UDC 614.842.5:349.211
DOI: 10.15587/1729-4061.2020.217970

ESTABLISHING PATTERNS OF HEAT TRANSFER TO TIMBER THROUGH A PROTECTIVE STRUCTURE

Yu. Tsapko
Doctor of Technical Sciences**
V. D. Glukhovsky Scientific Research Institute for Binders and Materials***
E-mail: juriyts@ukr.net

I. Rogovskii
PhD, Senior Researcher
Research Institute of Engineering and Technology**
E-mail: irogovskii@gmail.com

L. Titova
PhD, Associate Professor*
E-mail: ludmylkatitova@gmail.com

R. Shatrov
PhD, Associate Professor*
E-mail: 72rusik@ukr.net

A. Tsapko
Researcher
V. D. Glukhovsky Scientific Research Institute for Binders and Materials***
E-mail: alekseytsapko@gmail.com

O. Bondarenko
PhD, Associate Professor
Department of Building Materials***
E-mail: bondolya3@gmail.com

S. Mazurchuk
PhD
Department of Technology and Design of Wood Products**
E-mail: mazurchuk.s.m@ukr.net

*Department of Technical Service and Engineering Management named after M. P. Momotenko**
**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

The conducted studies of the impact of thermal action of a high-temperature magnesium flame on construction materials for timber protection from atmospheric factors revealed a pattern of temperature transfer to timber. It was proved that depending on the thermophysical properties of the material, this can lead to its ignition or slowing down the thermal conductivity process. That is why there arises the need to study the conditions for thermal conductivity and establish the mechanism for inhibition of heat transfer to timber. In this regard, a mathematical model of the process of transferring heat flow on the surface of timber when protected by coatings was developed. According to the experimental data and obtained dependences, it was established that the density of heat flow through a steel plate increases to a value of more than 200 kW/m², which is sufficient for ignition of timber. Instead, the density of heat flow through a vermiculite plate did not exceed 5.2 kW/m², which is not enough for its ignition. It was established that the main regulator of the heat transfer process is the heat-insulating properties of a construction product, its resistance to high temperature, because certain construction products, such as an asbestos-cement product, are destroyed under the influence of magnesium flame. That is why a significant impact on the process of protection of natural combustible material when applying the protective coating is made in the direction of heat insulation of the timber surface. This makes it possible to argue about the relevance of the detected mechanism of the formation of heat-insulating properties when it comes to the protection of storage sites of explosive products and the practical attractiveness of the proposed technological solutions. Thus, the features of inhibiting the process of transferring heat to timber during the action of the magnesium flame include heat insulation of timber surfaces by thermally resistant material. Thus, the temperature of a magnesium flame was created on the vermiculate surface, and it did not exceed 100 °C on the surface of the timber

Keywords: metal combustion, fire protection of timber, coating, thermal conductivity, surface treatment, thermophysical properties

Received date 27.10.2020
Accepted date 01.12.2020
Published date 21.12.2020

1. Introduction

The operation of buildings, structures, and premises at the warehouses of explosives storage is closely related to the use of a wide variety of construction and packaging products, which are made of timber. The process of ignition and explosion in the storage of ammunition, for example, instantly leads to progressive destruction. However, there are no sufficient methods of fire suppression, necessary to ensure the reliability of the operation of sites, which leads to the active destruction of combustible materials, consequent explosion, and propagation of new hotbeds.

Thus, unidentified people using unmanned flying vehicles dropped incendiary objects on the territory of the ammunition storage site. As a result, there occurred hotbeds of fire, which were difficult to extinguish. Despite the storage under canopies, some magnesium particles got under wooden boxes, in which the ammunition was stored.

A necessary measure to improve the safety of the operation of ammunition storage sites and to prevent and limit dangerous combustion factors is the isolation of flammable materials.

An unprotected timber sample was found to be capable of igniting and spreading flames around the surface after ignition, causing the structure to collapse [1, 2]. The use of heat-insulating materials makes it possible to slow down the warming of the material and to retain its functions in case of a fire for a specified period but requires considerable costs [3, 4]. In addition, the temperature of separate combustive substances by far exceeds the hydrocarbon flame [5]. That is why the effectiveness of using protective coatings is aimed at creating an insulating or a swelling layer on the surface, acting by the principle of thermal conductivity reduction [6].

Given that igniting products that are able to create a very high temperature (more than 2000 °C) have become widely spread today, there arises the need to protect the timber from the action of such temperatures.

