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MODELING THE PROCESS OF MOISTURE DIFFUSION BY A FLAME-RETARDANT COATING FOR WOOD

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Опис поведінки вогнезахисних покриттів в момент експлуатації дерев'яної будівельної конструкції є окремим і складним завданням, охоплює обидві стадії процесу захисту: як захист від вологи, так і подальший тепло перенос, який утворюється при спученні покриття. Доведено, що вони полягають у створенні на поверхні матеріалу шару, який запобігає проникненню вологи до деревини, коли починається розбухання дерев'яної конструкції і руйнування покриття. Завдяки цьому стає можливим визначення впливу антипіренів та властивостей захисних композицій на процес гальмування швидкості вологопоглинання деревини. При використанні вогнезахисних покриттів для деревини, на що вказують результати досліджень, є закономірними процеси утворення захисного шару під дією температури і зниження вологості, які уповільнюють процеси дифузії вологи. Вочевидь такий механізм вогнезахисного покриття є фактором регулювання ступеня утворення атмосферостійкого захисного шару і ефективності тепло- і вологоізолювання матеріалу. Проведено моделювання процесу передавання вологи вогнезахисним покриттям, визначено коефіцієнт дифузії та отримані залежності, що дозволяють одержувати зміну динаміки вологи при висушуванні вогнезахисного покриття. За отриманими залежностями розраховано коефіцієнт дифузії вологи для покриття при вогнезахисті, який сягає $0{,}163 \cdot 10^{-9}$ м^2/с. Результати визначення втрати маси зразка покриття під час сушки вказують на неоднозначний вплив природи засобу захисту на змінення вологості. Зокрема, це передбачає наявність даних, достатніх для якісного проведення процесу гальмування дифузії вологи та виявлення на його основі моменту часу, з якого починається падіння ефективності покриття. Особливості гальмування процесу просування вологи до деревини, яка оброблена вогнезахисним покриттям, полягають у декількох аспектах. А саме, застосуванням водонерозчинних антипіренів та інших компонентів, а також полімерного в'яжучого, які характеризуються утворенням на поверхні деревини тепловологозахисного шару

Ключові слова: захисні засоби, вогнестійкість, втрата маси, дифузія вологи, оброблення поверхні, ефективність захисту

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1. Introduction

At present, among the most common building materials is wood, which, in terms of its flammability group, belongs to the group of combustible materials of medium flammability. To reduce these deficiencies, fire-retardant treatment provides wood with the capability to withstand the effects of flame and its propagation. One of the ways to protect wood from fire is to apply a fireproof coating on its surface, which for some time prevents heat from accessing the wood.

The coating initially has the maximum value of flame-retardant efficiency with the same dynamics of its reduction; accordingly, it would have a lifetime that is much longer due to the reserve of the actual value of the efficiency parameter [1, 2]. Given the different character of change in the flame retardant properties due to the conditions and operation duration, the ratio of coatings' service life might prove to be unpredictable, since wood can adsorb moisture from air, which could lead to loss of adhesion by the coating, as well as and its shedding [3, 4]. In practice, it should be justified that a flame-retardant coating that provides for a certain standardized efficiency can only be used taking into consideration the character of change in its flame-retardant properties during operation.

Therefore, it is necessary to study the conditions of moisture diffusion through a coating to wood and to substantiate the conditions for protecting a material against the effect of water by the coating.

2. Literature review and problem statement

Modern fire protection methods include the use of swelling coatings. They represent complex systems of organic and inorganic components [5], characterized by high intumescent capacity. However, it is not obvious for which classes of operation they belong. The effectiveness of using flame retardants based on organic substances was shown in [6]. Due to the effect of fire retardants based on polyphosphoric acids and foaming agents, it is possible to significantly influence the formation of a porous layer of foam coke. Works [5, 6] show the component formulations, their efficiency, as well as the thermal characteristics of coatings, but the conditions of using coatings and their performance characteristics were not indicated.

