VILNIUS GEDIMINAS TECHNICAL UNIVERSITY

Vladas PRANIAUSKAS

INFLUENCE OF FLAME RETARDANTS ON FLAMMABILITY OF WOOD AND WOOD BASED PRODUCTS

SUMMARY OF DOCTORAL DISSERTATION

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Scientific Supervisor

Prof Dr Habil Romualdas MAČIULAITIS (Vilnius Gediminas Technical University, Technological Sciences, Civil Engineering – 02T).

The dissertation is being defended at the Council of Scientific Field of Civil Engineering at Vilnius Gediminas Technical University:

Chairman

Prof Dr Habil Juozas ATKOČIŪNAS (Vilnius Gediminas Technical University, Technological Sciences, Civil Engineering – 02T).

Members:

Assoc Prof Dr Algirdas JUOZAPAITIS (Vilnius Gediminas Technical University, Technological Sciences, Civil Engineering – 02T),

Prof Dr Habil Aivaras KAREIVA (Vilnius University, Physical Sciences, Chemistry – 03P),

Prof Dr Habil Audronis Kazimieras KVEDARAS (Vilnius Gediminas Technical University, Technological Sciences, Civil Engineering – 02T),

Prof Dr Habil Vytautas STANKEVIČIUS (Kaunas University of Technology, Technological Sciences, Civil Engineering – 02T).

Opponents:

Prof Dr Habil Stasys BOČKUS (Kaunas University of Technology, Technological Sciences, Materials Engineering – 08T),

Assoc Prof Dr Darius BAČINSKAS (Vilnius Gediminas Technical University, Technological Sciences, Civil Engineering – 02T).

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Address: Saulėtekio al. 11, LT-10223 Vilnius, Lithuania.

Tel.: +370 5 274 4952, +370 5 274 4956; fax +370 5 270 0112;

e-mail: doktor@vgtu.lt

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Vladas PRANIAUSKAS

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Mokslinis vadovas

prof. habil. dr. Romualdas MAČIULAITIS (Vilniaus Gedimino technikos universitetas, technologijos mokslai, statybos inžinerija – 02T).

Disertacija ginama Vilniaus Gedimino technikos universiteto Statybos inžinerijos mokslo krypties taryboje:

Pirmininkas

prof. habil. dr. Juozas ATKOČIŪNAS (Vilniaus Gedimino technikos universitetas, technologijos mokslai, statybos inžinerija – 02T).

Nariai:

doc. dr. Algirdas JUOZAPAITIS (Vilniaus Gedimino technikos universitetas, technologijos mokslai, statybos inžinerija – 02T),

prof. habil. dr. Aivaras KAREIVA (Vilniaus universitetas, fiziniai mokslai, chemija – 03P),

prof. habil. dr. Audronis Kazimieras KVEDARAS (Vilniaus Gedimino technikos universitetas, technologijos mokslai, statybos inžinerija – 02T),

prof. habil. dr. Vytautas STANKEVIČIUS (Kauno technologijos universitetas, technologijos mokslai, statybos inžinerija – 02T).

Oponentai:

prof. habil. dr. Stasys BOČKUS (Kauno technologijos universitetas, technologijos mokslai, medžiagų inžinerija – 08T),

doc. dr. Darius BAČINSKAS (Vilniaus Gedimino technikos universitetas, technologijos mokslai, statybos inžinerija – 02T).

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Adresas: Saulėtekio al. 11, LT-10223 Vilnius, Lietuva.

Tel.: (8 5) 274 4952, (8 5) 274 4956; faksas (8 5) 270 0112;

el. paštas doktor@vgtu.lt

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Introduction

Topicality of the problem. Nowadays, many scientific studies are carried out with wood based products and wood impregnated with flame retardant solutions. Much attention is given to the development of new flame retardant solutions: selection of components, their efficiency, and studies of the flammability of wood and wood based products impregnated with flame retardant solutions.

In order to ensure longer evacuation time and safe work of fire-fighters at the scene of fire, it is especially relevant to impregnate wooden structures when using them in construction, thus decreasing the flammability of wood and wood products. Besides, it is necessary to have an effective possibility to check the efficiency of the impregnation of wood with flame retardant solutions. Since the impact of climatic factors on the aging of impregnated with flame retardant solutions wood coating has not been studied so far, it is rational and important to perform operational studies (depending on the place and time of storage) and to evaluate possible changes in the flammability properties of samples. The issue of smoke production and CO_2 emission of wood impregnated with flame retardant solutions, in comparison to non-impregnated construction wood, in the course of burning of wooden buildings has also been studied insufficiently.

Research object. Influence of the flame retardant solutions on the coniferous wood and wood based products flammability characteristics (heat release rate, time to ignition, calorific value, total heat rate etc.).

Aim of the work. To study flammability characteristics of non-impregnated wood and wood based products as well as wood and wood based products impregnated with flame retardant solutions and, upon comparison of the obtained results, to determine the impact of impregnation on overall flammability characteristics and values of specific indicators. To determine the impact of atmospheric factors on aging of the flame retardants impregnated wood coatings. To develop a methodology, by means of which it would be possible to evaluate the quality of the coating of structural wood based products with flame retardant solutions.

To achieve the objectives of the research, the following ***tasks*** must be solved:

1. To test the impact of the smoothness of the wood surface and impregnation method on the penetration of flame retardant solutions by evaluation according to wood flammability indicators such as calorific value and weight of residues (salts).

2. To carry out standard studies of non-impregnated and impregnated wood and wood based products and, in accordance with normative kinetic flammability indicators, to determine flammability classes and evaluate the impact of flame retardant solutions on them.
3. To test impregnated and non-impregnated wood based products and to identify the parameters which have the biggest impact on the combustion process as well as to derive empiric equations for the forecasting of the time to ignition as a function in accordance with the other most important flammability indicators.
4. To carry out standard tests of non-impregnated and impregnated wood and wood based products and, in accordance with normative kinetic flammability indicators recorded during the combustion process, to evaluate the impact of flame retarders on smoke production and CO_2 emission.
5. To test the process of the aging impregnated with flame retardant solutions wood coatings and to determine changes in calorific value and weight of residues, as indicators characterising flammability, depending on the ambient conditions and time.