However, the use of timber coatings that protect from atmospheric factors does not always provide the required level of timber insulation from combustible material, which correspondently affects the implementation of fire measures. Taking into consideration the significant requirements for these indicators, there is a problem in determining the heat-resistant properties of atmosphere protective coatings of timber and the establishment of their effectiveness.

That is why it determines the need to investigate the conditions of timber insulation by a coating and to substantiate conditions of protection against the ignition source.

2. Literature review and problem statement

Paper [7] shows that the use of plate insulation materials (gypsum board and gypsum-fiber sheets, etc.) for external structures leads to material costs and an increase in the volume of a structure. However, such coatings are rigid and are destroyed by high thermal action. That is why in most cases, they are modified by polymer complexes and fire retardants, but they increase the smoke formation [8]. In addition, the issue, related to their resistance to washing out, remains unresolved.

The most promising flame retardant compositions include swelling coatings, which are complex systems of organic and inorganic components. The materials are characterized by high thermal insulation capacity, but the heat inhibition mechanism was not shown [9].

At the present stage, fire protection is aimed at creating the means that in the process of heating form a coke thermal insulating layer on the surface of a construction structure from organic materials [10]. Specifically, the model for calculating thermal conductivity, which takes into consideration phase transformations of a coating, but does not take into consideration heat transfer to the structure itself, was presented. That is why there is a need to study the change in thermal conductivity and to establish the effective action of the coating with the formation of a coke layer.

Research [11] describes the composites of epoxy resin, strengthened, and inhibited from fire by the surface treated with carbon fibers. However, such coatings have a dark color and change the surface of a wooden product when treated.

In addition, many coatings have a number of shortcomings, such as the application of separate components, loss of functional properties at an increase in the temperature of the environment [12]. This means that it was not determined exactly how the process of decomposition of a fire-retardant coating goes on.

The studies of protective materials made with the use of liquid glass were also conducted [13]. The obtained results are aimed at the development of technology and materials that combine fire resistance, low thermal conductivity, and the technological intensity of the products and protective coatings. However, the life cycle of the coating and the mechanism of thermal insulation were not determined.

Paper [14] suggested the use of polystyrene. This article describes the benefits of polystyrene as an insulator that meets all the insulation requirements in the process of designing buildings, including fire safety. Polystyrene of the fire resistance class is a prerequisite for compliance with fire safety rules and solving the problem of flammability and flame propagation on the surface of a polystyrene product. However, fire resistance of such protection of combustive structures was not pointed out, neither was the resistance to other combustive substances.

The results of the study of the impact of the graphite system with kaolin and titanium oxide on thermal properties, the swelling degree, and the integrity of the structures protected by films based on epoxy resins were presented in [15]. Analysis of thermal gravimetry showed that the resulting systems shift the reaction of the epoxy resin decomposition toward high temperatures. The presented results show that ceramic fire retardants can successfully interact with organic components that protect protective coatings. However, it is not known how this additive influenced the coating's burnout.

Thus, it was found from literary sources [8, 13, 14] that during operation, coatings protect the surface of timber from atmospheric factors, but the parameters that ensure fire resistance of timber, as well as the factors that affect this process, were not determined. That is why the establishment of parameters of timber protection and the impact of coatings on this process caused the need for research in this direction.

3. The aim and objectives of the study

The aim of this research is to study the process of thermal conductivity in the action of magnesium flames on the protective coating of wooden structures. This will make it possible to find the most effective protective measures for timber in the manufacture of building structures.

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

– to simulate the process of thermal conductivity at the thermal action of a high-temperature flame on the protective coating of a construction structure from timber and to establish the dependence of a heat flow on the properties;

– to establish the features of reducing the heat flow at the temperature impact of the magnesium flame on a wooden construction structure when using a thermal insulation coating.

4. The study materials and methods

4. 1. The examined materials and equipment used in the experiment

The research was carried out using the samples of zinc-coated tin measuring 120×120×1 mm, slate (asbestos cement) measuring 100×100×10 mm, and vermiculite measuring 120×150×20 mm produced in Ukraine to protect wooden products from atmospheric influence.

Experimental samples of the coating were mounted on wooden samples, which were made of pine timber that was 4 mm thick with average dimensions of 150×150 mm (Fig. 1).

Fig. 1. Sample of timber

Magnesium chips, at combustion of which the temperature of 2,200 °C is released, were used as fuel [16].