A description of the performance of intumescent coatings, one of the tasks of which is to relate experimental data to existing theoretical models, is given in work [7]. This makes it possible, at least in principle, to evaluate the simplifications accepted, only with respect to thermal stability, which consider a thermophysical model whose solution is given by polynomials that are not related to the physical content.

A mathematical model was considered for a change in the temperature and humidity fields of a fire-retardant coating based on the laws of conservation of matter and energy. The models immediately imply a specific type of functional dependences with a set of undefined coefficients, and the task is reduced to determining the numerical value for these coefficients, which is associated with high inaccuracy [8].

The effectiveness of application of the coating's components based on organic substances is shown in paper [9], where, due to the action of flame retardants based on polyphosphoric acids and foamers, one can significantly affect the formation of a protective layer of foam coke. However, it is necessary to study the conditions for barrier formation for thermal conductivity and moisture capacity and to establish the effective action of a coating with the protective layer formation.

A significant increase in the stability, density, and strength of a protective layer is achieved due to the targeted formation of certain additives that form high-temperature compounds [10]. However, there are no relevant physical and chemical data to confirm this process.

The effect of inorganic fillers on a water-based flame-retardant coating proved its effectiveness; however, the mechanism for swelling a coating was not specified and the operating conditions of the coating were not identified in [11]. The authors present an analytical model of the fire resistance and thermal degradation of the porous structure of foam coke in a fire-retardant coating, which takes into consideration the pore shapes, but a given model does not consider which phase transformations a coating undergoes when operating in a humid environment [12].

Paper [13] proposed a mathematical model and a procedure for numerical study into the kinetics of the state of heat and humidity of a capillary-porous body, built on the simultaneous equation for solving thermal conductivity and moisture transfer. However, the cited study is characteristic of inorganic material and cannot be attributed to wood.

Therefore, modeling the process of moisture diffusion through a fire-retardant coating for wood, the impact of the components that are part of them on this process, is an unresolved component in ensuring the fire resistance of building structures. This has necessitated our research in this area.

3. The aim and objectives of the study

The aim of this study is to identify patterns of moisture diffusion through a flame-retardant coating. This would make it possible to justify the application of a flame-retardant coating at sites with high humidity.

To achieve the goal, the following tasks were solved:

– to model parameters for moisture diffusion through a fire-retardant coating for wood;

– to establish patterns in moisture transport through a flame-retardant coating at a change in temperature and moisture content.

4. Materials and methods to study moisture diffusion through a flame-retardant coating for wood

4. 1. Examined materials used in the experiment

The research was performed using a system consisting of ammonium polyphosphate (APP), melamine, pentaerythritol (PER) and a dispersed PVA-based binder. The fillers such as titanium dioxide (8 %), talc (2 %) were added to the above formulation.

Experimental coating samples were prepared based on a system containing 18÷20 % of APP, 12÷14 % of melamine, 10÷12 % of PER, 16 % of dispersed PVA, and water. The resulting mass was agitated, fillers were injected in the amount of 10 % and disks with a diameter of 36 mm with a thickness of 3÷4 mm were formed: 3 pieces (Table 1, Fig. 1).

Table 1

Basic dimensions of samples

Basic data on a sample	Sample 1	Sample 2	Sample 3
Diameter, mm	36.1	36.0	36.2
Thickness, mm	5.3	3.3	5.4
Mass in a dry state, g	3.4	3.1	3.4

1 2 3

Fig. 1. Coating samples:
1 – a coating sample, 36.1 mm in diameter, 5.3 mm thick;
2 – a coating sample, 36.2 mm in diameter, 5.4 mm thick;
3 – a coating sample, 36.00 mm in diameter, 3.3 mm thick

The disks were sanded tightly together. Sample No. 3 was immersed in distilled water, excess water was removed using filter paper. The disks were assembled in one (14.22 mm thick), a thermocouple was inserted in the middle at a distance of 8.8 mm, the side surface of a sample was wet-isolated with paraffin, that is a measuring cell was created (Fig. 2).