Methodology of research. The methods applied in the study include such methods as the cone calorimeter test method, thermal radiation test method, single burning item (SBI) test method, and heat of combustion (calorific value) determination test method as well as natural and simulated aging of the flame retardants impregnated wood coatings in possible conditions of the operation of wood based products.

Scientific novelty. It has been proved that in case of increasing the yield of new impregnants certified in Lithuania over that recommended by the manufacturers, it is possible to reduce the initial flammability of structural pine and spruce wood products and to change the flammability class correspondingly as well as to reduce smoke and CO_2 emission from such wood during fire. Equations for the forecasting of the most important indicator of the flammability of impregnated and non-impregnated wood boards, i.e. time to ignition, have been developed. The dependence of the flammability properties of wood impregnated with flame retardant solutions on the sample holding place in possible operating conditions within a period of one year has been studied and it has been established that almost the whole effect of impregnation can be lost within one year in the least favourable studied operating conditions.

Practical value. A methodology for the evaluation of the quality of the coating of wooden structures with flame retardant solutions, which allows, having take samples from wooden structures, to determine whether or not they were coated with a flame retardant solution and whether or not an appropriate yield of the flame retardant solution was used. The results of the studies can be used for the evaluation of the quality of the coating of wooden structures with flame retardant solutions, identification of the flammability class, and forecasting of the most important flammability indicator of non-impregnated and impregnated wood based products.

Defended propositions

1. The factors influencing the impregnation efficiency of coniferous wood products are as follows: surface smoothness, yield of the flame retarder, when a uniform coating formation methodology is used – flame retarder grade and type of wood.
2. The use of flame retardant solutions for the impregnation of wood and wood based products results in the reduction of their flammability and propagation of flame.
3. The impregnation of coniferous wood products with investigated flame retardant solutions reduces the amount of the smoke production and emission of carbon dioxide during fire; however, the impregnation of wood strand boards and particle boards only reduces CO_2 concentration but the amount of smoke production during the burning of such products actually does not change.
4. The biggest negative impact on the aging of with flame retardant solutions impregnated wooden constructions coatings hold in possible operation places for a certain period of time is made by atmospheric precipitation, high air humidity, and temperature fluctuations.

The scope of the scientific work. The dissertation consists of the introduction, five chapters, and summary of the results. Also, there is one appendix.

The scope of the work comprises 164 pages; the text contains 11 numbered formulas, 69 figures, and 16 tables. In the course of the preparation of the dissertation, 169 literature sources were referred to.

1. Review of the flammability properties of wood and wood based products

The development of heat emission rate, combustion of wood and wood based products, and the specific features of their thermal decomposition and smoke production have been reviewed. The components of solutions used for the reduction of the wood combustion process and properties of such components have been studied. It was found in literature that some authors claim that the thickness of wood texture does not have any impact on its ignition, while other authors adhere to an absolutely different opinion. No data whatsoever were found in relation to the impact of the surface of planed and non-planed wood on the penetration of flame retardant solutions and on the aging of impregnated with flame retardant solutions wood coatings. No data on the possibility to check the quality of the coating of wooden structures with flame retardant solutions was found either.

2. Description of samples preparation, methodologies and equipment of the research

To the research used pine and spruce wood (most often used in construction) as well as the most popular oriented strandboards (thickness – 6 mm, 10 mm, 15 mm, and 18 mm), wood particleboards (thickness – 24 mm), laminated wood particleboards (thickness – 18 mm and 29 mm), and medium density fibreboard (thickness – 24 mm). The following flame retardant solutions were used for impregnation: certified in Lithuania flame retardant solutions Bak-1 (yield 450 ml/m^2) and Flamasepas-2 (yield 500 ml/m^2), new flame retardant solution KMP-3 (yield 450 ml/m^2) and two antiseptic flame retardant solutions Asepas 2 (yield 250 ml/m^2) and Bioteks Universal (yield 250 ml/m^2).

The studies have been carried out in accordance with the requirements of the standards LST ISO 5657:1999, ISO 5660-1:2002, LST EN 13823:2010, and LST EN ISO 1716:2010.

3. Research of the flammability of wood and wood based products

A smaller amount of calorific value was emitted in the course of combustion of non-impregnated spruce wood than that in the course of combustion of pine wood because pine wood is more resinous and this facilitates its pyrolysis. On the other hand, the weight of residues in pine wood is smaller than that of spruce and it illustrates their higher requirement and potential for mineral salts as a mineral material because of a more developed system of branches and needles (see Table 1).

Table 1. Indicators of spruce and pine wood (without a flame retarder coating)

Indicators of wood	Pine	Spruce
Moisture content, %	8	10
Average density, g/cm^3	0.501	0.477
Average weight of material under testing, g	0.6837	0.5972
Average calorific value (Q_S), MJ/kg	19.804	19.101
Average weight of residues after the test, g	0.9 x 10^{-3}	1.3 x 10^{-3}

When wood is covering with a yield of impregnants certified in Lithuania bigger that recommended by the manufacturers, calorific value deceases, and when wood is covering with a smaller yield, it increases (Fig. 1a). In values of the weight of residues, it reflects inversely (Fig. 1b).