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

The study on the simulation of the process of thermal conductivity of the coating during the thermal action was carried out using the basic provisions of mathematical physics [16].

Protective efficiency of timber was determined according to the working procedure, the essence of which was to experimentally determine the temperature on the surface of a wooden sample. Specifically, to affect the sample of coating with the magnesium flame (the model was solid combustible substance) with specified parameters and to record temperature on the surface of the timber during testing.

To obtain the values of thermal conductivity of timber coatings, special equipment was developed and manufactured, and magnesium flames that simulate a high-temperature ignition source were used (Fig. 2).

The sample of timber protected by coatings was placed on the table. The sample was fixed so that the end of the thermocouple should be pressed to the inner surface of the sample coating. The igniting substance in the amount of 8 g per 1 dm^2 of the surface was placed on the sample of the coating. Fuel was ignited and the sample was kept in the fuel flames during the burnout time and until there was no independent combustion and glowing. The temperature on the surface of the timber was controlled.

The changes were recorded and the insulating properties of the coating and the magnitude of heat flow, which is transferred to timber during combustion of magnesium flames, were determined by the measured magnitudes.

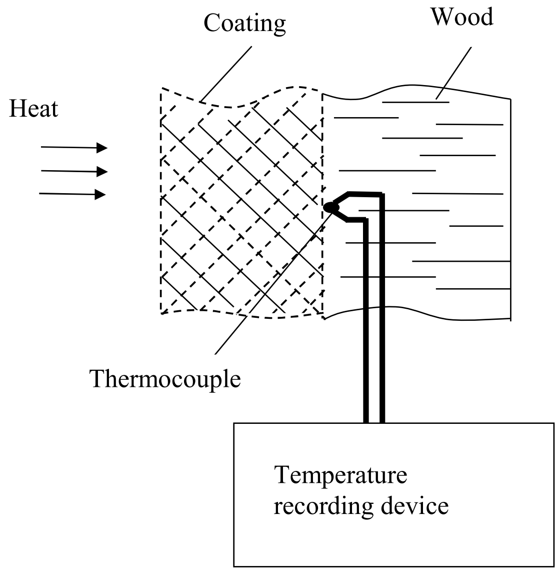

Fig. 2. The device to study the thermal conductivity of reed

5. Simulation of the thermal conductivity process at the thermal influence of a high-temperature flame on the protective coating of a wooden building structure

As a result of the treatment of cellulose-containing materials by protective coatings under the influence of the heat flow, the direction of heat transfer changes, that is, the insulating layer, which is largely able to absorb heat and decrease heat transfer to the material.

Taking into consideration the above, there is a question about the study of a heat flow on the boundary "timber – coating" during the heat influence.

In order to establish the heat flow to a timber layer, it was proposed to use the method of solving the problem of thermal conductivity for a double-component wall with different thermophysical properties (Fig. 3). At the initial point of time, the outer surface of the coating is instantly heated to the temperature $T_{\max}$, which is maintained constant throughout the entire heating process. Temperature is distributed through the coating until the critical temperature of the timber at the boundary of a coating – the wall of timber T_s.

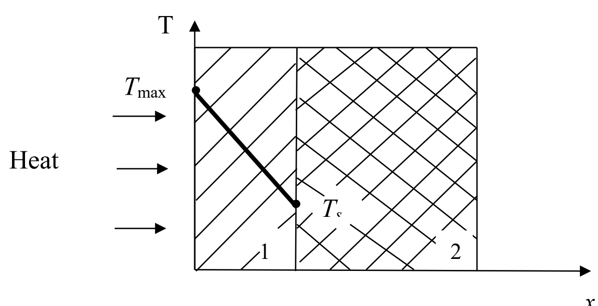

Fig. 3. Schematic of the heat transfer process: 1 — coating; 2 — timber

Differential equations of heat transfer at the boundary of two plates "timber – coating" take the following form:

$$\left(\frac{\partial}{\partial t}-a_1\frac{\partial^2}{\partial x^2}\right)T=0,\ \ (-\infty<x<0), \qquad (1)$$

$$\left(\frac{\partial}{\partial t}-a_2\frac{\partial^2}{\partial x^2}\right)T=0,\ (0<x<\infty;\ 0<t<\infty),\tag{2}$$