Fig. 2. Measuring cell

The mass of a wet middle sample (sample 2) was 3.74 g and the total sample mass was 12.62 g.

At the same time, the moisture content of the middle part of the sample and the entire sample was determined, which was 17.03 % and 5.05 %, respectively.

4. 2. Procedure for determining the indicators of samples' properties

The research into modeling the process of moisture diffusion through a coating was conducted using the basic provisions of mathematical physics.

To find values for a coefficient of moisture diffusion through a coating, special equipment was designed and manufactured (Fig. 3). A sample together with the thermocouple and a flat heater was put on scales to control the temperature and moisture loss by the sample.

We experimentally determined the process of moisture diffusion by a flame- retardant coating according to the method given in [14]. The method implies that a sample of the flame-retardant coating is placed on a flat heater, which in turn is placed on the scales. The heating was switched on, the mass loss of the sample was measured and the temperature in the middle of the sample was monitored. Based on the results of mass loss, the rate of moisture evaporation was determined and the coefficient of moisture diffusion from the sample of the flame-retardant coating was calculated.

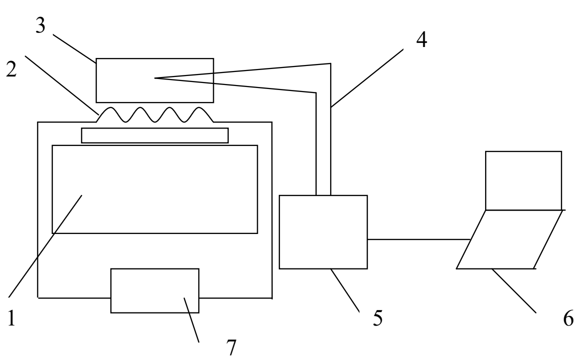

Fig. 3. Device for determining a coefficient of moisture diffusion through a coating: 1 – scales, 2 – flat heater, 3 – sample, 4 – thermocouple, 5 – analog-to-digital converter, 6 – computer, 7 – temperature controller

A criterion for the complete loss of moisture by a flame-retardant coating exposed to thermal action is the stability of coating mass over 3 days.

5. Modeling parameters of moisture diffusion through a flame-retardant coating for wood

As a result of treating wood with flame-retardant coatings, a capillary-porous layer is formed at the surface, which can protect the material from moisture penetration during operation. Wood itself is capable of absorbing moisture and swelling, which leads to loss of adhesion by the coating and its shedding.

Given the above, there is a task to study the mass transfer of moisture through the layer of a flame-retardant coating to wood at a change in heat and moisture content in the environment.

In order to define the process of moisture diffusion through the flame-retardant layer of a coating, the method for resolving a problem on mass transfer for a three-layer disk with different moisture capacity is suggested. At the initial time, the lower surface of the disk is heated to a temperature of drying (30 °C), which is maintained constant over the entire process of heating, with temperature distribution occurring through the coating. In this case, moisture is evaporated from the upper end of the disk (Fig. 4).

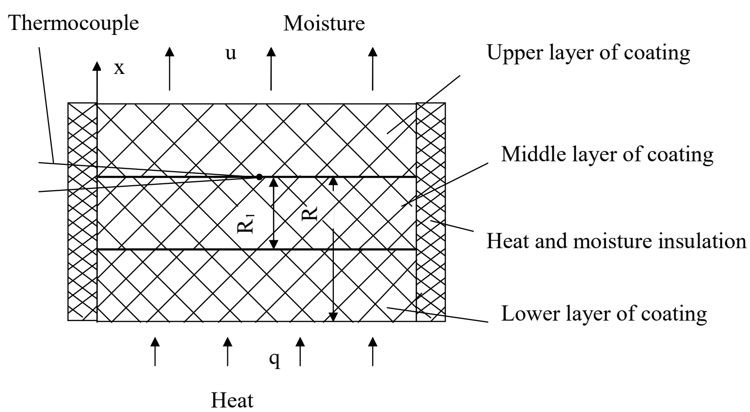

Fig. 4. Schematic of moisture diffusion process through a flame-retardant coating