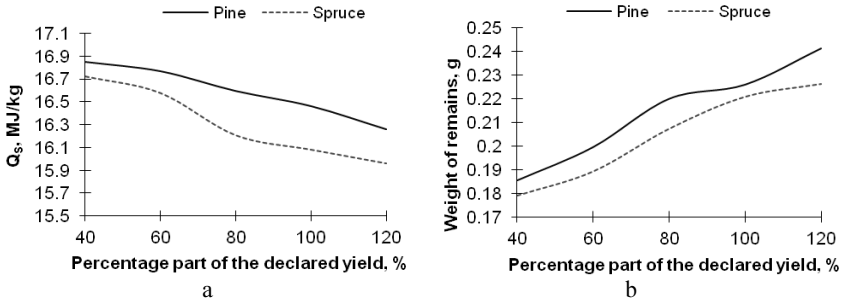

Fig. 1. Dependence of (a) calorific values and (b) average weight of residues (salts) of pine (planed) and spruce (non-planed) samples covered with "BAK-1" on the percentage part of the declared yield

The time to ignition of planed pine coated with a flame retardant solution from one side under the impact of 40 kW/m^2 heat flux is by nearly 3 times higher than that of sawn non-planed pine impregnated with the same flame retardant solution because we have losses of the impregnant in this case (Table 2). When comparing sawn and non-planed wood of volumetric and one-sided impregnation, wood of volumetric impregnation showed lower calorific value properties because the leak of the flame retardant solution was eliminated and losses of the flame retardant solutions were completely avoided in this case (Fig. 2). In order to ensure proper protection of primarily smooth surface wood against fire in case of one-sided impregnation, it is necessary to increase the yield of the flame retardant solution over the recommended one by 30 %.

Table 2. Time to ignition of planed and non-planed pine impregnated with the flame retardant solution BAK-1 under the impact of 40 kW/m^2 and 50 kW/m^2 superficial heat flux

Heat flux, kW/m^2	Time to ignition, s	
	Planed pine impregnated with the flame retardant solution BAK-1 (when impregnating the surface of only one side of the sample)	Non-planed pine impregnated with the flame retardant solution BAK-1 (when impregnating the surface of only one side of the sample)
50	133	49
40	780 – did not ignite	78

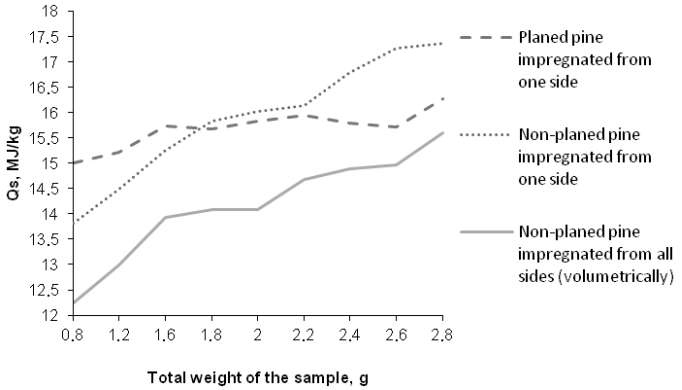

Fig. 2. Calorific value of planed and non-planed pine wood impregnated with the flame retardant solution "BAK-1" depending on the sample weight and impregnation method

The impregnation of pine wood with flame retardant solutions allows reducing its flammability and obtaining a higher flammability class. In the course of studies of non-impregnated pine wood, the maximum fire growth rate (FIGRA) = 373.4 W/s, and this corresponds to D flammability class. The FIGRA values of such wood impregnated with flame retardant solutions Flamasepas-2 (Fig. 3), Bak-1, and KMP-3 are equal to 92.2 W/s, 99.2 W/s, and 113 W/s, correspondingly. In all cases, upon impregnation of pine wood, B flammability classes were obtained.

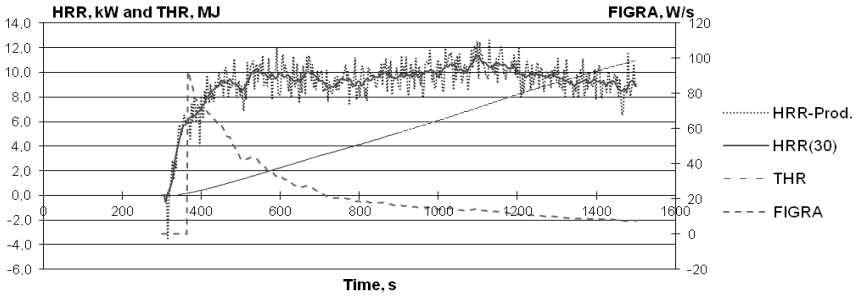

Fig. 3. HRR, THR, and FIGRA values of pine wood impregnated with the flame retardant solution Flamasepas-2 depending on time

After the impregnation wood particleboard with a flame retardant solution, the maximum fire growth rate (FIGRA) of the sample decreased more than twice, and this reduces the flammability of boards. When comparing non-impregnated wood particleboard with woodparticle board impregnated with the flame retardant solution Bak-1 (Fig. 4), the maximum fire growth rate (FIGRA) of the sample decreased from 615.7 W/s to 249.6 W/s, while the flammability class changed from D to C. As a result of the impregnation of wood based products in accordance with the yield of the flame retardant solution specified by the manufacturer, is halting the spread of flame.