under initial and boundary conditions

$$T\big|_{x=-\infty}=T_0,\ \ T\big|_{x=\infty}=0,\ \ T\big|_{x=-0}=T\big|_{x=+0}.\tag{3}$$

$$\lambda_1\frac{\partial T}{\partial x}\bigg|_{x=-0}=\lambda_2\frac{\partial T}{\partial x}\bigg|_{x=+0},\tag{4}$$

$$T\big|_{t=0}=\begin{cases}T_0 & x\prec 0\\ 0 & x\succ 0\end{cases}.\tag{5}$$

$$T_0,\ a_1,\ a_2,\ \lambda_1,\ \lambda_2=\text{const},\tag{6}$$

where a_1, a_2 are the factors of thermal conductivity of the coating and timber, $m^2\times s^{-1}$; λ_1, λ_2 are the factors of thermal conductivity of the coating and timber, $W\times m^{-1}\times{}^\circ C^{-1}$; T is the temperature, °C; x is the coordinate, m.

It is necessary to determine the instant temperature value at the boundary "timber – coating" T_s and, accordingly, to find the value of heat flow between the regions:

$$Q_0=\lambda_2\frac{\partial T}{\partial x}\bigg|_{x=+0}.\tag{7}$$

Given that for the left semi-plane x<0, the initial condition is not equal to zero, make the substitution:

$$T=T_0-T^*,\tag{8}$$

where T_0 is the maximum temperature at the boundary "timber – coating".

After that, the problem of determining temperature T^* will be recorded in the following form:

$$\left(\frac{\partial}{\partial t}-a_1\frac{\partial^2}{\partial x^2}\right)T^*=0,\ (-\infty<x<0,\ 0<t<\infty),\tag{9}$$

under conditions

$$T^*\big|_{x=-\infty}=0,\ \ T^*\big|_{t=\infty}=0.\tag{10}$$

For region $x<0$, taking into account the Laplace transform, it is possible to write down the relation of temperature and a heat flow in the form given in [17].

$$\left(P^{1/2}-\sqrt{a_1}\frac{\partial}{\partial x}\right)\cdot T^*\big|_{x=0}=0,\tag{11}$$

where P is the Laplace operator.

Returning to initial variable T, we obtain:

$$P^{1/2}\left(T_0-T_s\right)=\frac{T_0}{\sqrt{\pi\cdot t}}-P^{1/2}\cdot T_s=-\sqrt{a_1}\frac{\partial T}{\partial x}\bigg|_{x=-0}.\tag{12}$$

For region $x>0$, respectively, we have:

$$P^{1/2}T_s=-\sqrt{a_2}\frac{\partial T}{\partial x}\bigg|_{x=+0}.\tag{13}$$

Combining (12) and (13) with the conditions of equality of flows (4), we obtain:

$$P^{1/2}T_s=\frac{\sqrt{a_1}}{\sqrt{a_1}+\sqrt{a_2}}\frac{T_0}{\sqrt{\pi\cdot t}}.\tag{14}$$

Taking into consideration the Laplace transform, we get the temperature value on the boundary of the wall:

$$T_s=\frac{\sqrt{a_1}}{\sqrt{a_1}+\sqrt{a_2}}\cdot T_0.\tag{15}$$

Then according to (7), the heat flow through the boundary at maximum temperature is described by the equation:

$$Q_s=\frac{\sqrt{a_1a_2}}{\sqrt{a_1}+\sqrt{a_2}}\frac{\lambda_2}{a_2}\frac{T_0}{\sqrt{\pi\cdot t}}.\tag{16}$$

The density of the heat flow from magnesium combustion can be expressed by the equation [18]:

$$q_s=\frac{Q_s}{s^2}=\frac{\sqrt{a_1a_2}}{\sqrt{a_1}+\sqrt{a_2}}\cdot\frac{\lambda_2}{a_2}\cdot\frac{T_0}{\sqrt{\pi\cdot t}}\cdot\frac{1}{s^2},\tag{17}$$

where s^2 is the burning area of combustion of a combustible substance, m^2.

Thus, the estimated dependences that make it possible to obtain the value of heat flow on the surface of timber when protected by coating were obtained. However, they provide an opportunity to directly calculate the shift of the value of a heat flow depending on temperature.

6. Experimental studies of thermal conductivity at the temperature impact of magnesium flame on a wooden building structure using thermal insulation coating and their results

To establish the thermal conductivity of the coating at the protection of timber, the research into temperature transfer at the action of magnesium flame, which simulates the source of high temperature, was carried out. The results of the studies on temperature transfer conducted under laboratory conditions are shown in Fig. 4–6.

