M. J., Tran D. N. H., Tung T. T., Kabiri S., Losic D. // *ACS Applied Materials & Interfaces*. 2017. Vol. 9, Issue 11. P. 10160–10168. doi: <https://doi.org/10.1021/acsami.7b00572>
8. Cirpici B. K., Wang Y. C., Rogers B. Assessment of the thermal conductivity of intumescent coatings in fire // *Fire Safety Journal*. 2016. Vol. 81. P. 74–84. doi: <https://doi.org/10.1016/j.firesaf.2016.01.011>
9. Oriented Clay Nanopaper from Biobased Components – Mechanisms for Superior Fire Protection Properties / Carosio F., Kochumalayil J., Cuttica F., Camino G., Berglund L. // *ACS Applied Materials & Interfaces*. 2015. Vol. 7, Issue 10. P. 5847–5856. doi: <https://doi.org/10.1021/am509058h>
10. Effect of Dolomite Clay on Thermal Performance and Char Morphology of Expandable Graphite Based Intumescent Fire Retardant Coatings / Gillani Q. F., Ahmad F., Mutalib M. I. A., Melor P. S., Ullah S., Arogundade A. // *Procedia Engineering*. 2016. Vol. 148. P. 146–150. doi: <https://doi.org/10.1016/j.proeng.2016.06.505>
11. An investigation into waterborne intumescent coating with different fillers for steel application / Md Nasir K., Ramli Sulong N. H., Johan M. R., Afifi A. M. // *Pigment & Resin Technology*. 2018. Vol. 47, Issue 2. P. 142–153. doi: <https://doi.org/10.1108/prt-09-2016-0089>
12. Carosio F., Alongi J. Ultra-Fast Layer-by-Layer Approach for Depositing Flame Retardant Coatings on Flexible PU Foams within Seconds // *ACS Applied Materials & Interfaces*. 2016. Vol. 8, Issue 10. P. 6315–6319. doi: <https://doi.org/10.1021/acsami.6b00598>
13. Effects of inorganic fillers on the shear viscosity and fire retardant performance of waterborne intumescent coatings / Fan F., Xia Z., Li Q., Li Z. // *Progress in Organic Coatings*. 2013. Vol. 76, Issue 5. P. 844–851. doi: <https://doi.org/10.1016/j.porgcoat.2013.02.002>
14. Loycyanskiy L. G. *Mekhanika zhidkosti i gaza*. Moscow: Nedra, 1970. 904 p.
15. Fel'dman L. P., Svyatniy V. A., Kasimov O. I. Issledovanie utechek vozduha cherez vyrabotannoe prostranstvo uchastka metodami matematicheskogo modelirovaniya // *Razrabotka mestorozhdeniy poleznykh iskopaemykh*. 1971. Issue 22. P. 105–110.
16. Perel'man V. I. *Kratkiy spravochnik himika*. Moscow: Goskhimizdat, 1963. 624 p.