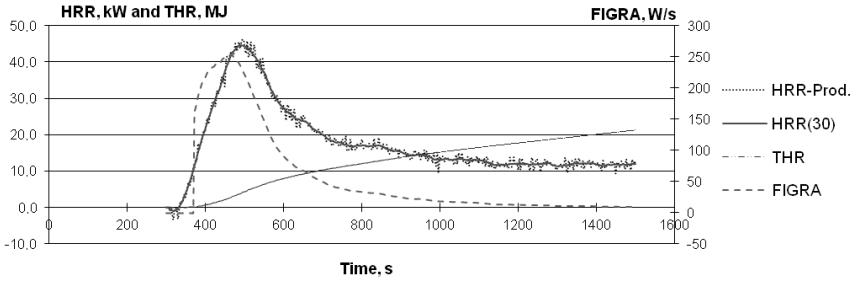

Fig. 4. *HRR*, THR, and *FIGRA* values of a wood particleboard (WPB) impregnated with the flame retardant solution "BAK-1" depending on the time

Besides, forecasting of the time to ignition (TTI, s) of impregnated (Equations 1 and 2) and non-impregnated (Equations 3 and 4) boards can be in accordance with the heat flux impacting the sample (Q, kW/m²) and, more accurately, also its thickness (S, mm). The aforementioned indicators are

sufficient for quite accurate forecasting and deciding on the flammability of oriented strandboards (OSB) and wood particleboards (WPB).

$$TTI_1 = (52.128 - 0.683Q) * (TTI_1 \leq 45.276) + (201.774 - 3.818Q) * (TTI_1 > 45.276), \quad (1)$$

$$TTI_2 = (60.725 - 0.762Q - 0.434S) * (TTI_2 \leq 45.276) + (196.62 - 3.818Q - 0.421S) * (TTI_2 > 45.276), \quad (2)$$

$$TTI_3 = (74.334 - 1.137Q) * (TTI_3 \leq 34.74) + (299.813 - 6.416Q) * (TTI_3 > 34.74), \quad (3)$$

$$TTI_4 = (75.430 - 1.106Q - 0.177S) * (TTI_4 \leq 34.739) + (265.634 - 5.2681Q - 0.488S) * (TTI_4 > 34.739), \quad (4)$$

Where: $TTI_{1\text{-}4}$ – time to ignition, s; Q – superficial heat flux value impacting the sample, kW/m²; S – thickness of OSB or WPB boards, mm; $*(TTI_{1,2} \leq 45.276)$ – means that the samples are impacted by a heat flux > 40 kW/m²; $*(TTI_{1,2} > 45.276)$ – means that the samples are impacted by a heat flux ≤ 40 kW/m²; $*(TTI_{3,4} \leq 34.74)$ – means that the equation is applicable when the samples are impacted by a heat flux > 40 kW/m², and this equation will be applicable to WPB when the samples are impacted by a heat flux > 45 kW/m²; $*(TTI_{3,4} > 34.74)$ – means that the equation is applicable when the samples are impacted by a heat flux ≤ 40 kW/m² and this equation will be applicable to WPB when the samples are impacted by a heat flux ≤ 45 kW/m².

4. Research of smoke production during the combustion of wood and wood based products

Since a majority of victims of fires are killed by suffocation by smoke rather than as a result of a direct exposure to flame, the goal of this study is to determine the impact of flame retardant solutions on the emission of smoke from wood and wood products.

In the course of combustion of non-impregnated pine wood, the smoke emission amounted to 165 m^2, SMOGRA was equal to 22.9 cm^2/s^2, and a hazardous CO_2 concentration of 1.46 % was reached. In the meanwhile, in the course of combustion of pine wood impregnated with the flame retardant solution Flamasepas-2, smoke emissions amounted to 125 m^2, SMOGRA value was equal to 2.8 cm^2/s^2, and a concentration of CO_2 of 0.35 % was reached, while in the course of combustion of pine wood impregnated with the flame retardant solution Bak-1 (Fig. 5), smoke emissions amounted to 85 m^2, SMOGRA value was equal to 1.5 cm^2/s^2, and the same concentration of CO_2 equal to 0.35 % was reached.

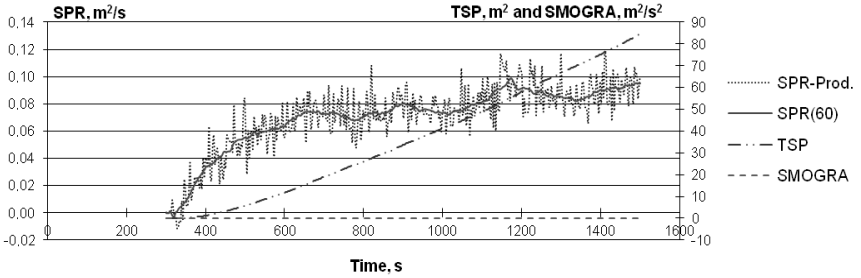

Fig. 5. SPR, TSP, and SMOGRA values of pine wood impregnated with the flame retardant solution BAK-1 depending on time

When studying a 6 mm thick OSB, the gross amount of smoke emission prior to the termination of the test, due to exceeding test criteria and fast propagation of flame, was equal to 90 m^2 and a hazardous concentration of CO_2 emissions of 9 % was reached, while for an impregnated board, at the same moment of time, the gross amount of smoke emission was equal to 75 m^2 and the concentration of CO_2 was lower at 2.3 %. However, when studying a 24 mm thick WPB, the following results were obtained: gross amount of smoke emission of 170 m^2, SMOGRA equal to 7.8 cm^2/s^2, and concentration CO_2 emissions equal to 1.3 %. For an impregnated board (Fig. 6), the gross amount of smoke emissions reached the value of 180 m^2, SMOGRA became equal to 19.5 cm^2/s^2, and the concentration of CO_2 emissions decreased to 0.65 %.

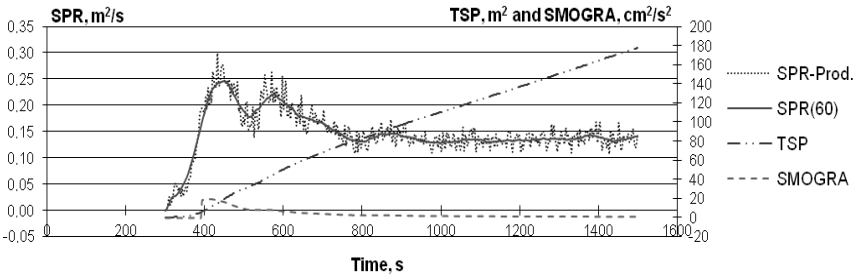

Fig. 6. SPR, TSP, and SMOGRA values of 24 mm thick wood particleboard (WPB) impregnated with the flame retardant solution BAK-1 depending on time

Therefore, it can be stated that the impregnation of wood strand and particle boards of the types OSB and WPB with flame retardant solutions can allow a considerable reduction of CO_2 concentration; however, the amount of

smoke formed in the course of combustion of such products residues almost unchanged.