The differential equations describing the process of thermal diffusion of moisture through a flame-retardant coating are composed of the heat and mass transfer equations [15]:

$$\frac{\partial T}{\partial \tau}=a\frac{\partial^2 T}{\partial x^2}+\frac{\varepsilon\cdot r}{c}\frac{\partial u}{\partial \tau}, \tag{1}$$

$$\frac{\partial u}{\partial \tau}=\frac{\partial}{\partial x}\left(d_m\frac{\partial u}{\partial x}\right)+\frac{\partial}{\partial x}\left(d_m\cdot\delta\frac{\partial T}{\partial x}\right), \tag{2}$$

where T is the temperature, °C; a is the coefficient of temperature diffusivity, m^2/s; τ is the time of sample drying, s; u is the moisture of a sample, %; d_m is the moisture diffusion coefficient, m^2/s; δ is the thermogradient coefficient, 1/degree; ε is the phase transition coefficient; r is the specific heat of water evaporation, J/kg.

At a constant drying speed, the change in humidity is constant:

$$\frac{\partial u}{\partial \tau}=\frac{\partial \bar{u}}{\partial x}=N(\text{const}). \quad (3)$$

After substituting (3) in (1) and appropriate transformations, the equation takes the following form:

$$\frac{\partial^2 T}{\partial x^2}=\frac{\varepsilon\cdot r\cdot \gamma_0}{\lambda}N=0. \quad (4)$$

Since

$$a=\frac{\lambda}{c\cdot\gamma_0}, \quad (5)$$

where λ are the coefficients of thermal conductivity of a material, W/(m·°C); c is the thermal capacity of a wet material, J/(kg·K); γ_0 is the density of a coating, kg/m^3.

Temperature distribution in a sample is described by equation:

$$T=Ax^2+Bx+C. \quad (6)$$

Considering the initial and boundary conditions:
– at

$$x=0 \quad T=T_w, \quad x=R \quad T=T_n;$$

– at

$$x=x_1 \quad T=T_1, \quad x=x_2 \quad T=T_2. \quad (7)$$

We obtain:

$$A=\frac{\Delta T_1+(T_w-T)\dfrac{x_1-x_2}{R}}{\left[\left(x_1^2-x_2^2\right)-\left(x_1-x_2\right)\cdot R\right]},$$

$$B=\frac{T_n-T_w}{R}, \quad C=T_w. \quad (8)$$

After integrating (2) for x in the range from 0 to R and appropriate transformations we obtain:

$$\frac{\partial \bar{u}}{\partial \tau}=\frac{1}{R}d_m\frac{\partial u}{\partial x}\bigg|_0^R+\frac{1}{R}d_m\delta\frac{\partial T}{\partial x}\bigg|_0^R. \quad (9)$$

We accept the parabolic law of moisture distribution in a body:

$$u=a_1x^2+bx+c_1, \quad (10)$$

and initial and boundary conditions:
– at x=0

$$d_m\cdot\gamma_0\frac{\partial u}{\partial x}+d_m\cdot\gamma_0\cdot\delta\frac{\partial T}{\partial x}=0, \quad (11)$$

or
– at x=0

$$\frac{\partial u}{\partial x}=-\delta\frac{\partial T}{\partial x}. \quad (12)$$

Then, from (6), (10), we obtain:

$$\frac{\partial u}{\partial x}=2a_1\cdot x+b, \quad \frac{\partial T}{\partial x}=2A\cdot x+B. \quad (13)$$