The studies showed that the slate was heated under the influence of the magnesium flame, which led to its complete destruction. Then the sample of metal was tested.

During the action of magnesium flame on a steel plate, intensive temperature transfer on the back surface of the sample began, which led to timber carbonization and burnout. Instead, there was no combustion of timber on the sample of vermiculite.

The results of the studies on determining the dynamics of temperature on the surface of timber conducted under laboratory conditions are shown in Fig. 7.

The studies showed that the sample of a steel plate could not withstand the temperature impact (curve 2) at the action of the heat flow. Specifically, there was an intensive transfer of heat to timber, exceeding the ignition temperature of timber by 1.5 times, which continued more than 200 s. At the action of the flame on the sample of timber protected by vermiculite (curve 3), the temperature on the inner surface did not exceed 100 °C, the ignition of timber did not occur.

This method is limited only to determining the temperature on the surface of timber from the action of magnesium flames, specifically, to insulating capacity, because heat transfer is characterized by thermophysical properties of the coating.

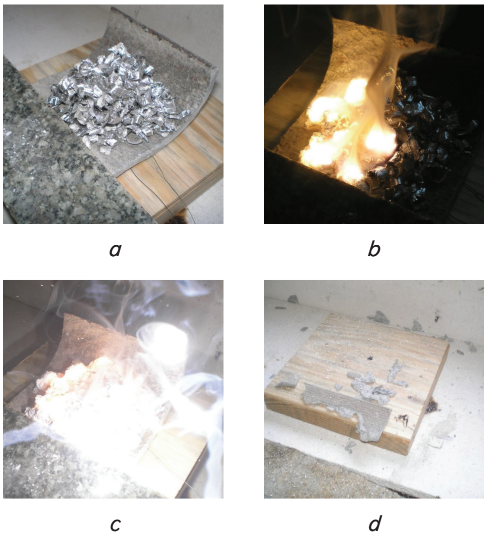

Fig. 4. Results of the tests on magnesium combustion on the slate: *a* — tested structure; *b* — magnesium ignition; *c* — intensive combustion of magnesium; *d* — destruction of slate

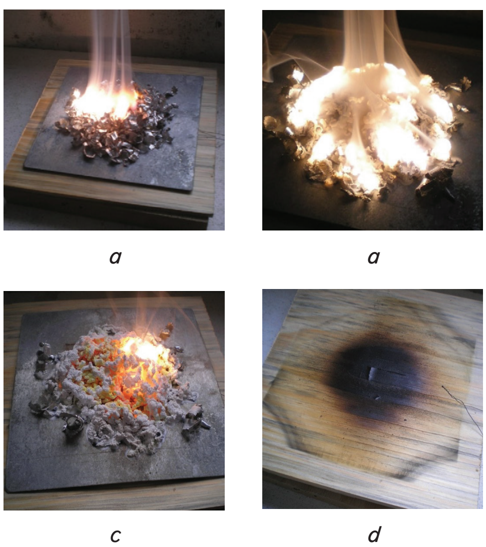

Fig. 5. Results of tests on magnesium flame burning on a steel plate: *a* — magnesium ignition; *b* — intensive combustion; *c* — burnout; *d* — timber after combustion

Thermophysical characteristics necessary to calculate the heat flow for timber, steel, and vermiculite are shown in Table 1.

Table 1

Thermophysical characteristics of materials

Indicator	Name of material		
	Timber [19]	Steel [17]	Vermiculite [20]
Temperature conductivity factor, m/s^2	$0.17 \cdot 10^{-6}$	$11.72 \cdot 10^{-6}$	$0.031 \cdot 10^{-6}$
Thermal conductivity factor, W/(m·K)	0.132	47	0.05

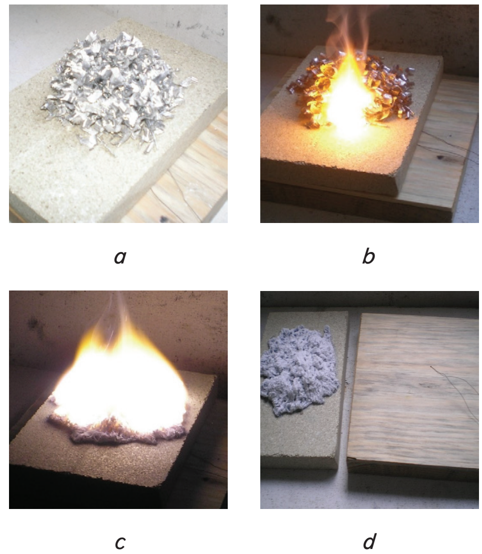

Fig. 6. Results of the tests of magnesium flame combustion of vermiculite: *a* — test structure; *b* — magnesium combustion; *c* — intensive combustion; *d* — timber after combustion

The data from Table 1 show different thermophysical characteristics of materials, hence it follows that the thermal effect through the wall of the coating will be different.