5. Aging of the flame retardants impregnated wood coatings

The calorific value and amount of residues (salts) of the pine wood samples impregnated with the flame retardant solutions BAK-1 and Flamasepas-2 and that remained after the test almost did not change. Samples impregnated with the flame retardant solution BAK-1 lost 3.7 % of the flame retarder protection, when the pine wood samples impregnated with the flame retardant solution Flamasepas-2 lost 2 % of salts and 2 % of the flame retarder protection. Pine wood samples impregnated with the flame retardant solution BAK-1, which were kept outside on a roof, loose 76 % of the flame retarder protection and 68 % of salts as soon as after 3 months. After 12 months, these samples lost 94 % of flame retarder protection and 95.6 % of salts, while the calorific value was almost the same as that of non-impregnated pine wood (Fig. 7 and 8). In the meanwhile, pine wood samples kept outside on a roof which were impregnated with the flame retardant solution Flamasepas-2 after 3 months loose 91 % of flame retarder protection and 87.8 % of salts, and after 12 months loose 94.7 % of flame retarder protection and 94.8 % of salts. Wood impregnated with the flame retarding solution experiences the negative impact of atmosphere because wood classified in B flammability characteristic may reach the D flammability characteristic as soon as after half a year.

The fastest aging rate among pine wood samples impregnated with the flame retardant solutions BAK-1 and Flamasepas-2 that were not exposed to precipitation was shown by samples that were kept outdoors under a roof. After 12 months, pine wood samples impregnated with the flame retardant solution BAK-1 lose 32.5 % of the flame retarder protection and 35.3 % of salts (Fig. 7 and 8). After 12 months, pine wood samples impregnated with the flame retardant solution Flamasepas-2 lose 29.2 % of the flame retarder protection and 27.3 % of salts.

The calorific capacity and quantity of residues of pine wood samples impregnated with the flame retardant solutions BAK-1 and Flamasepas-2 that were stored inside a non-heated room changed inconsiderably. After 12 months, pine wood samples impregnated with the flame retardant solution BAK-1 lose 16.1 % of the flame retarder protection and 21.1 % of salts (Fig. 7 and 8). After 12 months, pine wood samples impregnated with the flame retardant solution Flamasepas-2 lose 11 % of the flame retarder protection and 13.4 % of salts.

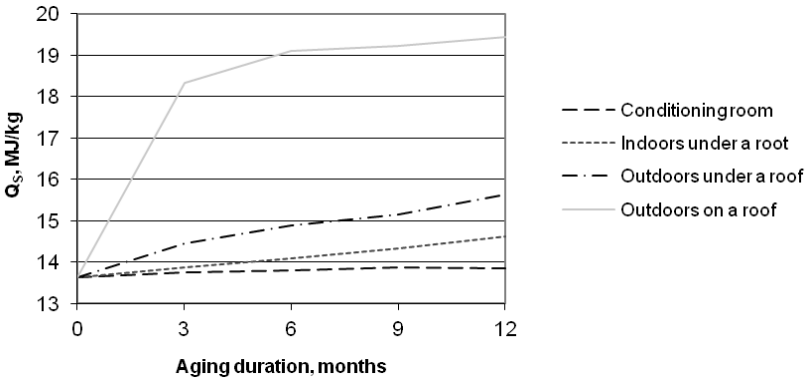

Fig. 7. Dependence of calorific value (Q_s) on the sample aging time in case of different exposition place when studying pine wood impregnated with Bak-1

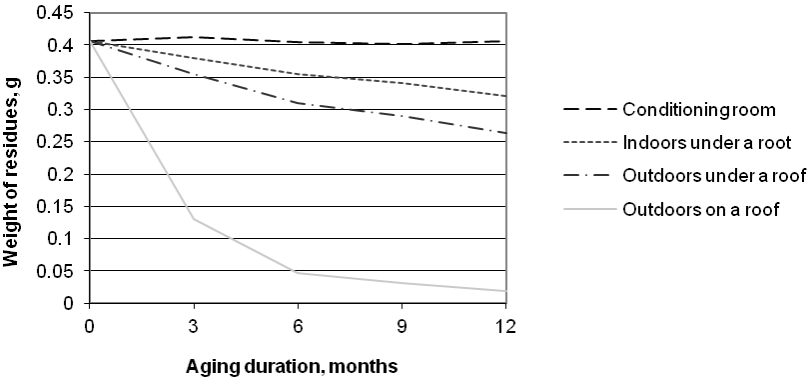

Fig. 8. Dependence of the weight residues on the sample aging time in case of different exposition place when studying pine wood impregnated with Bak-1

The biggest impact (negative changes in calorific value and weight of residues) on the aging of wood impregnated with a flame retardant solution is made by precipitation (in the form of rain or sleet). All other atmospheric factors (changes in sun radiation, wind, pressure, humidity, precipitation, and temperatures) accelerate the process of aging. In case of changes in relative humidity and fluctuations in air temperature, the aging of the flame retarder occurs considerably slower.