After integrating (13) for x in the range from 0 to R and appropriate transformations we obtain:

$$\frac{\partial u}{\partial x}\bigg|_0^R=\left(\frac{\partial u}{\partial x}\right)_{x=R}-\left(\frac{\partial u}{\partial x}\right)_{x=0}=2a_1\cdot R, \quad (14)$$

$$\frac{\partial T}{\partial x}\bigg|_0^R=\left(\frac{\partial T}{\partial x}\right)_{x=R}-\left(\frac{\partial T}{\partial x}\right)_{x=0}=2A\cdot R. \quad (15)$$

Hence

$$\frac{\partial \bar{u}}{\partial \tau}=2d_m\cdot a_1+2d_m\cdot\delta\cdot A. \quad (16)$$

Using boundary conditions (11), (12), we obtain:

$$a_1=\frac{3\delta\cdot B(R-R_1)}{2\left(R^2-R_1^2\right)}-\frac{3(\bar{u}_1-\bar{u})}{R^2-R_1^2}. \quad (17)$$

Substituting (17) into (16), we obtain the thermo-gradient coefficient:

$$\delta=\left[\frac{\partial \bar{u}}{\partial \tau}+\frac{6d_m\cdot(\bar{u}_1-\bar{u})}{R^2-R_1^2}\right]\cdot\frac{1}{A^*d_m}, \quad (18)$$

where

$$A^*=\frac{3B}{R+R_1}+2A.$$

For isothermal conditions, since A^*=0, we obtain:

$$d_m=-\frac{\partial \bar{u}}{\partial \tau}\frac{\left(R^2-R_1^2\right)}{6(\bar{u}_1-\bar{u})}, \quad (19)$$

where $\partial\bar{u}/\partial\tau$ is the rate of moisture mass loss by a sample, %; R is the distance to a thermocouple, m; R_1 is the thickness of the middle part of a sample, m; $\bar{u}$ is the moisture capacity of a sample, %; $\bar{u}_1$ is the moisture capacity of the middle part of a sample, %.

Thus, a dependence has been derived from the system of heat and mass transfer, initial and boundary conditions, to determine the coefficient of moisture diffusion through a coating.

6. Experimental study into moisture mass loss by a flame-retardant coating for wood and its results

To determine the coefficient of moisture diffusion, a study was conducted into its evaporation under the action of a heating device. The results from determining the temperature and a change in moisture through a coating under the action of a heater are shown in Fig. 5, 6.

One can see from Fig. 5 that under the action of a heater on coating samples, intensive heat transfer started and a slight increase in the middle of the sample occurred over 3 days. The temperature did not change thereafter.

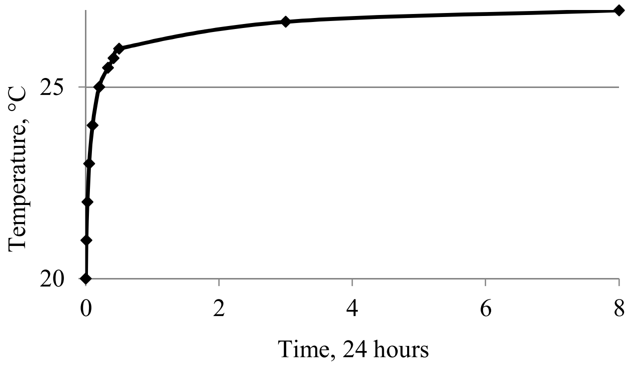

Fig. 5. Temperature change in the middle of the measuring cell depending on drying time

The intensive mass loss by the sample continued to fall over 8 days, after that, it leveled to a certain extent (Fig. 6).

The moisture loss by the sample was calculated from equation:

$$u = \frac{m_0 - m_1}{m_0} \cdot 100\ \%, \qquad (20)$$

where m_0 is the sample mass before tests, g; m_1 is the sample mass after drying, g.