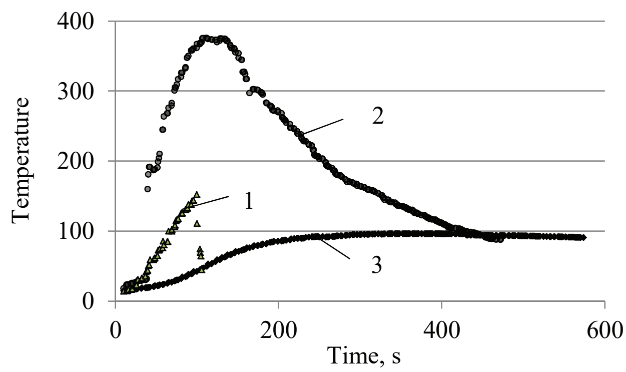

Fig. 7. Dynamics of a temperature increase on the surface of timber during testing of coating: 1 — slate; 2 — steel plate; 3 — vermiculate plate

7. Results of determining the heat flow action at the temperature influence of a magnesium flame on a building structure from timber when applying the coating

Fig. 8 shows the calculation of density of heat flow *q*, depending on the time of influence *t* on timber at magnesium flame combustion.

As Fig. 8 shows, at an increase in temperature, the density of heat flow through the steel plate increases up to the value of more than 200 kW/m^2. This value is sufficient for ignition of timber (the minimum value is about 12.0 kW/m^2 [21]), and then gradually decreases due to fuel burnout. Instead, the density of heat flow through the vermiculite plate did not exceed 5.2 kW/m^2, which is not enough for its ignition. At the same time, the process of growth of a heat flow shifted to longer terms.

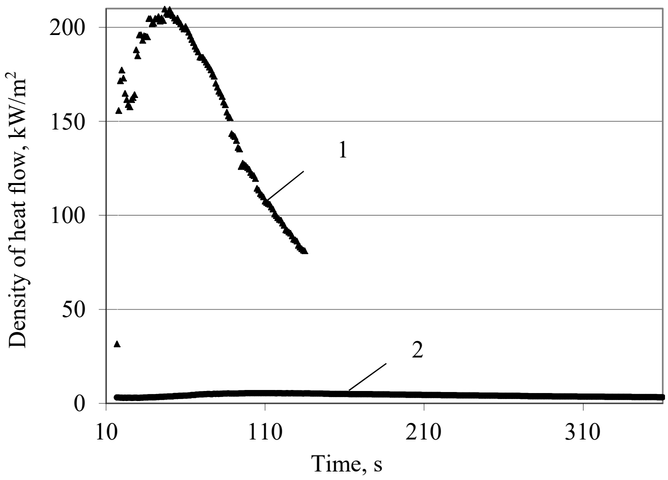

Fig. 8. Dependence of heat flow density on time of heating the environment through the sample of coating: 1 – steel plate; 2 – vermiculite plate

8. Discussion of the results of the research into the process of transferring high temperature of a magnesium flame through the coating

When using construction materials to protect the timber from atmospheric factors under the thermal action of high-temperature magnesium flame, as indicated by the results of research (Fig. 7), the process of transferring temperature to timber is natural. Depending on the thermophysical properties of the material, this can lead to its ignition, or slowing down the thermal conductivity process. Obviously, this mechanism of coating influence is a factor of regulating the degree of formation of heat flow density and effectiveness of timber insulation (Fig. 8). This is in line with the data known from works [7, 8], the authors of which also attribute the effectiveness of thermal protection against high-temperature action to the use of thermal insulation products. This work fully reveals the mechanism of timber protection, transfer, and implementation of high-temperature insulation, but there is also a need to evaluate this process, create a physical and mathematical model. Unlike the results of research [9, 10], the obtained data on the impact of construction products on heat transfer to timber and changes in insulating properties make it possible to argue the following:

– the main regulator of the heat transfer process is the heat-insulating properties of a construction product, its resistance to high temperature, as some construction products are destroyed under the influence of magnesium flame;

– a significant impact on the process of protection of natural combustible material in the application of a protective coating is made in the direction of thermal insulation of the wooden surface.