General conclusions

1. Research show that the initial efficiency of the impregnation of coniferous wood products is influenced by their surface smoothness, yield of the flame retarder, when a uniform coating formation methodology is used – species of wood and grade of the flame retarder.
2. It has been established that the time to ignition of planed pine coated with a flame retardant solution from one side under the impact of 40 kW/m^2 heat flux is by nearly 3 times higher than that of sawn non-planed pine impregnated with the same flame retardant solution. In order to achieve proper protection from fire of sawn nonplaned and planed wood impregnated with the flame retardant solutions in accordance with the yield recommended by the manufacturers, it must be impregnated with a much higher yield of flame retardant solution (over 30 %).
3. It has been established by the studies that the maximum fire growth rate (FIGRA) of non-impregnated pine wood = 373.4 W/s (D flammability class), and the FIGRA values of such wood impregnated with flame retardant solutions Flamasepas-2, Bak-1, and KMP-3 are equal to 92.2 W/s, 99.2 W/s, and 113 W/s, correspondingly (flammability class B). Therefore after impregnation coniferous wood with flame retardant solutions flammability class can be reduced from D to B.
4. It has been proved by experiments that the impregnation of coniferous wood products enables to decrease the quantity of smoke production and carbon dioxide emission during fire. In the course of combustion of pine wood impregnated with flame retardant solutions Flamasepas-2 and Bak-1, compared with not impregnated pine wood, decreased by 8.2 and 15.3 times while the absolute decrease in the amount of smoke reaches 1.3 and 1.9 times. In the course of combustion of non-impregnated pine wood, and a hazardous CO_2 concentration of 1.46 % was reached, while the highest concentration of CO_2 reached in the case of pine wood impregnated with the flame retardant solution Flamasepas-2 and Bak-1 is 0.35 %.
5. It has been established that changes and time of exposure in atmospheric factors (sun radiation, wind, pressure, humidity, precipitation, and temperatures) has a direct negative impact on pine wood impregnated with the flame retardant solutions Bak-1 and Flamasepas-2 by removing the flame retarder protection and with domination of the “wash-out and drying” mechanism. After one year of storage in field conditions, the calorific value decreased by 94.0 % and 94.7 %, and the indicator of the weight of residues decreased by 96.5 % and 94.7 %, correspondingly.

6. By studies of medium density fibreboard and laminated wood particleboard with various thickness, it has been established that time to ignition is a function combining such arguments as the time within which the maximum heat release rate is achieved, total heat release, maximum heat release rate, amount of the superficial heat flux impacting the sample and effective heat of combustion.
7. It has been established that the impregnation of oriented strandboards and wood particleboards with flame retardant solutions Bak-1 and Flamasepas-2 allows a considerable reduction of their flammability class (from D to C) and CO_2 concentration (up to 4 times); however, the amount of smoke formed in the course of combustion of such products residues almost unchanged.
8. Equations for the forecasting of the time to ignition of impregnated and non-impregnated boards in accordance with the heat flux impacting the sample and, more accurately, also its thickness have been derived.
9. According to the test results a methodology allowing evaluating the quality of the coating of wood structures with flame retardant solutions in accordance with the study of calorific capacity and weight of residues has been developed.

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About the author

In 2006, he acquired the Bachelor’s degree in the Main School of Fire Service, Warsaw. In 2008, he acquired the Master’s degree at the Faculty of Construction in Vilnius Gediminas Technical University. In 2008–2012, he has been a doctoral student of Vilnius Gediminas Technical University. Currently, he works in the Fire Research Centre of the Fire and Rescue Department under the Ministry of the Interior.

ANTIPIRENŲ POVEIKIS MEDIENOS IR JOS GAMINIŲ DEGUMUI

Mokslo problemos aktualumas. Šiandieną nemaža mokslinių tyrimų atliekama su medienos gaminiais ir mediena, impregnuota antipireniniais tirpalais. Daug dėmesio skiriama naujų antipirenininių tirpalų kūrimui: sudedamųjų dalių parinkimui, jų veiksmingumui ir antipirenininiais tirpalais impregnuotos medienos ir medienos gaminių degumo tyrimams.

Siekiant užtikrinti ilgesnį žmonių evakuacijos laiką ir saugų ugniagesių darbą gaisravietėje, itin aktualu projektuojamas ir statyboje naudojamas medines konstrukcijas impregnuoti antipirenininiais tirpalais, taip mažinant medienos ir jos gaminių degumą. Be to, būtina turėti efektyvią galimybę greitai patikrinti medienos impregnavimo antipirenininiais tirpalais veiksmingumą. Kadangi iki šiol nebuvo tirtas klimatinių veiksnių poveikis antipirenininiais tirpalais impregnuotos medienos dangos senėjimui, racionalu ir svarbu atlikti eksploatacinius tyrimus (atsižvelgiant į laikymo vietą ir laiką) ir įvertinti galimus bandinių degumo savybių pokyčius. Mažai ištirtas ir naujais antipirenininiais tirpalais impregnuotos medienos, palyginti su neimpregnuota statybine mediena, dūmų susidarymas ir CO_2 išsiskyrimas degant mediniams pastatams.

Tyrimų objektas – antipirenininių tirpalų įtaka spygliuočių medienos ir medienos gaminių degumo rodikliams (šilumos išsiskyrimo greičiui, laikui iki užsidegimo, suminiam šilumingumui, visai išskirtai šilumai ir kt.).

Darbo tikslas – ištirti neimpregnuotos ir antipirenininiais tirpalais impregnuotos medienos ir jos gaminių degumo rodiklius, o palyginus gautus rezultatus – nustatyti impregnavimo poveikį kompleksiniams degumo rodikliams ir konkrečių rodiklių vertėms. Nustatyti atmosferinių veiksnių poveikį antipirenininiais tirpalais impregnuotos medienos dangos senėjimui. Sukurti metodiką, kurią taikant būtų įmanoma įvertinti konstrukcinės medienos gaminių padengimo antipirenininiais tirpalais kokybę. Darbo tikslui pasiekti reikia spręsti šiuos ***uždavinius***:

1. Ištirti, kokią įtaką antipirenininių tirpalų įsigėrimui turi medienos paviršiaus lygumas ir impregnavimo būdas, vertinant pagal medienos degumo rodiklius, tokius kaip suminis šilumingumas ir liekanų (druskų) masė.
2. Atlikti standartinius neimpregnuotos bei impregnuotos medienos ir jos gaminių tyrimus ir pagal normatyvinius kinetinius degumo rodiklius nustatyti degumo klases bei įvertinti antipirenininių tirpalų įtaką.