The rate of sample mass loss was calculated based on Fig. 6 from equation:

$$\frac{\partial \overline{u}}{\partial \tau} = \frac{u}{\tau}, \qquad (21)$$

where u is the sample moisture, %; τ is the time of tests, s.

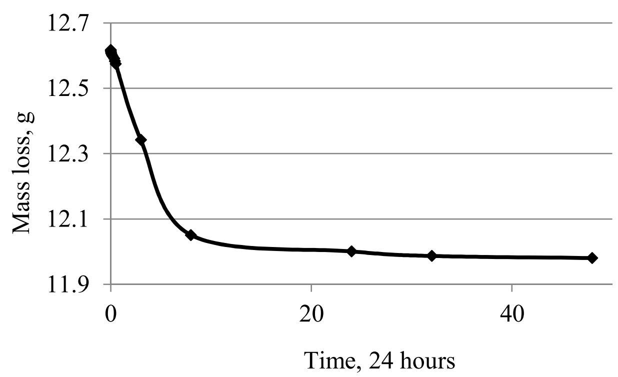

Fig. 6. Results of mass loss by the measuring cell during drying

Based on equation (19), the diffusion coefficient was calculated, which for a given sample was $0.163 \cdot 10^{-9}$ m^2/s, which attributes the product to those materials that slowly conduct moisture.

8. Discussion of results from studying the process of the progress of phase transformations

When using flame-retardant coatings for wood, as it is indicated by the results of our study (Fig. 6), it is a natural process to form a protective layer under the action of temperature and a decrease in moisture, which slow down the processes of moisture diffusion. It seems likely that such a mechanism of the flame-retardant coating is a factor in regulating the degree of formation of a weatherproof protective layer and the efficiency of thermal and moisture insulation of the material. This agrees with the data reported in [6, 16], where the authors also relate the effectiveness of protection against moisture to using insoluble flame retardants. In contrast to the results from studies [8, 17], the data obtained on the impact of moisture diffusion process by a flame-retardant coating and changes in moisture-insulating properties allow us to argue about the following:

– the main regulator of the process is not only the formation of a coating layer, but also the use of water-insoluble flame retardants and a polymeric binder, which, under the action of temperature-humidity fields, provide for the coating adhesion;

– significant effect on the process of wood protection from fluctuations in temperature and moisture when applying a flame-retardant coating is produced towards the formation of water-insoluble capillary porous coatings at the surface of a natural combustible material.

Such conclusions may be considered appropriate from a practical point of view, since they allow a reasonable approach to determining the required formulation for a fire retardant. From a theoretical point of view, they suggest the determination of the mechanism of fire protection processes, which are certain advantages of this study. The results of determining the mass loss by a coating sample during drying (Fig. 6) indicate the ambiguous impact of the nature of a protective agent on the change in moisture. In particular, this implies the availability of data sufficient for the qualitative conducting of the process of inhibition of moisture diffusion and the detection, on its basis, of the moment that gives rise to a fall in coating efficiency. Such a detection will allow us to investigate the transformation of a coating surface, which moves in the direction of elevated temperature, and to identify those variables that significantly affect the onset of the transformation of this process.

9. Conclusions

1. We have modeled the process of moisture transfer by a flame-retardant coating, determined the diffusion coefficient and derived estimation dependences, which make it possible to establish a change in the moisture dynamics during drying of a flame-retardant coating. Based on the derived dependences, a diffusion coefficient at fire protection was calculated, which reaches $0.163 \cdot 10^{-9}$ m^2/s for a coating.

2. Features of slowing down the process of moisture transport inside wood, which is treated with a flame-retardant coating, include several aspects. Namely, the use of water-insoluble flame retardants and other components, as well as a polymeric binder, which are characterized by the formation of a heat and moisture-proof layer at wood surface. This indicates the possibility of targeted control over the processes of moisture transfer to wood through the use of a flame-retardant coating.

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