Such conclusions may be considered appropriate from the practical point of view, as they make it possible to substantiate the heat-insulating properties of the protective coating. From the theoretical point of view, they make it possible to argue about determining the mechanism of the processes of protection against high-temperature action, which are certain merits of this study. The results of determining the heat flow density (Fig. 7) indicate an unclear impact of the nature of the protection on a temperature change. Specifically, this involves the availability of the data that are sufficient to evaluate the process of temperature inhibition and to establish a decrease in heat resistance. This will make it possible to study the transformation of the coating surface destroyed under the influence of elevated temperature (burnout) and to determine the parameters that significantly affect the beginning of the transformation of the thermal insulation process.

Based on these results, it can be stated about the existence of an interesting pattern associated with the formation of heat resistance to the action of flames and its capability to insulate timber for a certain period. However, there are certain constraints, specifically, to establish a critical thickness of insulation when the capability falls.

Further research may be aimed at studying the processes of establishing the relationship between the components and properties of heat-insulating materials and their impact on the insulation processes.

9. Conclusions

1. The simulation of the thermal conductivity process at the protection of timber during thermal action on a construction structure of a high-temperature magnesium flame was carried out, the temperature on the timber surface was determined and dependences that enabled obtaining a change in the heat flow on the surface of timber were obtained. According to the experimental data and obtained dependences, it was established that the density of a heat flow through a steel plate increases to a value of more than 200 kW/m^2, which is sufficient for timber ignition. Instead, the density of a heat flow through the vermiculite plate did not exceed 5.2 kW/m^2, which is not enough for its ignition.

2. The features of inhibiting the process of heat transfer to timber during the action of a magnesium flame are related to heat insulation of the timber surface by heat-resistant material. Thus, the temperature of a magnesium flame was created on the vermiculite surface, and it did not exceed 100 °C on the surface of the timber.

Acknowledgment

We express gratitude for the financial support of the work performed within the framework of the funding budget No. 3 DB-2018, as well as for the development of scientific topics in the program of scientific cooperation COST Action FP 1407 “Understanding the modification of timber through an integrated scientific and environmental approach” within the framework of the program of the European Union HORIZON2020.

References

1. Tsapko, Y., Lomaha, V., Bondarenko, O. P., Sukhanevych, M. (2020). Research of Mechanism of Fire Protection with Wood Lacquer. Materials Science Forum, 1006, 32–40. doi: https://doi.org/10.4028/www.scientific.net/msf.1006.32
2. Tsapko, Y., Lomaha, V., Tsapko, A., Mazurchuk, S., Horbachova, O., Zavialov, D. (2020). Determination of regularities of heat resistance under flame action on wood wall with fire-retardant varnish. Eastern-European Journal of Enterprise Technologies, 4 (10 (106)), 55–60. doi: https://doi.org/10.15587/1729-4061.2020.210009