3. Ištirti impregnuotus ir neimpregnuotus medienos plokščių pavidalo gaminius ir išryškinti parametrus, labiausiai lemiančius degimo procesą bei išvesti empirines laiko iki užsiliepsnojimo, kaip funkcijos, prognozavimo lygtis pagal kitus svarbiausius degumo rodiklius.
4. Atlikti standartinius neimpregnuotos bei impregnuotos medienos ir jos gaminių tyrimus ir pagal normatyvinius kinetinius rodiklius, fiksuojamus degimo proceso metu, įvertinti antipirenų įtaką dūmų susidarymui ir CO_2 išsiskyrimui.
5. Ištirti, kaip vyksta antipireniniais tirpalais impregnuotos medienos dangos senėjimas, ir nustatyti, kaip kinta suminis šilumingumas, liekanų masė ir rodikliai, charakterizuojantys degumą, atsižvelgiant į aplinkos sąlygas ir laiką.

Tyrimų metodika. Darbe taikomi kūginio kalorimetro, šiluminės spinduliuotės, vieno degančio objekto bei degimo šilumos (šilumingumo) nustatymo bandymo metodai ir natūralus bei modeliuotas antipirenais impregnuotos medienos dangos sendinimas galimomis medinių konstrukcijų eksploatacijos sąlygomis.

Mokslinis naujumas. Įrodyta, kad padidinus gamintojų rekomenduojamą naujų, Lietuvoje sertifikuotų impregnantų išeigą, galima sumažinti pradinį konstrukcinių pušies ir eglės gaminių degumą bei atitinkamai pakeisti degumo klasę, taip pat sumažinti išsiskiriančių dūmų ir CO_2 kiekius iš tokios medienos kilus gaisrui; sukurtos impregnuotų ir neimpregnuotų medienos plokščių svarbiausio degumo rodiklio – laiko iki užsiliepsnojimo prognozavimo lygtys; ištirta antipireniniais tirpalais impregnuotos medienos degumo savybių priklausomybė nuo bandinių išlaikymo vietos galimomis eksploatavimo sąlygomis vienerių metų laikotarpiu ir nustatyta, kad blogiausiomis tirtomis natūralios eksploatacijos sąlygomis per metus įmanoma prarasti beveik visą impregnavimo efektą.

Praktinė vertė. Sukurta medinių konstrukcijų padengimo antipireniniais tirpalais kokybės įvertinimo metodika, kuri leidžia, paėmus mėginius iš medinių konstrukcijų, nustatyti, ar jos padengtos antipireniniu tirpalu ir ar naudota tinkama antipireninio tirpalo išeiga. Tyrimų rezultatai gali būti naudojami medinių konstrukcijų padengimo antipireniniais tirpalais kokybei įvertinti, degumo klasei nustatyti, neimpregnuotų bei impregnuotų medienos gaminių svarbiausiam degumo rodikliui prognozuoti.

Ginamieji teiginiai

1. Spygliuočių medienos gaminių impregnavimo efektyvumą veikiantys veiksniai yra šie: paviršiaus lygumas, antipireno išeiga, kai taikoma vienoda dangos suformavimo metodika – antipireno ir medienos rūšis.
2. Naudojant antipireninius tirpalus medienai ir jos gaminiams impregnuoti sumažėja jų degumas ir liepsnos išplitimas.
3. Spygliuočių medienos gaminių impregnavimas tirtais antipireniniais tirpalais sumažina gaisro metu susidarančių dūmų ir išsiskiriančio anglies dvideginio kiekį, tačiau medienos skiedrų ir drožlių plokščių impregnavimas sumažina tik CO_2 koncentraciją, bet degant tokiems gaminiams susidarančių dūmų kiekis praktiškai nesikeičia.
4. Galimose eksploatacijos vietose tam tikrą laiką išlaikytų antipireniniais tirpalais impregnuotų medinių konstrukcijų dangų senėjimui didžiausią neigiamą įtaką turi atmosferos krituliai, didelė oro drėgmė ir temperatūros svyravimai.

Darbo apimtis. Disertaciją sudaro įvadas, penki skyriai ir rezultatų apibendrinimas. Taip pat yra vienas priedas.

Darbo apimtis yra 164 puslapiai, neskaitant priedų, tekste panaudota 11 numeruotų formulių, 69 paveikslai ir 16 lentelių. Rašant disertaciją buvo panaudoti 169 literatūros šaltiniai.

Pirmasis skyrius skirtas literatūros apžvalgai. Skyriaus pabaigoje pateikiamos išvados ir formuluojami disertacijos uždaviniai.

Antrajame skyriuje aptariamos tyrimams naudotos medžiagos, gaminiai, įranga ir metodikos.

Trečiajame skyriuje tiriama antipireninių tirpalų įtaka medienos bei jos gaminių degumui.

Ketvirtajame skyriuje tiriama antipireninių tirpalų įtaka medienos ir jos gaminių degimo metu susidarančių dūmų ir anglies dvideginio kiekiui.

Penktajame skyriuje pristatomi antipireniniais tirpalais padengtų medinių konstrukcijų dangų natūralaus senėjimo rezultatai. Darbo pabaigoje suformuluojamos bendrosios išvados.