3. Gots, V. I., Berdnyk, O. Y., Rogozina, N. O., Maystrenko, A. A. (2019). Production of modified basalt fibre for heat-insulating products manufacturing. IOP Conference Series: Materials Science and Engineering, 708, 012082. doi: https://doi.org/10.1088/1757-899x/708/1/012082
4. Berdnyk, O. Y., Lastivka, O. V., Maystrenko, A. A., Amelina, N. O. (2020). Processes of structure formation and neoformation of basalt fiber in an alkaline environment. IOP Conference Series: Materials Science and Engineering, 907, 012036. doi: https://doi.org/10.1088/1757-899x/907/1/012036
5. Dibrova, O., Kyrychenko, O., Motrichuk, R., Tomenko, M., Melnyk, V. (2020). Fire safety improvement of pyrotechnic nitrate-metal mixtures under external thermal conditions. Technology Audit and Production Reserves, 1 (1 (51)), 44–49. doi: https://doi.org/10.15587/2312-8372.2020.199252
6. Krivenko, P., Guzii, S., Al-Musaedi, H. A. J. (2015). Atmospheric Corrosion Protection of Metallic Structures Using Geocements-Based Coatings. Solid State Phenomena, 227, 239–242. doi: https://doi.org/10.4028/www.scientific.net/ssp.227.239
7. Krüger, S., Gluth, G. J. G., Watolla, M.-B., Morys, M., Häßler, D., Schartel, B. (2016). Neue Wege: Reaktive Brandschutzbeschichtungen für Extrembedingungen. Bautechnik, 93 (8), 531–542. doi: https://doi.org/10.1002/bate.201600032
8. Gaff, M., Kačík, F., Gašparík, M., Todaro, L., Jones, D., Corleto, R. et. al. (2019). The effect of synthetic and natural fire-retardants on burning and chemical characteristics of thermally modified teak (Tectona grandis L. f.) wood. Construction and Building Materials, 200, 551–558. doi: https://doi.org/10.1016/j.conbuildmat.2018.12.106
9. Zhao, P., Guo, C., Li, L. (2018). Flame retardancy and thermal degradation properties of polypropylene/wood flour composite modified with aluminum hypophosphite/melamine cyanurate. Journal of Thermal Analysis and Calorimetry, 135 (6), 3085–3093. doi: https://doi.org/10.1007/s10973-018-7544-9
10. Nine, M. J., Tran, D. N. H., Tung, T. T., Kabiri, S., Losic, D. (2017). Graphene-Borate as an Efficient Fire Retardant for Cellulosic Materials with Multiple and Synergetic Modes of Action. ACS Applied Materials & Interfaces, 9 (11), 10160–10168. doi: https://doi.org/10.1021/acsami.7b00572
11. Shi, X.-H., Chen, L., Zhao, Q., Long, J.-W., Li, Y.-M., Wang, Y.-Z. (2020). Epoxy resin composites reinforced and fire-retarded by surficially-treated carbon fibers via a tunable and facile process. Composites Science and Technology, 187, 107945. doi: https://doi.org/10.1016/j.compscitech.2019.107945
12. Md Nasir, K., Ramli Sulong, N. H., Johan, M. R., Afifi, A. M. (2018). An investigation into waterborne intumescent coating with different fillers for steel application. Pigment & Resin Technology, 47 (2), 142–153. doi: https://doi.org/10.1108/prt-09-2016-0089
13. Erdoğan, Y. (2016). Production of an insulation material from carpet and boron wastes. Bulletin Of The Mineral Research and Exploration, 152, 197–202. doi: https://doi.org/10.19111/bmre.74700
14. Ramli Sulong, N. H., Mustapa, S. A. S., Abdul Rashid, M. K. (2019). Application of expanded polystyrene (EPS) in buildings and constructions: A review. Journal of Applied Polymer Science, 136 (20), 47529. doi: https://doi.org/10.1002/app.47529
15. Mastalska-Popławska, J., Kadac, K., Izak, P., Gierej, M., Stempkowska, A., Góral, Z. (2020). The influence of ceramic additives on intumescence and thermal activity of epoxy coatings for steel. Journal of Applied Polymer Science, 138 (9), 49914. doi: https://doi.org/10.1002/app.49914
16. Tsapko, Y., Tsapko, A. (2017). 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, 5 (10 (89)), 55–60. doi: https://doi.org/10.15587/1729-4061.2017.111106
17. Janna, W. S. (2018). Engineering Heat Transfer. CRC Press, 692. doi: https://doi.org/10.1201/9781439883143
18. Potter, M. C. (2019). Engineering Analysis. Springer. doi: https://doi.org/10.1007/978-3-319-91683-5
19. Tsapko, Y. V., Tsapko, A. Y., Bondarenko, O. P. (2020). Modeling of thermal conductivity of reed products. IOP Conference Series: Materials Science and Engineering, 907, 012057. doi: https://doi.org/10.1088/1757-899x/907/1/012057
20. Jannot, Y., Degiovanni, A., Schick, V., Meulemans, J. (2020). Thermal diffusivity measurement of insulating materials at high temperature with a four-layer (4L) method. International Journal of Thermal Sciences, 150, 106230. doi: https://doi.org/10.1016/j.ijthermalsci.2019.106230
21. Bartlett, A. I., Hadden, R. M., Bisby, L. A. (2019). A Review of Factors Affecting the Burning Behaviour of Wood for Application to Tall Timber Construction. Fire Technology, 55 (1), 1–49. doi: https://doi.org/10.1007/s10694-018-0787-y