Bendrosios išvados

1. Atlikus tyrimus nustatyta, kad spygliuočių medienos gaminių pradinį impregnavimo efektyvumą įtakoja jų paviršiaus lygumas, antipireno išeiga, kai taikoma vienoda dangos suformavimo metodika, antipireno ir medžio rūšis.
2. Nustatyta, kad „BAK-1“ antipireniniu tirpalu iš vienos pusės impregnuotos obliuotos pušies medienos laikas iki užsiliepsnojimo,

veikiant 40 kW/m^2 šilumos srautu, yra beveik tris kartus didesnis negu tuo pačiu antipirenu impregnuotos pjautos neobliuotos pušies. Norint pasiekti pjautos neobliuotos ir obliuotos medienos, iš vienos pusės impregnuotos antipireniniu tirpalu tinkamą apsaugą nuo ugnies, ją būtina veikti gerokai didesnės išeigos tirpalu (per 30 %).

3. Tyrimais nustatyta, kad neimpregnuotos pušies medienos didžiausias bandinio šilumos išsiskyrimo greičio ir trukmės santykis *FIGRA* = 373,4 W/s (degumo klasė D), o antipireniniais tirpalais „Flamasepas-2“, „BAK-1“ ir „KMP-3“ impregnuotos pušies medienos *FIGRA* vertės atitinkamai lygios 92,2 W/s, 99,2 W/s ir 113 W/s (degumo klasė B). Todėl spygliuočių medieną impregnavus antipireniniais tirpalais galima sumažinti degumo klasę iš D į B.
4. Eksperimentais įrodyta, kad spygliuočių medienos gaminių impregnavimas sudaro galimybę sumažinti gaisro metu susidarančių dūmų ir išsiskiriančio anglies dvideginio kiekį. Degant antipireniniu tirpalu „Flamasepas-2“ ir „BAK-1“ impregnuotai pušies medienai dūmų kiekio padidėjimo rodiklis *SMOGRA,* lyginant su neimpregnuota pušies mediena, sumažėjo atitinkamai 8,2 ir 15,3 karto, kai absoliutus dūmų kiekio sumažėjimas siekia 1,3 ir 1,9 karto. Degant neimpregnuotai pušies medienai pasiekiama pavojinga 1,46 % CO_2 koncentracija, o degant antipireniniu tirpalu „Flamasepas-2“ ir „BAK-1“ impregnuotai pušies medienai daugiausia pasiekiama 0,35 % CO_2 koncentracija.
5. Nustatyta, kad atmosferos veiksnių (kritulių, drėgmės, temperatūrų, vėjo ir saulės spinduliuotės) poveikio ilgalaikiškumas ir kaita tiesiogiai neigiamai veikia antipireniniais tirpalais „BAK-1“ ir „Flamasepas-2“ impregnuotą pušies medieną, pašalinant antipireno apsaugą ir dominuojant „išplovimo ir nudžiūvimo“ mechanizmui. Po vienerių metų laikymo lauko sąlygomis suminio šilumingumo rodiklis sumažėjo atitinkamai 94,0 ir 94,7 %, o liekanų masės – 96,5 ir 94,7 %.
6. Įvairaus storio neimpregnuotų vidutinio tankio plaušo plokščių ir laminuotų medžio drožlių plokščių degumo tyrimais nustatyta, kad laikas iki užsiliepsnojimo yra funkcija, jungianti tokius argumentus, kaip laikas, per kurį pasiekiamas didžiausiasis šilumos išsiskyrimo greitis, visa išskirta šiluma, didžiausiasis šilumos išsiskyrimo greitis, paviršinio šilumos srauto dydis, kuriuo veikiamas bandinys, ir efektyvioji degimo šiluma.
7. Nustatyta, kad impregnavus antipireniniais tirpalais „BAK-1“ ir „Flamasepas-2“ orientuotųjų medienos skiedrų plokštes ir medžio drožlių plokštes, galima sumažinti jų degumo klasę (iš D į C) ir CO_2

koncentraciją (iki 4 kartų), tačiau degant tokiems gaminiams susidarančių dūmų kiekis beveik nesikeičia.

8. Išvestos empirinės lygtys, leidžiančios prognozuoti impregnuotų ir neimpregnuotų plokščių laiką iki užsiliepsnojimo pagal šilumos srautą, kuriuo veikiamas bandinys, o tiksliau – ir jų storį.
9. Pagal gautus tyrimų rezultatus sukurta metodika, leidžianti nustatyti medinių konstrukcijų impregnavimo antipireniniais tirpalais kokybę pagal suminio šilumingumo ir liekanų masės tyrimo rezultatus.

Trumpos žinios apie autorių

Vladas Praniauskas gimė 1983 m. gruodžio 1 d. Vilniuje.

2006 m. įgijo saugos inžinerijos bakalauro laipsnį Varšuvos aukštojoje ugniagesybos mokykloje. 2008 m. įgijo saugos inžinerijos magistro laipsnį Vilniaus Gedimino technikos universiteto Statybos fakultete. 2008–2012 Vilniaus Gedimino technikos universiteto doktorantas. Šiuo metu dirba Priešgaisrinės apsaugos ir gelbėjimo departamento prie Vidaus reikalų ministerijos Gaisrinių tyrimų centre.

Vladas PRANIAUSKAS

INFLUENCE OF FLAME RETARDANTS ON FLAMMABILITY OF WOOD AND WOOD BASED PRODUCTS

Summary of Doctoral Dissertation
Technological Sciences, Civil Engineering (02T)

Vladas PRANIAUSKAS

ANTIPIRENŲ POVEIKIS MEDIENOS IR JOS GAMINIŲ DEGUMUI

Daktaro disertacijos santrauka
Technologijos mokslai, statybos inžinerija (02T)

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Vilniaus Gedimino technikos universiteto
leidykla „Technika“,
Saulėtekio al. 11, 10223 Vilnius,
http://leidykla.vgtu.lt
Spausdino UAB „Ciklonas“
J. Jasinskio g. 15, 01111 Vilnius